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Air Force Cambridge Research Laboratories

REPORT ON RESEARCH

For the Period July 1967 – June 1970

387

AFCRL-71-0022

Report on Research at AFCRL

JULY 1967 — JUNE 1970

SURVEY OF PROGRAMS AND PROGRESS

THE AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
AIR FORCE SYSTEMS COMMAND
BEDFORD, MASSACHUSETTS

DECEMBER 1970

AIR FORCE (1) 19 FEBRUARY 1971 - 450C

Foreword

This is the fifth in a series of *Reports on Research* at the Air Force Cambridge Research Laboratories issued over the past ten years. With this report, AFCRL concludes the first 25 years of its history, a history that began on September 20, 1945, when a new Army Air Force research laboratory was established in Cambridge, Mass., with the unpromising name, the Cambridge Field Station. Over the next 25 years, the laboratory was to make contributions to Air Force operations, to technology, and to scientific knowledge out of all proportion to its size and to the Air Force investment in its programs. This report covers a three-year segment of the AFCRL history through June 1970. A most cursory survey of the report will reveal that the AFCRL program spans a broad domain. But in this breadth and diversity, one is returned again and again to a unifying tonic chord—to the Air Force missions of surveillance, detection, communications and navigation. Explicitly or tacitly, the chord is always present in the text. In examining the report, one sees that a sizable portion of the research involves the aerospace environment. Environmental forecasting, a goal of this research, may well come to be recognized as AFCRL's most enduring legacy. Presently a tentative and imperfect Air Force capability, environmental forecasting, if it is to be realized for the Air Force in the full measure that AFCRL's ambitions set for it, will be realized through the kinds of research—electromagnetic-atmospheric interactions, optical and radio astronomy, solar particle emissions. studies of atmospheric composition, chemistry and density—that for the period of this report engaged much of AFCRL's attention.

DALE J. FLINDERS
Colonel, USAF
Commander

Contents

Air Force Cambridge Research Laboratories

This report covers the research programs of the Air Force Cambridge Research Laboratories (AFCRL) for the three-year period, July 1, 1967 through June 30, 1970. AFCRL is an element of the United States Air Force and is the Air Force center for research in the environmental and physical sciences. The main laboratory buildings of AFCRL are located at L. G. Hanscom Field at Bedford, Mass., 20 miles west of Boston.

The research programs of AFCRL are conducted within the context of the following statement: *Conducts research in those areas of the environmental, physical and engineering sciences offering the greatest potential to the continued superiority of the Air Force's operational capability; conducts specifically assigned exploratory development efforts involving the environmental, physical and engineering sciences; participates in establishing advanced technologies whose exploitation will lead to new Air Force capabilities.*

AFCRL, A GENERAL VIEW: Research in the environmental and physical sciences referred to in the mission statement can be translated to mean geophysics and electronics. Geophysics includes geology, geodesy, meteorology, upper atmosphere chemistry and dynamics, solar phenomena, radio and optical astronomy and the properties of near space. Electronics research at AFCRL includes data processing, communications, electronic materials and devices, antenna systems, plasma studies and much else.

AFCRL's main laboratory complex is located at L. G. Hanscom Field, Bedford, Mass., 20 miles west of Boston.

To carry out this research, AFCRL, as of June 30, 1970, had a complement of 1235 military and civilian personnel —1058 civilians and 177 officers and airmen. This represents an increase of 133 over the total complement of 1102 three years earlier at the beginning of the reporting period. The general ratio of military to civilian personnel—about 15 percent—has remained unchanged for the past ten years. The period saw a substantial increase in the PhD ratio. On July 1, 1967, the number of doctorates at AFCRL was 135. On June 30, 1970, the number had increased to 162.

AFCRL is an in-house laboratory. This means that most of the research at AFCRL is conceived and conducted by AFCRL scientists. The in-house research is supplemented by contract research. Purely contractor research will not be reviewed in this report, except where it is so closely interwoven with in-house programs that separate discussion would be artificial.

Each of the several hundred research tasks making up the total AFCRL program is related to an Air Force requirement. Among the Air Force requirements to which AFCRL is particularly sensitive are reconnaissance, surveillance, detection, communications, information processing and use, environmental prediction, and aircraft and missile operations.

"Requirements" has close kinship to "relevance." Relevance in the context of DOD research came into high prominence during 1969 with the passage of Section 203—the Mansfield amendment. This amendment brought with it in late 1969 a re-examination of all AFCRL research endeavors—a re-examination that is continuing. As a result, several long-term research programs were marked for termination.

But the Mansfield amendment was in

itself only a manifestation of a deep change in attitudes in many quarters toward the role of science and the DOD support of it. Faced with revised criteria against which to judge his research programs, the R&D manager was forced to reappraise past assumptions. Should the research of an especially qualified and nationally recognized scientist, for example, be supported at a high level even though his research may be of less direct Air Force relevance than the research of others? AFCRL, historically, has given an affirmative answer, the rationale being that benefits accrue to the Air Force by bringing to military planning a special expertise in the evaluation of technical endeavors.

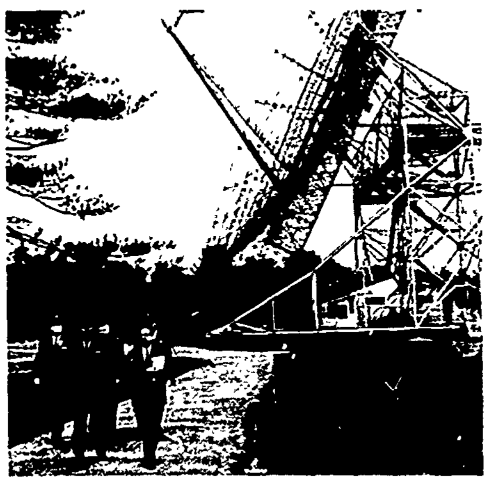
In this connection, AFCRL has encouraged the participation of its scientists in the affairs of professional societies. Such participation, it is believed, lends vitality and substance to a research laboratory and reflects prestige on Air Force research. One form of participation is the editorship of professional journals. As of June 30, 1970, for example, two major professional journals, *Applied Optics* and the *IEEE Transactions on Antennas and Propagation*, were edited by AFCRL scientists, and AFCRL scientists served as associate editors on two other journals, the *Journal of Applied Meteorology* and the *Journal of Crystal Growth*.

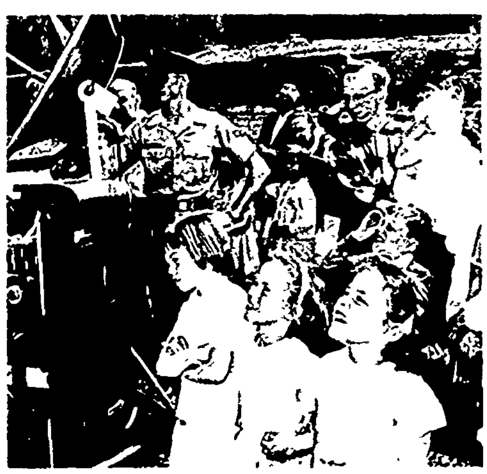
AFCRL is an in-house laboratory, its own scientists initiating and conducting a research program that spans a large part of the physical and environmental sciences.

TRANSFER TO AFSC: On July 1, 1970, AFCRL was transferred to the Air Force Systems Command where it reports to AFSC's Director of Laboratories. At that time, AFCRL's previous headquarters, the Office of Aerospace Research, was discontinued, and all Air Force research and development activities were unified under a single command.

During the current reporting period, however, AFCRL reported to the Office of Aerospace Research, an independent Air Force element with headquarters in Arlington, Virginia. OAR was a small element, numbering about 2000 persons, 1200 of whom were at AFCRL. OAR came into being in April 1961, when the old Air Research and Development Command was abolished and separate commands for research and development were established. The transfer of Air Force research under AFSC therefore constitutes a remerger of Air Force reseach and development under a single command.

The purpose of the merger was to effect a closer coupling between research and development to assure that the products of research will more quickly be translated into Air Force technology. It is expected that savings in manpower will also be effected through the operation of a single headquarters staff, an important consideration during a period of declining military budgets.



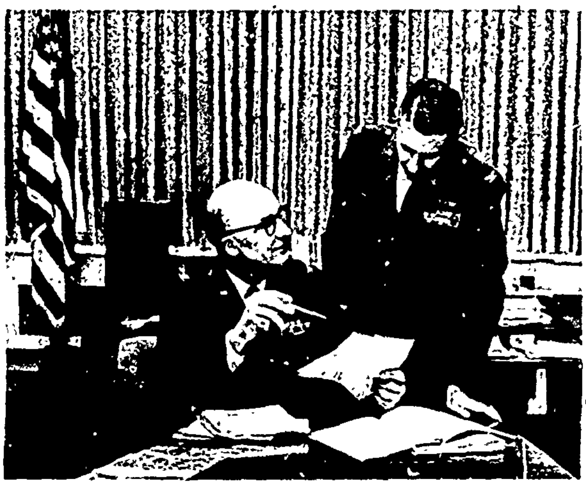


ORGANIZATIONAL STRUCTURE: At the conclusion of the reporting period, AFCRL consisted of ten laboratories plus the Sacramento Peak Solar Observatory in New Mexico. These laboratories are the Data Sciences, Microwave Physics, Aerospace Instrumentation, Space Physics, Ionospheric Physics, Meteorology, Terrestrial Sciences, Optical Physics, Aeronomy, and Solid State Sciences Laboratories. In addition, AFCRL operates a small West Coast Office consisting of five persons whose primary responsibility is that of liaison with SAMSO and with AFCRL West Coast contractors. Another small detachment, Detachment 5, at Patrick AFB, Florida, was transferred from the jurisdiction of Hq. OAR to AFCRL in November 1969.

The laboratory structure noted above represents a change from that of the previous reporting period. Two new elements were carved from the nine laboratories of three years ago. From the Upper Atmosphere Physics Laboratory and the Space Physics Laboratory, those programs relating to ionospheric research were taken to form a new laboratory, the Ionospheric Physics Laboratory. The Sacramento Peak Observatory was removed from the Space Physics Laboratory and became a separate organizational entity. Concurrently, the reduced Upper Atmosphere Physics Laboratory was redesignated the Aeronomy Laboratory. These organizational changes became effective on March 4, 1968.

In July 1968, Colonel Dale J. Flinders became the Commander of AFCRL, succeeding Colonel Robert F. Long. Colonel Flinders came to AFCRL from his position as Commander of the USAF Environmental Technical Applications Center in the Air Weather Service. The AFCRL Vice Commander was Colonel Orville J. Kvamme, who reported to AFCRL in August 1967 and whose assignment terminated on July 1, 1970,

AFCRL is a frequent host to visitors in many categories. *Upper Left:* Three officers of the Royal Thailand Air Force visited one of AFCRL's C-130 flying laboratories which conducted experiments in Thailand. *Upper Right:* Under Secretary of the Air Force Dr. John L. McLucas (l) was at the Sacramento Peak Observatory for the dedication of the AFCRL Solar Tower Vacuum Telescope. *Center Left:* Walter Cronkite and a CBS-TV camera crew spent a day at AFCRL gathering material which later appeared in two CBS documentaries. *Center Right:* AFCRL Commander Colonel Flinders (l) escorts visitors from higher headquarters to the Sagamore Hill Radio Observatory. In the background is the 150-ft radio telescope. *Bottom Left:* With AFCRL's Van de Graaff generator in the foreground, visitors from the U.S. Navy listen to a discussion of AFCRL's radiation hardening research. *Lower Right:* At an Open House for families of AFCRL employees, a meteorological radiosonde was sent aloft by balloon.



AFCRL Commander Colonel Dale J. Flinders (l) assumed command in July 1968, succeeding Colonel Robert F. Long. At right is AFCRL Vice Commander Colonel Charles A. Smith who assumed the post in July 1970.

with his transfer to AFSC's Electronic Systems Division. Named as his successor as Vice Commander, effective July 1970, was Colonel Charles A. Smith.

THE YEARLY BUDGET: The yearly budgets of the three years of this report are shown in the accompanying tables. The figures are the total operating budget (except for certain services and supplies by other Air Force agencies) of AFCRL. The yearly totals cover salaries, equipment, travel, supplies, and those funds going into contract research. The largest single annual expenditure is for salaries which accounted for approximately $15 million of the FY-1970 budget of $55.1 million. The FY-1968 budget of $51 million was a ten-year low but the budget rebounded the following year in FY-1969 to $62.4 million largely because of a substantial increase in funds received from ARPA and DASA. The FY-1971 budget is expected to drop to the $50 million level.

The funds received from AFCRL's headquarters, OAR, and to a lesser extent those received from AFSC, are used to conduct programs of a continuing long-range nature. More discretion is provided AFCRL administrators and scientists in the expenditure of funds from these two sources than is allowed in the expenditure of funds from other sources. Funds from other agencies are earmarked for specific research projects.

AFCRL receives much support from other elements of the Air Force. The services furnished by AFSC elements at Hanscom Field with respect to procurement, personnel administration, aircraft maintenance, by Air Force test ranges with respect to rocket launch assistance and ground station operations, and by Holloman AFB, New Mexico, in its support of AFCRL's Sacra-

TABLE 1
SOURCES OF FY-1968 FUNDS

OAR	$42,406,500
AFSC	4,116,321
ARPA	1,571,700
NASA	611,000
DASA	1,786,356
Army	344,295
National Security Agency	129,397
Navy	38,000
Dept. of Commerce	500
TOTAL	$51,004,069

TABLE 2
SOURCES OF FY-1969 FUNDS

OAR	$47,298,146
AFSC	2,027,118
ARPA	7,155,188
DASA	3,954,884
NASA	1,664,692
National Security Agency	170,000
Navy	114,350
Army	59,600
Air Weather Service	24,456
TOTAL	$62,468,434

TABLE 3
SOURCES OF FY-1970 FUNDS

OAR	$43,495,000
AFSC	2,509,493
ARPA	5,665,072
DASA	2,302,707
NASA	815,092
National Security Agency	135,845
Navy	40,000
Army	69,742
Air Weather Service	19,952
FAA	30,000
AFLC	42,434
AFTAC	21,500
ESSA	231
TOTAL	$55,147,068

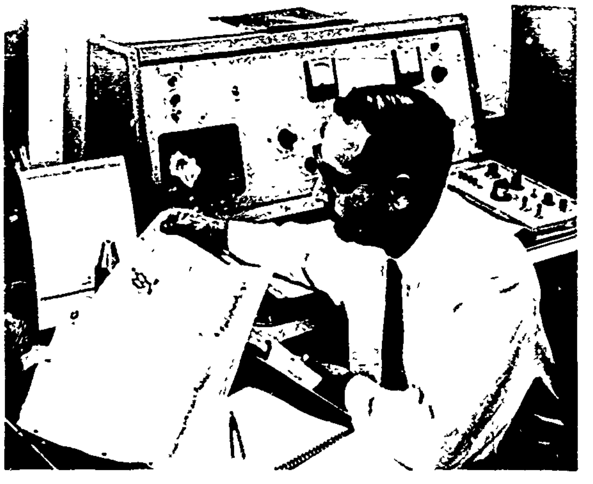
mento Peak Observatory and the Balloon detachment represent approximately 500 manyears of service, or the equivalent of a 40 percent augmentation of AFCRL's manpower complement of 1235.

More than half of the AFCRL budget during the reporting period was spent for contract research—mostly for the fabrication of special instruments or for the reduction and analysis of data. The average value of each contract is small relative to that of contracts managed by Air Force development laboratories. Of the $55.1 million FY-1970 budget, $28.7 million was expended for contract research. As of June 30, 1970, AFCRL had 601 contracts in effect. Of these, 201 were with industrial concerns, 208 were with U.S. universities, and 133 were with foreign universities and companies. The remaining 59 contract documents were with research foundations, other government agencies and for special procurement actions.

The character of AFCRL's contract program differs substantially from the contract programs of most other government R&D laboratories. AFCRL contracts almost always call for work that is in direct support of research carried out within AFCRL. They are monitored by scientists who are themselves active, participating researchers, and who plan the research, initiate a line of inquiry, organize the program, interpret the results and share the workload of the actual research.

CAPITAL ASSETS: The replacement cost of AFCRL's facilities, research equipment, computers and library collection would be about $68.3 million. This figure does not include the five AFCRL research aircraft. The two KC-135 and three C-130 aircraft—airframes and interior instruments—have an estimated value of $33 million. Nor does the figure include AFCRL's new computational facility which is scheduled for occupancy in November 1970. Cost of this new building, located within the

At the Smithsonian museum in Washington, D.C., a display on AFCRL's balloon program was exhibited for 18 months. Part of the display is shown here.

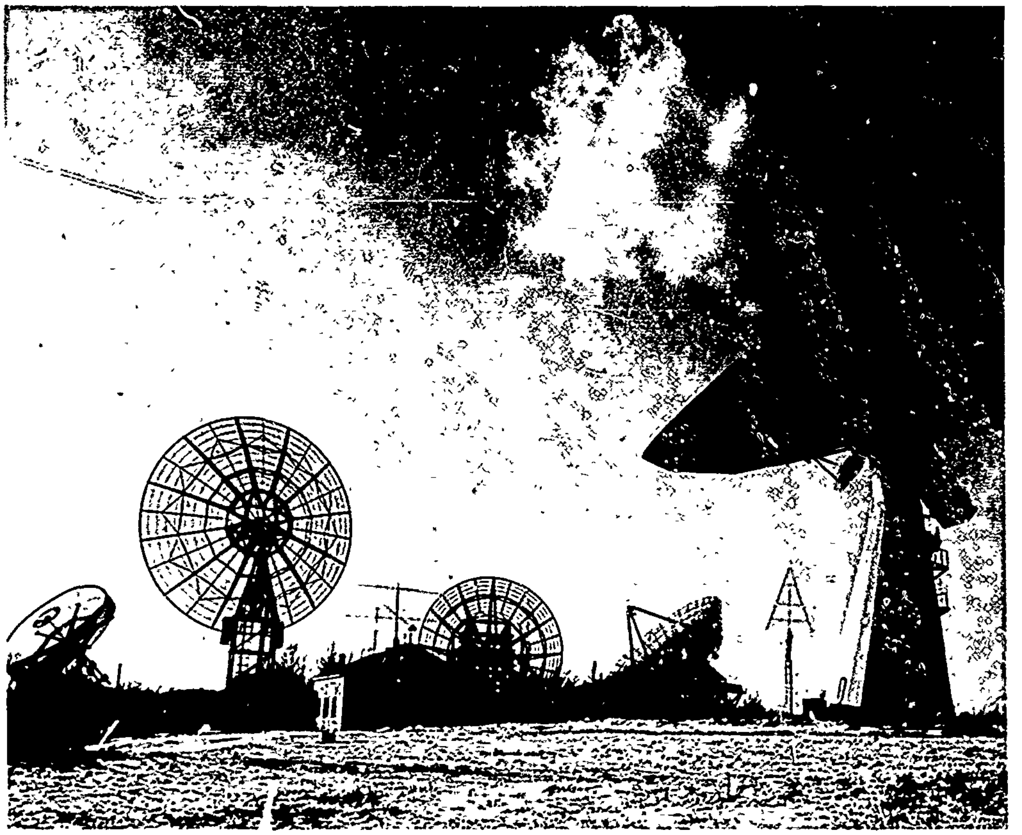


Of 1235 AFCRL employees (as of June 30, 1970), more than 600 are scientists and engineers. Of this number, 162 hold doctorate degrees.

main AFCRL laboratory complex, is $2 million.

The new building is one of two major facilities constructed during the period. The other is the solar vacuum telescope, towering 135 feet on the mountaintop occupied by the Sacramento Peak Observatory. This unique telescope, described in Chapter II, was dedicated and placed in operation on October 15, 1969. Cost of the facility and associated equipment was $1.5 million. Another new building is a small seismic facility located near the main complex at Hanscom Field and placed in operation in 1968.

The largest local site is the Sagamore Hill Radio Observatory in Hamilton, Mass., where AFCRL operates two large radio telescopes, one with an 84-foot dish, the other with a 150-foot dish. Also at the radio observatory are several smaller dishes, plus riometers and other equipments for monitoring ionospheric effects. Other local off-base sites are a weather radar research facility at Sudbury, Mass., and a 350-acre antenna range in Ipswich, Mass. Last,



At the Sagamore Hill Radio Observatory in Hamilton, Mass., are a number of large dishes and antenna arrays, many of which are shown here. In the foreground, at right, is the 84-ft radio telescope.

in Waltham, Mass., the Laboratory operates a high-precision millimeter wave radio telescope (15 to 100 GHz).

Outside Massachusetts, AFCRL has large permanent sites in New Mexico, Arizona, and California. One of AFCRL's two balloon launch facilities is located in New Mexico, at Holloman AFB; the other is at Chico, California. At Sunspot, New Mexico, is the Sacramento Peak Solar Observatory, perhaps the most completely instrumented facility in the world for solar optical astronomy. A new facility, the Lunar Laser Observatory, was established during the period 40 miles north of Tucson, Arizona. This observatory, funded in part by NASA, is operated by five AFCRL employees and was constructed for the sole purpose of conducting lunar ranging experiments in connection with reflector arrays placed on the moon by Apollo astronauts. The facility has a 60-inch telescope through which laser light is passed. The reflected light is then detected by the same telescope.

The most remote permanent facility is the Geopole Observatory near Thule, Greenland, a site that has been operated by AFCRL since 1958. From this site, AFCRL has obtained a 12-year continuous record of arctic magnetic activity, auroral phenomena and ionospheric variations. Originally contractor-operated, the site has been manned by AFCRL employees (usually about three) since 1968.

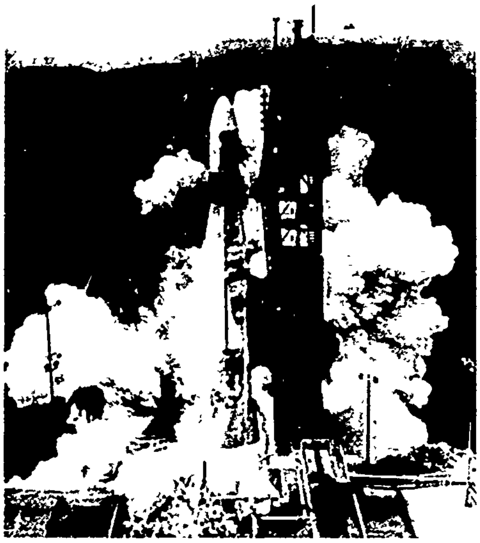
Four additional observatories, none of which are AFCRL facilities in the sense of those described above, should be noted. One of these is a new lunar-planetary observatory with a 24-inch telescope located at an elevation of 13,000 feet on Mauna Kea, Hawaii. AFCRL funded the construction of this observatory which initially was operated jointly by AFCRL and the University of Hawaii. It was placed in operation in 1968, but because AFCRL in 1970 terminated its lunar-planetary studies, the use of the facility will revert largely to the University of Hawaii.

Because of AFCRL's early funding of the Cerro Tololo Observatory in Chile, AFCRL stellar astronomers have enjoyed special observing rights at the facility since it was placed in operation in 1967. A programming realignment in the early part of 1970 resulted in the discontinuance of AFCRL's use of this observatory.

During the period, AFCRL, on behalf of the Air Weather Service, established a new radio observatory in the Philippines. Although AFCRL radio astronomers periodically use the site and regularly obtain data from it, this facility is not on the roster of AFCRL field sites. Nor is NASA's Wallops Island, Virginia, radar site where AFCRL radar meteorology personnel make extensive use of the powerful radars.

In addition to the permanent installations which AFCRL operates or uses, a number of temporary sites are established annually for special observations or operations. In the case of a meteorology site at Liberal, Kansas, trailers are transported each summer from Hanscom Field to leased acreage covering five square miles of wheatfields for studies of small-scale meteorological phenomena. More typical of temporary field sites were the eight sites set up to observe the March 7, 1970 solar eclipse.

RESEARCH VEHICLES: AFCRL is one of the largest users of research vehicles in the country. From its balloon launch sites in New Mexico and California, AFCRL during the three-year period launched 384 large research balloons, 125 of these being in FY-1970. These balloons carried payload packages and experiments for SAMSO, DASA,



On July 11, 1968, two AFCRL satellites, the OV1-15 and OV1-16, were placed in orbit by this booster.

NASA, the Army and university scientists with military contracts. AFCRL scientists, however, are the largest users. The AFCRL balloon group holds all the balloon records with respect to maximum balloon size (34 million cubic foot volume), maximum altitude reached (161,000 feet), and maximum payload carried aloft (seven tons)—records as of June 30, 1970.

During the past three years, AFCRL launched a total of 166 research rockets with most of these being launched from Eglin AFB, Florida (57), Ft. Churchill, Canada (54), White Sands Missile Range (14), and Wallops Island (13). In addition ten were launched from Brazil, nine from Puerto Rico and seven from Kauai, Hawaii. Since the launch of its first rocket in August 1946—a German V-2—AFCRL as of June 30, 1970, had launched a total of 807 large research rockets. An equal number of smaller meteorological rockets have been launched.

Rockets are used to examine almost every aspect of the earth's upper atmosphere and near-space environment—atmospheric winds, temperatures and densities; the electrical structure of the ionosphere; solar ultraviolet radiation; atmospheric composition; the earth's radiation belts; cosmic ray activity; and airglow and the aurora. The kinds of rockets most frequently used by AFCRL are the Nike Iroquois (NIRO), the Nike Cajun, the Black Brant, and Aerobee.

Satellite instrumentation in recent years was somewhat diminished from that of the middle 1960's. The previous reporting period, covering two years, had seen AFCRL-designed payload packages installed in 25 NASA and Air Force satellites. During the three-year period of this report, AFCRL-designed packages were carried aboard 13 satellites. Only five of these satellites were exclusively instrumented by AFCRL.

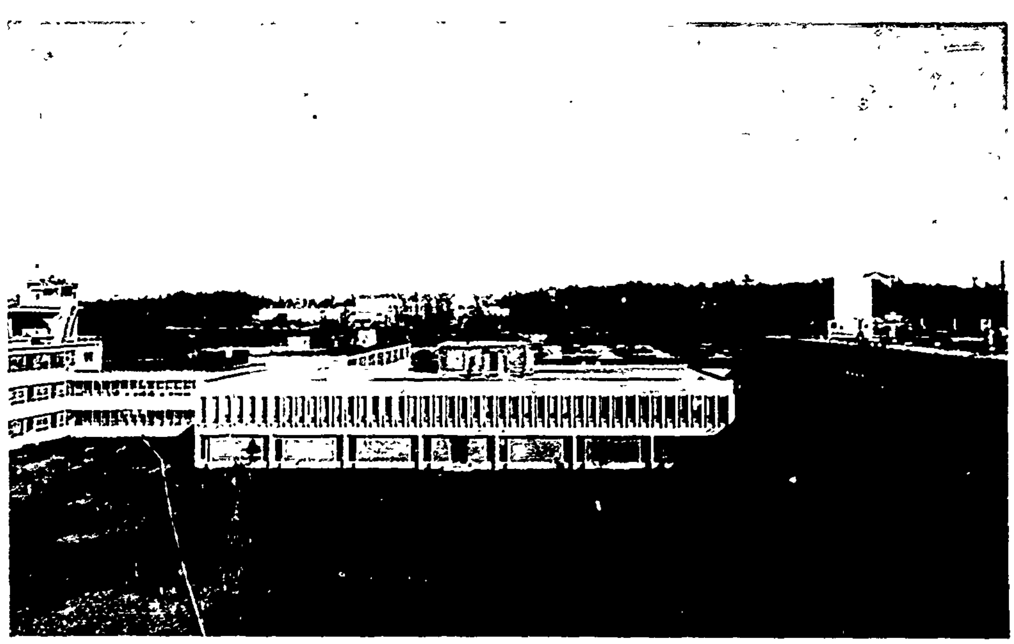
During the three-year period of this report, AFCRL launched 166 large research rockets, one of these being the Javelin shown here as it was uncrated at the Churchill Research Range in Canada.

AFCRL uses a fleet of five instrumented aircraft—two KC-135s and three C-130s. The KC-135s have been a part of the AFCRL inventory for more than a decade, and the C-130s for almost as long. In 1969, one of AFCRL's older C-130's, a plane with a long AFCRL history going back to arctic research in the 1950's, was replaced by a later model. Two of the aircraft, a KC-135 and a C-130, are instrumented for measuring the transmission, scattering and reflectance of optical radiation in the atmosphere. The other KC-135 is used for making ionospheric and associated observations, observations that take the aircraft all over the world, but with recent focus being on the arctic auroral zone. Another C-130 is instrumented for meteorological observations, while the third (the recently acquired replacement) is used for airborne remote sensing and gravity measurements.

SERVICES AND SUPPORT: Services and support consist of engineers and machine shops to design and fabricate special instruments and hardware, computational capability, library acquisitions, logistical planning for field expeditions, travel arrangements and diplomatic clearances, supplies, editing, technical photography, artwork and publications.

Research productivity is geared—closer than is generally acknowledged—to the quality and responsiveness of the service and support functions. OAR broadly delegated to its Laboratories the administrative flexibilities to assure that the services and support functions react sensitively and promptly to the needs of laboratory scientists.

Thus, decisions to sponsor national and international scientific conferences (22 of which AFCRL sponsored during the three years of this report) has resided at AFCRL. AFCRL has had local



AFCRL's new Computation Center was occupied in late 1970. The Center houses a CDC 6600.

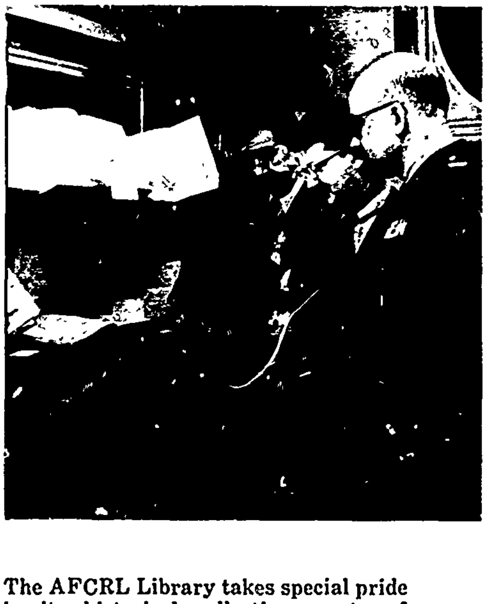
authority for a range of equipment and supply purchases and for logistics actions. The responsibility for clearing all scientific papers was similarly delegated by OAR. In this connection, AFCRL scientists published 183 in-house reports, presented 1035 papers at scientific meetings, and published 709 articles in scientific journals during the three years ending June 30, 1970. These publications and presentations are listed at the conclusion of each laboratory chapter of this report.

A service of basic importance is that of preparing and analyzing data acquired from observations. The basic computer in AFCRL's general computation center during the three-year period was a dual IBM 7094-II and IBM 7044 system. In November 1970, with the completion of the new computer building, this system will be replaced by a CDC 6600, a system with more memory, faster speed, larger capacity, and more auxiliary storage than the existing system. The CDC 6600 time-sharing computer allows for the placement of remote terminals in various laboratory work areas within the main AFCRL complex.

The very presence of an outstanding library collection, such as that of the AFCRL Research Library, quite apart from the convenience of ready access to all needed references, lends a special quality of scholarship and an added dimension to AFCRL's research environment.

The library's geophysics collection is exceeded by few research libraries in the world. Each year, the library acquires some 4500 new monographs and it regularly receives more than 2200 periodicals. Among these periodicals are the scientific journals of Red China, making the library a national collection center for Chinese scientific literature. In connection with the foreign journals received by the library, the library maintains a translation service through which foreign journal articles, on the request of scientists, are translated into English and made available to the scientific community.

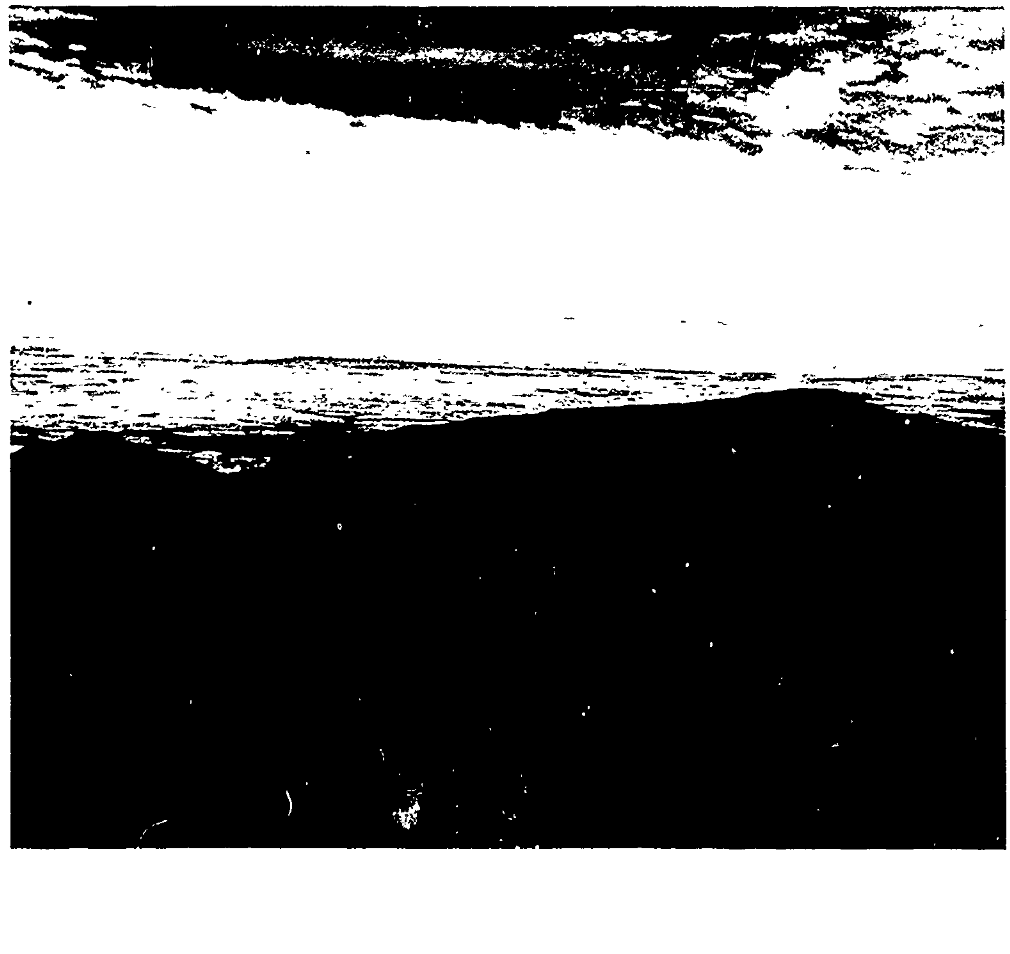
A 1963 search for airglow data, known to have been gathered by the Fourth Lord Rayleigh early in this century, led to the fortuitous acquisition at almost a token cost of the original scientific notebooks of both the Third and Fourth Lords Rayleigh. These became the basis for the library's Rayleigh archival collection. The library's extensive historical collection (again fortuitously acquired soon after World War II) contains the complete set of the *Philosophical Translations of the Royal Society of London* dating back to 1665, the *Histoire of the Paris Academy* dating back to 1699, and the *Commentarii of the Russian Academy of Science* dating back to 1726.



The AFCRL Library takes special pride in its historical collection, parts of which are periodically placed on display. A number of science volumes of the late 18th and early 19th Centuries are on display here.

THE CLASSIFIED PROGRAM: This report does not cover the total AFCRL program, but only that portion that can be discussed outside the constraints of security. About 10 to 15 percent of the AFCRL program is classified, at best a rough estimate. An attempt to shred out the relative amounts of AFCRL resources expended on classified work would result in many arbitrary judgments since instruments and equipments used for classified research also serve for unclassified research programs, and seldom does any one scientist work exclusively on one particular classified project.

The Sacramento Peak Observatory is located atop a peak at 9200 feet altitude in the Sacramento Mountains in New Mexico. In the valley below are the White Sands Missile Range and Holloman Air Force Base.



II The Sacramento Peak Observatory

The Sacramento Peak Observatory is a facility of the United States Air Force. Established in 1952, it is among the world's leading solar research centers. The Observatory is located at an altitude of 9200 feet at Sunspot, New Mexico, about 17 miles south of Cloudcroft. It sits atop a peak of the Sacramento Mountains where clear skies prevail most of the year and the atmosphere is turbulence-free and transparent.

The Peak is relatively isolated and most Observatory employees and their families—150 people—live on the grounds. From the Observatory, they can see the flat New Mexico desert floor stretching far below. Clearly viewed are the White Sands Missile Range and Holloman AFB, both closely associated with other AFCRL research activities —rocket launches from White Sands, and balloon launches from Holloman AFB.

The Sacramento Peak Observatory is concerned with the sun's visible spectrum, the region to which the eye is most sensitive. Other AFCRL laboratories observe other regions of the electromagnetic spectrum. AFCRL's Ionospheric Physics Laboratory (Chapter VI) with its radio telescopes observes solar radio emissions in the meter, centimeter and decimeter regions. The Microwave Physics Laboratory (Chapter IX) observes millimeter wave emissions. The Optical Physics Laboratory (Chapter IV) observes the infrared. And the Aeronomy Laboratory (Chapter VIII) observes x-ray and ultraviolet radiation. It is unlikely that

Dr. John W. Evans has been Director of the Sacramento Peak Observatory since it was first placed in operation in 1952.

any other laboratory in the world can match the scope and depth of AFCRL's solar observation program or has approached the problem of solar-terrestrial effects on such a comprehensive front.

The sensitivity, range and resolution of Air Force electromagnetic systems for radar surveillance, optical/infrared reconnaissance, communications and navigation at any given time are predetermined by some prior state of the sun. Throughout this report are references to these systems and to their performance under shifting and changing environmental conditions. The sun is the dominant modulating influence on the environment in which these systems operate.

The ionosphere and its effects on radio propagation, light emissions from airglow and aurora and effects on optical reconnaissance, and atmospheric densities and temperatures and effects on missile targeting are all controlled by precursor states of the sun. The basic reason that the Air Force maintains and supports solar research is the tactical and strategic advantage that can be gained from the ability to predict the level of performance of EM systems days, weeks and perhaps months into the future.

TELESCOPES AND INSTRUMENTATION

During the previous reporting period, the Sacramento Peak Observatory was administratively a part of AFCRL's Space Physics Laboratory. In March 1968, it was given separate laboratory status under AFCRL. In previous

The two principal Observatory buildings at Sac Peak are the Big Dome in the foreground and the more recently completed Tower Vacuum Telescope.

AFCRL *Reports on Research*, the outstanding facilities of the Observatory were only sketchily touched upon. These past omissions will be corrected in this section which will be devoted to a rather complete survey of the facilities available to astronomers at the Observatory.

During the three years of this report, the single most important addition to the facilities was the Tower Vacuum Telescope. This is the most important new solar observing facility constructed anywhere in the world within the past decade. Principal speaker at the dedication ceremonies on October 15, 1969, was the Under Secretary of the Air Force Dr. John L. McLucas. Attending were a hundred or so officials.

With the completion of the tower vacuum telescope, the Sacramento Peak Observatory now has four basic observing facilities. These facilities and associated instruments are described below.

TOWER VACUUM TELESCOPE: The Observatory's tower vacuum telescope was placed in operation in October 1969. It is a unique instrument, the first in a new generation of specialized solar observing instruments. With an instrumental resolving power of less than 0.2 sec of arc, the telescope's acuity matches that of the most powerful telescopes—stellar or solar—in the world.

The telescope is 365 ft long. Of this vertical length, 227 ft are set in a deep shaft beneath the ground. The aboveground portion of the telescope is enclosed in a massive conical tower 138 ft high. The central core of the telescope consists of a 321-ft long evacuated tube having a maximum diameter of 10 ft. The entire optical system—from the objective port at the top of the tower to the 64-inch reflecting mirror at the bottom of the shaft—is contained in this evacuated chamber. The

The tower vacuum telescope is the most important new solar observing facility constructed anywhere in the world in the past decade. The new facility was dedicated October 15, 1969.

Instrumentation associated with the tower vacuum telescope is placed on a platform that revolves in carrousel fashion as the optical system rotates to follow the sun.

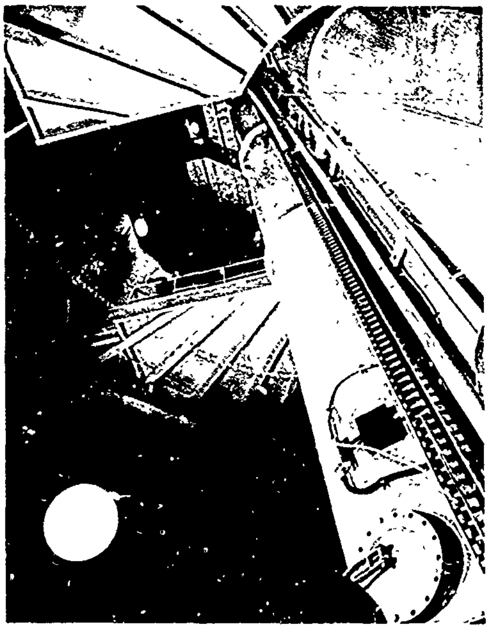
telescope was conceived and designed by a Sac Peak astronomer, Dr. Richard B. Dunn. Construction of the tower telescope began in April 1966.

The combination of the tower and vacuum features in a telescope of the size and complexity of the new Sacramento Peak telescope gives astronomers at the Observatory an instrument of unequaled image stability. The objective port is located well above most of the air turbulence and heat currents that swirl up when the sun heats the ground. This eliminates a major source of image dancing and jitter which obscure detail. Further image stability is achieved by enclosing the optical system in a vacuum, thereby eliminating internal air currents. This central tube weighs 250 tons and is evacuated to .25 torr, a pressure which corresponds to that found at an altitude of about 180,000 ft.

Additional protection against image-distorting heat currents across the incoming light beam is provided by embedding water-cooled pipes in the concrete walls of the tower. By controlling the temperature of the water flowing in these pipes, the temperature of the tower walls can be maintained at equilibrium with the air temperature outside the tower.

The vacuum tube is suspended from above like a pendulum and floats on an 11-ton pool of mercury located near the top of the tower. The mercury provides a friction-free bearing for smoothly rotating the entire core assembly for tracking the sun.

The telescope itself has an aperture of 30 inches. Light from the sun enters through a quartz window 4 inches thick and 34 inches in diameter. Two flat mirrors, each 43 inches in diameter, reflect the light (first along a brief horizontal path, then downward) through the 321-ft length of the cylinder to a



Vertically aligned within a central evacuated optical chamber of the tower telescope are two large spectrographs for photographic and photoelectric observations.

focusing mirror 183 ft beneath ground level. This 64-inch focusing mirror has a focal length of 180 ft. It can be tilted to direct light upward and to form an image of the sun on one of several selected instruments at ground level.

All of the instruments are clustered about the central shaft and rotate with the shaft. The largest of these instruments are two evacuated spectrographs for photographic and photoelectric observations. These spectrographs are mounted vertically pointing directly to the main mirror. Smaller instruments are located on the 40-ft diameter rotating platform at ground level.

BIG DOME: Since 1952, most of the Observatory's work has centered around the instruments in the Big Dome —a name informally assigned pending a more meaningful one. None was found, and in time, "Big Dome," came to be affectionately accepted in its own right. The structure is not a dome, but a cone designed to shed snow.

It houses five telescopes, four of which are located on a 27-ft equatorial spar. Of the four, three are 16-inch telescopes. The first, a 16-inch coronagraph designed primarily for observations of solar limb features, is of the standard Lyot type but with secondary optics that correct the chromatic aberration of the single lens objective. The coronagraph feeds light down through the hollow polar axis to form a fixed solar image in an observing laboratory.

A second 16-inch telescope is used for mapping magnetic fields in active centers on the sun. It has a compact spectrograph 6 ft long with a 10-inch grating, equipped with an analyzer for measuring sightline magnetic fields and velocities. A moving mirror system scans the solar image while a digital magnetic tape records the electrical signals from which a computer can map the field strength and velocity over the scanned area in the form of a contour diagram.

A third 16-inch single lens telescope photographs the sun through a birefringent filter that transmits either the H alpha line of hydrogen or the D_3 line of helium.

The fourth instrument is a 9-inch coronagraph with a scanning system and spectrometer for photoelectric measurements of the intensities of the coronal emission lines. The signal-to-noise ratio of the photoelectric cells is much larger than that of a photographic emulsion, and yields a correspondingly lower threshold of coronal measurement through the overwhelming light of the blue sky. Hence the coronal emission can be mapped to greater heights than is possible with photographic instruments.

The Big Dome, completed in 1952, was the first major facility constructed at Sac Peak. Within this facility are the Observatory's most sophisticated and varied instrumentation for research on the corona, prominences, and the magnetic fields in sunspot groups.

An additional 12-inch horizontal fixed telescope, fed by a coelostat mirror system south of the building, forms a second fixed image of the sun in the observing laboratory. It is a refractor of 37 ft focal length with an achromatic objective.

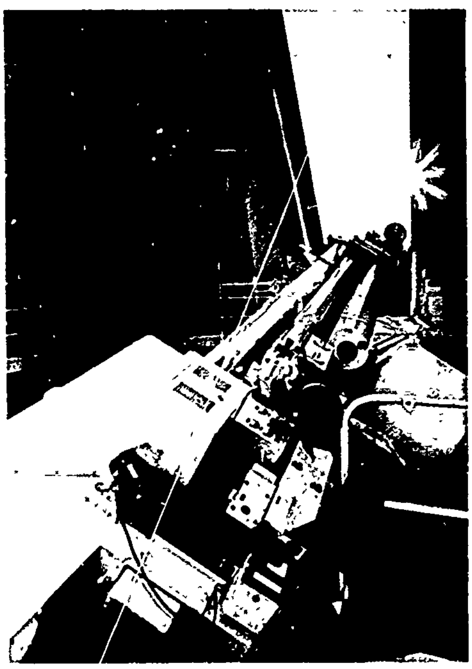
Associated with these telescopes are fixed instruments for analyzing the light. A 43-ft Littrow spectrograph is used either photographically or as a photoelectric double pass scanning spectrometer of high resolution. Several gratings are used interchangeably, to achieve dispersions from 2 to 18 mm per angstrom.

A fast universal spectrograph of medium dispersion photographs the spectrum from 3400 to 9000 angstroms. Its purpose is to study the faint lines of the corona and prominences, and to explore the spectrum of objects whose characteristic spectra are not fully known.

The spectroheliograph is unique. It is basically a scanning scatter-free double spectrometer which normally photographs the sun simultaneously in the light of the H alpha, D_3 and K (ionized calcium) lines. The level of scattered light in the double system is very low, a most important feature in an instrument which takes its light from the centers of dark absorption lines.

Finally, the observing laboratory has a dual camera system for photographing solar details simultaneously in the H alpha and K lines. A dichroic beam splitter sends blue light to one camera through a K line birefringent filter, and red light to the second camera through an H alpha filter. Its purpose is to match the small structures seen in the two lines, free of the ambiguities due to small image distortions introduced by rapid fluctuations in atmospheric refraction.

HILLTOP DOME: At the Hilltop Dome, the Observatory's solar patrol observations are conducted. By solar patrol is meant the photographic recording of the face of the sun routinely every minute or so throughout the day. Video cameras and magnetic recordings have large roles in the activities at the Hilltop Dome. The Hilltop Dome contains a 12-ft spar that carries patrol instruments and occasionally serves as a platform for experimental equipment. Recorded are all major solar activities, particularly the

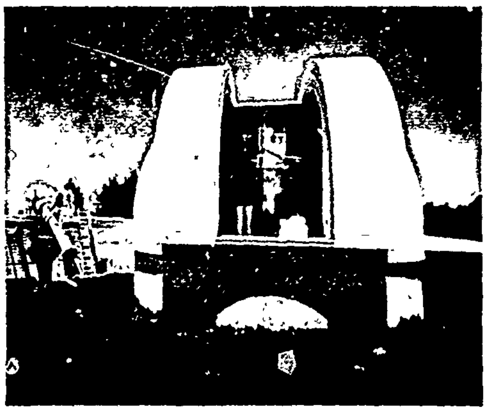


Four telescopes are located on a 27-ft equatorial spar in the Big Dome. Two views of the telescopes arrayed on this spar are shown.

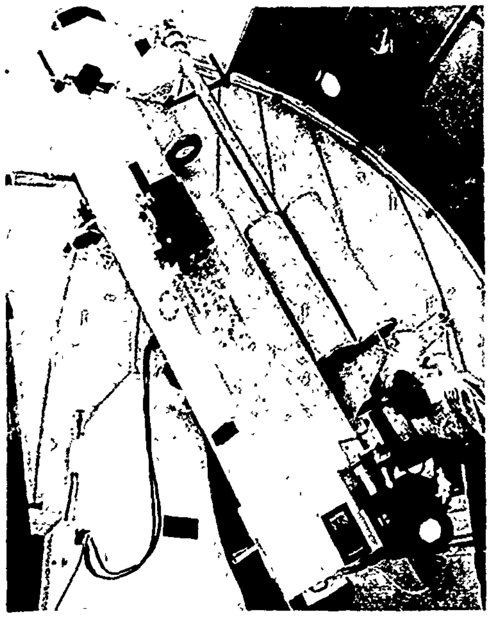
flares and associated phenomena responsible for the radiations that affect the ionosphere and nearby space. The two most important instruments are in the H alpha telescope and the white light sunspot telescope. Both run continuously, photographing the sun on fine grain 35 mm film at intervals varying from 10 seconds to 2 minutes (depending on the solar activity) whenever the sun is visible.

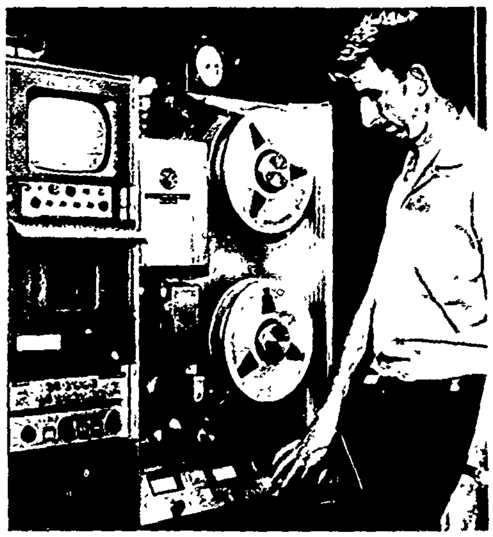
The H alpha telescope is a 4-inch single lens refractor with a half angstrom H alpha birefringent filter and a 35 mm cine camera actuated by a timer. A beam splitter between filter and camera reflects 30 percent of the light to a video camera. A programmer cycles the filter controls to take in series pictures at the center of the H alpha line, at plus and minus 0.5 angstrom in the wings of the line, and in the continuum 2 angstroms from line center.

The video camera and closed circuit TV are the sources for a real-time display of the H alpha image of the sun on monitor screens placed throughout the Observatory complex. No matter where an astronomer may be there is usually a TV screen handy showing the disk of the sun.



At the Hilltop Dome, the Observatory's solar patrol activities are conducted. By solar patrol is meant the photographic recording of the face of the sun each minute or so throughout the day.





On a 12-ft spar in the Hilltop Dome are mounted four telescopes for solar patrol observations. Associated instrumentation includes a video camera whose pictures are transmitted by means of a closed circuit TV system (lower photo) to TV screens throughout the Observatory complex.

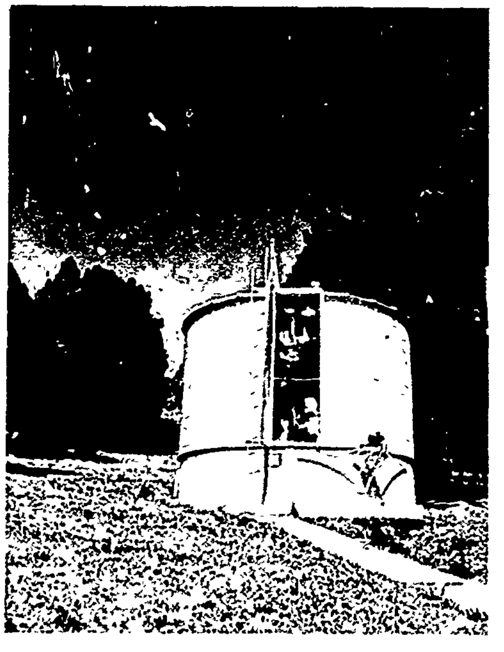
An important adjunct to the H alpha video system is the videometer. This device dissects the video signal and displays in real-time the area, peak brightness and integrated H alpha brightness of a flare on a three-channel chart record. Previously these data could be obtained from a long series of photographs only by an exceedingly laborious procedure, long after the event.

The white light patrol telescope is a simple 6-inch refractor that forms a 22 mm solar image in a second 35 mm cine camera controlled by a timer. An extremely fine grain film easily shows the small-scale granulation of the solar surface in spite of the small image size. The purpose of the white light telescope is to follow the development of the sunspots.

A third instrument on the 12-ft spar, known as the "quad telescope," consists of four 8-inch reflectors each of which forms an image of a small area from a large solar image through an H alpha filter on one quadrant of a video camera. The four mirrors can be pointed independently to show four different active centers on the sun with a larger scale and better resolution than is possible with the smaller H alpha telescope. A standard video tape records the four images at intervals of 10 seconds. They can be played back at 30 frames per second providing a cine display of the activity for the past couple of hours speeded up by a factor of 300.

GRAIN BIN DOME: This "dome," a modification of a Sears-Roebuck grain bin, is the oldest instrument shelter on Sacramento Peak. Erected in 1951, it contains a 10-ft spar on which are mounted two patrol instruments, a 4-inch spectrocoronagraph and a 6-inch cine coronagraph. Both are used primarily for coronal observation.

The spectrocoronagraph has a 6-ft Littrow spectrograph for photographing the coronal emission lines at all position angles around the limb in 8 exposures. Normally, one set of exposures per day is sufficient to keep track of the relatively slow changes in the coronal spectrum.



The first telescopes at Sac Peak were installed in the Grain Bin Dome (it's actually a grain bin purchased from Sears-Roebuck) erected in 1951. It contains a 10-ft spar on which are mounted a 4-in spectrocoronagraph and a 6-in cine coronagraph.

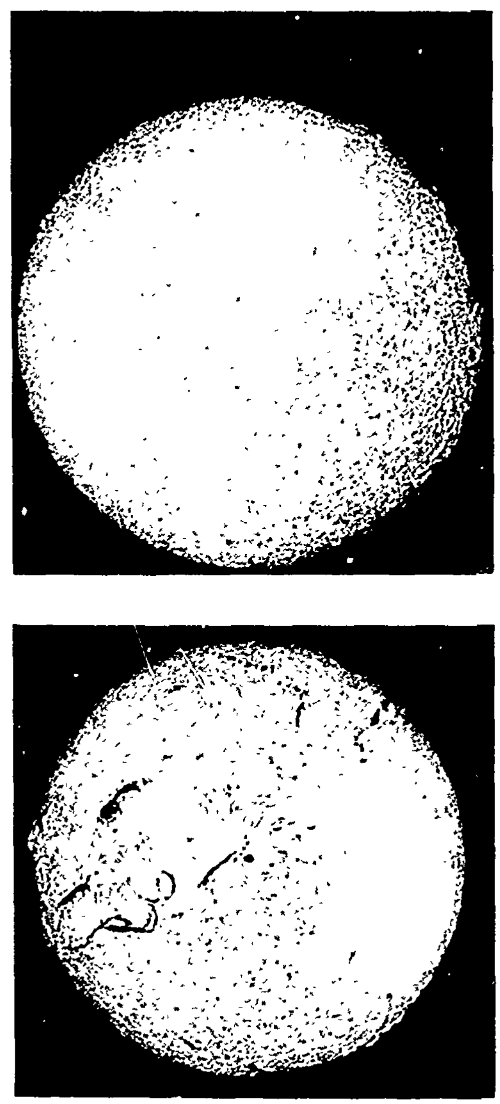
The cine coronagraph records a 60-degree sector of the solar limb on 35 mm film at timed intervals. It has a birefringent filter that can be adjusted to either the green coronal line (5303 angstroms) or the H alpha line. It produces time-lapse movies of coronal changes, which had been little observed until this coronagraph showed surprising bursts of vigorous activity, often associated with parallel prominence activity. The Sacramento Peak Observatory is the only institution to make movies of the corona regularly.

THE SUN: GENERAL PROPERTIES

The sun is the one sample star near enough to earth to be studied in detail. It is an astrophysical laboratory where magnetic and plasma phenomena on a gigantic scale can be observed directly.

The sun is a 1.4 million km diameter globe of hydrogen and helium gas, with traces of all the remaining elements, many of which show up prominently on the solar spectrum in spite of their exceedingly low abundances. The thermonuclear conversion of hydrogen to helium at the center provides the prodigious flux of energy which escapes from the surface mainly as radiation in the visible and infrared regions of the spectrum, but with small amounts of energy which have been detected over the whole spectrum from x-rays to the longest radio waves. Another minor fraction of the energy escapes as a steady flux of low energy particles that constitute the solar wind, and sporadic bursts of faster particles varying in energy from a few keV to a few GeV.

Observation of the sun is limited to the transparent solar atmosphere down to the white surface, which is the sharp upper boundary of an opaque fog of negative hydrogen ions at a temperature of 6000 degrees K. The temperature decreases through the 300 km photosphere to a minimum of about 4300 degrees in the lower chromosphere. It then rises through the 1000 to 2000 km layer of the chromosphere to about 100,000 degrees at the abrupt interface with the overlying corona. Here the temperature suddenly increases to the coronal level of about 1,500,000 degrees, with a corresponding drop in density. Beyond the interface, the temperature



Hydrogen-alpha photo of the quiet sun (above) and the active sun (below) are shown. These photos were taken in opposite phases of the 11-year solar cycle.

and density in the corona gradually decrease with no further known discontinuities until they merge with the interstellar background somewhere beyond the earth's orbit.

The normal solar atmosphere is the scene of constant and vigorous action. The white surface consists of bright granules, the tops of rising hot convective cells analogous to cumulus clouds, separated by a canal-like network of darker downward moving material. The photosphere and lower chromosphere are traversed by vertically oscillating waves that probably carry the energy that sustains the high temperatures of the chromosphere and corona. Through the chromosphere, a fur of hair-like spicules shoot up several thousand km into the corona with velocities of 20 or 30 km/sec. All of this action occurs in the presence of magnetic fields, the influence of which is not as yet understood.

ACTIVE FEATURES: The steady state sun is occasionally disrupted by the onset of an active center, a region of strong magnetic field which excites and powers a number of spectacular features known collectively as solar activity. Sunspots are the most conspicuous of these. They are visible in the simplest tele-

The quiet chromosphere contains this forest of spicules which reach typical heights of 5000 km and last 10 to 20 minutes. They feed material upward to maintain the steady flow of the solar wind and replace coronal losses by condensation into prominences.

scopes and were discovered by Galileo and Scheiner in 1610. Sophisticated instruments that transmit only the light of a single line in the spectrum like H alpha of hydrogen, reveal a great deal more in an active center (as well as in the undisturbed regions). The slowly varying features in addition to the sunspots are the plages and stable dark filaments, which generally endure through the lifetime of the active center, anywhere from a few hours to several months.

The most exciting activities, however, are the explosive flares and the many fast phenomena associated with them. The flare itself appears as an irregular bright patch in an active center, which reaches its greatest size and intensity in a matter of minutes, and then fades somewhat more slowly back to invisibility. Associated with the flare may be surge prominences and sprays, lancing 100,000 km or more up into the corona, and loop prominences surrounded by abnormally hot (4,000,000 degrees) coronal condensations.

A flare's invisible features are more significant than its visible ones. Vigorous bursts of radio synchrotron radiation, which vary in form and intensity over the whole frequency range from 10 MHz to 300 GHz, signal the emission of corresponding bursts of fast particles with sufficient intensity to alter drastically the content of interplanetary space and the structure of the earth's ionosphere. The x-ray brightness of a flare often exceeds that of a blackbody at 100,000,000 degrees. The magnetic field of the active center is the only known source of energy adequate for these phenomena, but the physical mechanism of the energy conversion is not understood, and will not be until more sophisticated observational data from the ground and from space are available.

RESEARCH PROGRAM

The research at the Observatory is concerned with the physical characteristics (temperature, density and size scale) and dynamics of the inhomogeneous solar atmosphere and active features. The program emphasizes the role of the structure of magnetic fields, particularly in the active centers where magnetic fields dominate all other influences.

The goal of this research is that of forecasting the onset and magnitude of those flares which are the source of the explosive emissions that so profoundly affect the aerospace environment. At the present time, families of prediction indices are elusive. But relatively coarse indicators, leading to short-term probabilities that events of magnitude will occur, are available and are useful.

With the knowledge presently available, Sacramento Peak astronomers have assisted the Air Weather Service in formulating prediction criteria for its Space Forecasting System. (See

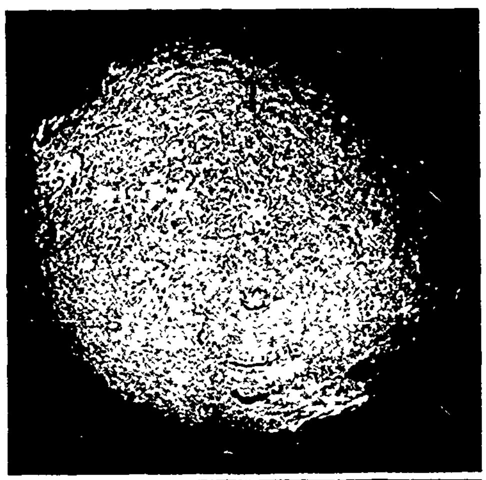
A 6-in telescope projects an image of the white sun on an observing screen for quick assessment of sunspot activity. The positions and sizes of the spots are easily recorded by tracing them on a piece of white paper.

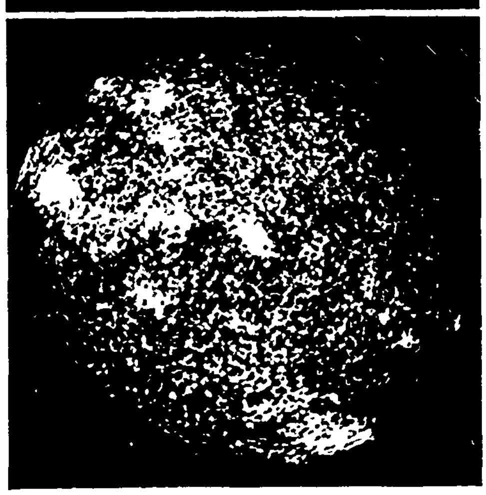
Chapter VII.) In 1969, the Air Weather Service sent observers to Sacramento Peak to assume responsibility for the Solar Patrol Program. Under this program, the sun is continuously monitored and reports are routinely channeled to the AWS Space Forecasting Center where, combined with radio and other observations, the optical data are used in operational forecasting of environmental conditions in the ionosphere and near space for the Air Force.

Using optical data alone, success of the predictions is only moderate. They fail to anticipate about 12 percent of the large solar flares, for example, while more than 30 percent of the alerts called are false alarms. This is better than nothing, but falls far short of the operational needs. Improvement can come only through a better understanding of the physics of the sun. This is the objective of the research program of the Sacramento Peak Observatory, selected aspects of which are reviewed in the following sections.

SUNSPOTS AND POINT MAGNETIC FIELDS: Sunspots are the visible manifestations of magnetic fields. The objective of sunspot research during the report period was to determine the relation between magnetic fields, mass motions and brightness in the small structures of the dark central umbra of the sunspot and the outer periphery of the sunspot, the less dark radially filamentary penumbra. Nothing quantitative was known about these relations, although it was recognized that no real understanding of the sunspots or their role in flare production could even begin without this information.

The necessary observations consisted of photographs and magnetospectrograms with sufficient spatial resolution to show in detail the intensity, velocity, magnetic and spectroscopic difference between such small structures as the bright and dark filaments which are typically less than 1000 km apart (or 1.3 arc seconds). They are most difficult observations, formerly beyond the state of the art, calling for the utmost instrumental refinement, observer skill, and superb "seeing." Work on this problem at Sac Peak is only a beginning, but in an area where the earlier information was near zero, it constitutes an important step ahead.





Photographs in the light of different lines of the solar spectrum show features at the temperatures characteristic of the lines. Here the sun is photographed simultaneously in the hydrogen alpha (upper) and calcium K lines.

The most extensive sunspot program was based on 13 sets of spectrograms, each of which yielded profiles of intensity and circular polarization across a magnetically sensitive line and a magnetically neutral line at each of 900 separate points in a medium sized sunspot about 80,000 km in diameter. The observations extended over one complete transit of the spot across the solar disk (due to solar rotation) to show its characteristics in light varying from grazing to vertical incidence. This program led to the following results.

The destination of the magnetic lines of force coming out of a sunspot has long been a mystery. It is now solved. Surrounding the spot are several thousand highly concentrated magnetic fields about 1000 km in diameter, predominantly of sign opposite to that of the sunspot. The total magnetic flux of these point fields balances that of the sunspot. They are necessarily the places where the lines of force re-enter the body of the sun. The magnetic loop is then closed under the surface.

The point fields were also found subsequently with the Sac Peak magnetograph and studied in some detail. A given point endures for at least several hours and is the origin of repeated outbursts of Ellerman "bombs," tiny flare-like, five-minute brightenings with peculiar spectra which often eject surge prominences. Occasionally a point also produces a small flare, a fact which strengthens the long-standing suspicion that bombs and flares are identical except for the chromospheric level at which they occur (the flares being higher than the bombs).

MAGNETIC FIELD STRUCTURE: Magnetic fields and velocity fields within the sunspot proper have a decided structure clearly related with the structure seen in direct photographs. All structures that are brighter than their surroundings, the bright filaments in penumbrae, the bright umbral dots, and light bridges across umbrae, have upward velocities and weakened magnetic fields more nearly horizontal than in the darker surroundings. Furthermore, the well-known horizontal outward motion of penumbral material (Evershed effect) is confined almost entirely to the darker filaments. The spectrographic measurement of this effect was resoundingly confirmed by the much more definite results from the first photographs through the Observatory's new tunable birefringent filter.

The center of solar activity surrounding a sunspot group is a region of intense magnetic activity. Small "fibriles" lie along the lines of force, and define the magnetic field configuration.

TWO UNEXPECTED DISCOVERIES: In the course of sunspot studies observers noted some rapid changes in the H and K lines of ionized calcium over sunspot umbrae. They made motion pictures in the K line through a birefringent filter and immediately discovered startling "umbral flashes" which had been entirely unsuspected. The flashes are small transient bright areas about 2000 km in diameter. They brighten in less than a minute and fade away in another two minutes. As they fade, they move rapidly across the sunspot umbra toward the nearest boundary, and usually a new flash begins the cycle all over again at the same site. At any one time several flashes will be in progress in a large spot. The physical nature of these flashes will remain a mystery until more observational data can be had. One thing they cannot be is moving clouds of material, since the motion is directly across the strongest magnetic fields on the sun.

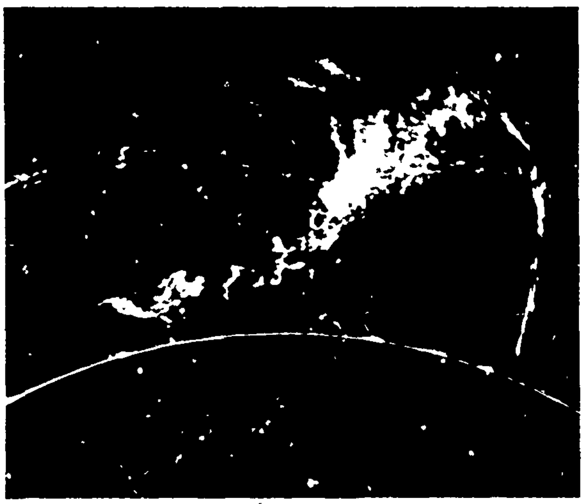
Another surprise came from the first monochromatic photographs of sunspots in the light of the oxygen line at 7772 angstroms. The penumbra is practically invisible, having almost the same brightness as the surrounding white surface. A theoretical examination of the character of the 7772 line showed that the abnormal brightness is due to the presence of the penumbral magnetic field, the strength of which can be determined by measuring the relative brightness of the penumbra. The agreement with the fields measured by the Doppler-Zeeman Analyzer is satisfactory. The oxygen line now provides a means for actually photographing magnetic fields directly, although the dynamic range of this method is decidedly limited.

SOLAR FLARES: Flare research has concentrated on observational and theoretical evidence for the Sac Peak impact theory for flare production. An active region is normally centered on a sunspot group dominated by two large spots of opposite magnetic polarity. Scattered around them are a dozen or more minor spots, usually with the same polarity as the nearest large spot but with an occasional non-conformist of opposite polarity.

Generally a "neutral line" can be drawn between the large spots, along which the measured sightline component of the magnetic field vanishes, and it is inferred that the field vector is horizontal. Characteristically, photographs in the H alpha line of hydrogen show a long dark filament (i.e., prominence) resting on the horizontal field, winding its way between the spots like a black rope. Occasionally such a filament appears to vanish from the normal H alpha picture, but reappears when the filter passband is shifted to shorter wavelengths. The horizontal magnetic plateau has suddenly become a high mountain, lifting the filament upward with sufficient velocity to Doppler shift its H alpha absorption out of the normal filter passband. The filament material flows like water down both sides of the mountain into the chromosphere and two bright ribbons develop in the regions of impact.

These are the observed facts. The impact theory proposes that the impact of this falling material on the chromosphere provides the energy for a characteristic two ribbon flare, one ribbon on each side of the original filament location, and parallel to it. This concept is supported by spectroscopic measurement of the Doppler shifts in the upward moving filament and the downward flow. Ascending prominences at the limb, with downward moving fragments are a familiar sight. Thus observations suggest a coherent qualitative picture of the primary flare phenomenon. The questions are whether or not the kinetic energy of the falling material is sufficient for a flare, and whether the process of dissipation by atomic collisions occurs at the correct level in the chromosphere.

An extended theoretical investigation



A fundamental aspect of solar research is that of understanding and explaining the huge energy mechanisms of the sun, one aspect of which are the prominences, small and large, shown in these two photos. In the upper photo, note the extension of the small prominence onto the solar disk as dark absorbing material.

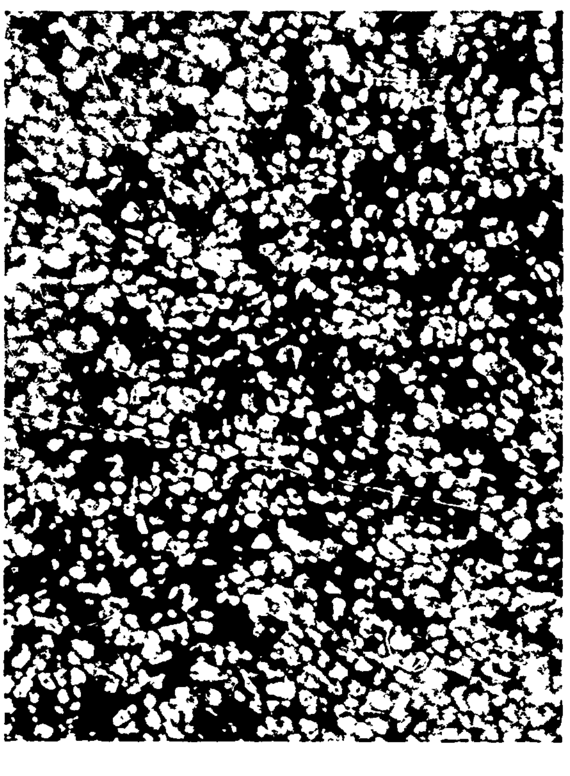
shows that the observed velocities combined with reasonable assumption about the prominence and coronal densities could indeed produce the H alpha appearance of a flare, with the correct time scale and chromospheric location. Some of the energy is converted directly into heat and some into shock waves whose dissipation is still obscure.

Some aspects of this theory are still unsatisfactory. It does not provide any obvious mechanism for the production of the non-thermal x-rays and high energy particles that are associated with large flares. The gross energy of the shock waves is probably sufficient for these, but the details of its conversion in the magnetic environment are complicated and remain to be worked out. An additional problem is that many flares occur without any visible evidence of an ascending filament. Thus it is assumed that the falling material was originally raised in some invisible form (a familiar phenomenon in limb prominences), or that there is more than one flare mechanism, or that falling material has nothing to do with flares. The choice will be possible only when more detailed, spectroscopic observations of preflare activity in active centers become available.

GRANULATION: The granulation seen in white light photographs of the sun consists of small bright areas surrounded by a network of dark intergranular lanes. It was assumed that the granules are the tops of upward moving convective columns, but until recently there has been very little quantitative information about them.

To determine sizes and numbers of granules, Sac Peak astronomers enlarged several good photographs and traced the dark lane network in ink. Since a single photograph includes about 10,000 granules, this was an exceedingly laborious job. The cells thus defined were usually polygons with an average diameter of 1100 km. There are approximately 6,300,000 of them on the sun at any given time. A study of microdensitometer traces was translated to a temperature difference of about 125 degrees K between the granules and the dark lines. During its 10-minute lifetime, a granule will move only a tenth of its diameter.

To determine the horizontal and vertical flow of materials within a granule, the Observatory used what is becoming its most versatile and productive instrument, the tunable birefringent filter. The filter has a pass band of 0.25 angstrom.



The quiet solar surface has a distinct granular structure. Individual granules — really, convective cells — of upwelling material have an average diameter of about 1100 km.

The system can record two images at slightly different wavelengths on either side of an absorption line. When regions are viewed toward the solar limb, sightline velocities produce a brightening in one picture as one wavelength is Doppler shifted away from the absorption line, and a darkening in the other as it is shifted into the line. The difference of the brightness in the two pictures is a measure of the flow velocity of material in the granule cell.

Maximum upward convection at the granule center has been determined to be about 400 meters a second. As in any convective system, this upwelling material (predominantly hydrogen) flows outward horizontally when it reaches the upper boundary of the cell. From a zero horizontal velocity at the center of the granule, the flow increases radially outward to a maximum velocity of about 250 meters a second at a distance of 500 km. At 1000 km from the granule center the velocity has decreased to about 50 meters a second. The Sac Peak astronomers making the study found no evidence of a vortex movement in the outward flow. At the periphery of the granule there is a moderate downwelling of material.

SUPERGRANULATION: Granules are the visible manifestations of convection from the solar interior. Granules are only surface phenomena, however, extending as they do only about a thousand km or so beneath the visible surface of the sun. They rest on another layer of unseen convection cells, cells much larger and having preferred diameters of about 30,000 km. These supergranules were first observed instrumentally in 1959.

Supergranules may extend down to 10,000 to 15,000 km. Their large convections suggest a possible mechanism whereby magnetic fields in active centers are carried away and distributed over the sun by random walks. If so, supergranulation is a vital entity in the energy economy of the solar atmosphere. The early observations at Sac Peak and elsewhere showed that the bright network in the light of the chromospheric K line of ionized calcium approximately outlined the supergranule cells. Because the K line tends to be bright in regions of enhanced magnetic field, a supergranule is pictured as a cell where material from the solar interior wells up and flows horizontally to the boundary sweeping magnetic fields to the edges of the cell where they are concentrated.

Confirmation of this picture required observations of the vertical motions (very much smaller than the horizontal motions), the magnetic fields, the horizontal drift of granulation toward the boundaries, and a determination of temperature differences along the radii of the supergranules. All of these measurements are exceedingly difficult because the effects are very small and tend to be swamped by much larger effects unrelated to supergranulation. Fortunately, a supergranule lasts much longer (about 20 hours) than any of the disturbing phenomena, and it has been possible to average the disturbances out well enough to obtain a rough measure of the supergranule characteristics.

Using a variety of instruments and approaches, Sac Peak astronomers have measured most of the characteristics of supergranules—their vertical and horizontal velocities, their magnetic fields and their temperature cross sections.

CHROMOSPHERE AND CORONAL HEATING: The chromosphere and corona are regions of very high temperature, resting on a relatively cold temperature minimum below and exposed to the cold of outer space above. They lose heat

Each day at noon a photograph of the sun is taken and mounted beside that of the previous day. In this way a daily chronological record extending over the last five 27-day solar rotations is posted for easy reference to daily changes in solar features.

and radiant energy in both directions at a prodigious rate.

By what process is the temperature of the chromosphere and corona maintained in the face of this large energy drain? The most promising theory, now blessed with considerable observational support from Sac Peak and other observatories, is that the kinetic energy of the convecting granules at the surface excites waves in the convectively stable photosphere and lower chromosphere. These waves carry the energy mechanically into the upper chromosphere and corona, where they are dissipated in the form of heat. The work at the Observatory has been concerned mainly with various aspects of the mechanical upward transport of this energy, with primary focus being on vertical oscillations in the solar atmosphere.

Vertical oscillations in the solar atmosphere were discovered (by Leighton and his associates) in 1959 on evidence that some astronomers regarded as non-definitive. Sac Peak in 1960 and 1961 confirmed this discovery decisively and defined the quantitative character of the oscillations.

Initial spectrographic measurements showed that the oscillations have a sharply defined period of 300 seconds, and usually last three or four cycles before dying out, only to begin again in the same place. They appeared to be coherent over areas varying from 3000 km to about 10,000 km in diameter. They occurred everywhere over the surface of the sun except at active centers. Superficially, these waves fit the theoretical idea of mechanical transport of energy very nicely. But it is not yet clear that they carry sufficient energy to heat the chromosphere and corona.

During the period of this report, Sac Peak astronomers greatly improved their observations by applying the tunable birefringent filter mentioned in several previous contexts to the problem of solar atmosphere oscillations. Velocity filtergrams taken sequentially with this instrument could be projected as movies. They show the oscillating areas on the sun very clearly. Measurements taken from the film show the average diameter of these areas to be around 10,000 km, somewhat larger than that derived from earlier spectrograms.

The Doppler-Zeeman Analyzer was also used. The output is a digital record on magnetic tape ready for computer processing. The computer program presented the final results in the form of a motion picture. The 300 second waves dominate the motions shown, and the typical scale of the oscillating regions turns out to be 23,000 km with some very large regions 75,000 km in diameter.

As matters stand, therefore, Sac Peak has several conflicting results with respect to areas which must be reconciled. The size scale of the oscillating regions is the index to the size of the energy source, presumed to be the granules which are not generally moving in synchronism. The theory of energy transport into the chromosphere and corona will hinge on the correct determination of the size scale of these oscillating regions.

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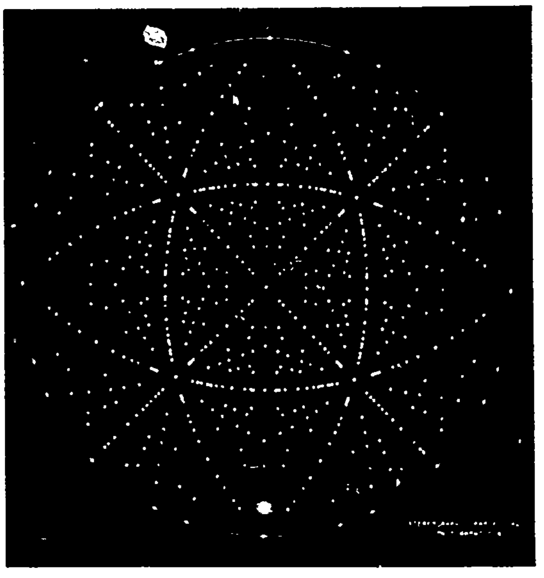
Diffraction X-ray pattern of silicon along one of the crystallographic axes of the crystal is simulated by computer. The symmetry of the pattern is a reflection of the atomic arrangement within the crystal.



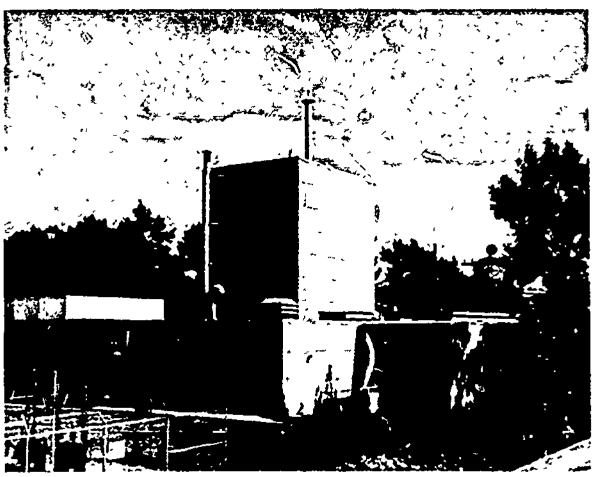
III Solid State Sciences Laboratory

The Solid State Sciences Laboratory conducts research on electromagnetic materials—optical, semiconductor, and magnetic—and the phenomena they exhibit. The goal of this research is to uncover novel properties that may be exploited in Air Force technology.

The general goals of the research of this Laboratory are those which motivate all electronics solid state research. These are new componentry of enhanced reliability and performance and reduced size, weight, and power requirements. But the focus of the Laboratory program is on the requirements peculiar to the Air Force. Among these special requirements are materials and devices that can take high radiation dosages without performance degradation and that can operate in high temperature environments. Laser crystals that can withstand without damage the stress of high power operation, and improved infrared sensors also fall into the category of research of special Air Force interest.

The Laboratory's facilities for conducting electromagnetic materials research are outstanding and in some cases unique. Few optical, semiconductor, or magnetic crystals of any type cannot be produced by the Laboratory. The capability includes both the synthesis of isolated crystals and the preparation of single crystal thin films on substrate material.

Coupled closely with crystal growth facilities are a host of analytical techniques and instrumentation for determining structure, purity and properties of the crystals. Fabrication facilities and analytical instrumentation are also available for experimental device development. For the study of the effects of ionizing radiation on materials and devices, AFCRL operates an irradiation facility with a diversity of radiation sources.



This building houses several radiation sources used in support of research by member laboratories of AFCRL, other government laboratories, and universities. Within this facility are a 14 kilocurie Cobalt-60 source, a 3 MeV Van de Graaff generator, a 1.5 MeV Dynamitron, and a 2 MeV Flash X-ray machine.

The Laboratory routinely uses computers for automated, on-line control and data analysis. In addition to its IBM 1800 process control computer, the Laboratory is linked by a remote station to AFCRL's general computer facility. Great savings in time and scientific manpower have resulted as the computer has taken over the laborious task of scanning, plotting and analyzing data.

Because of its extensive in-house facilities, the Laboratory relies only in a minimum way on contract assistance. Almost all of the work reported in th chapter is purely in-house research.

CRYSTAL GROWTH

The Solid State Sciences Laboratory conducts the largest in-house research program on electromagnetic materials of any DOD laboratory, the program encompassing more than 95 percent of the Air Force effort. Materials of interest are those with properties that potentially meet some specific or anticipated Air Force requirement. These requirements usually exceed those of products developed for the commercial market. Ultra-reliability and operation in high temperature and radiation environments are examples of specifications exceeding need in commercial products.

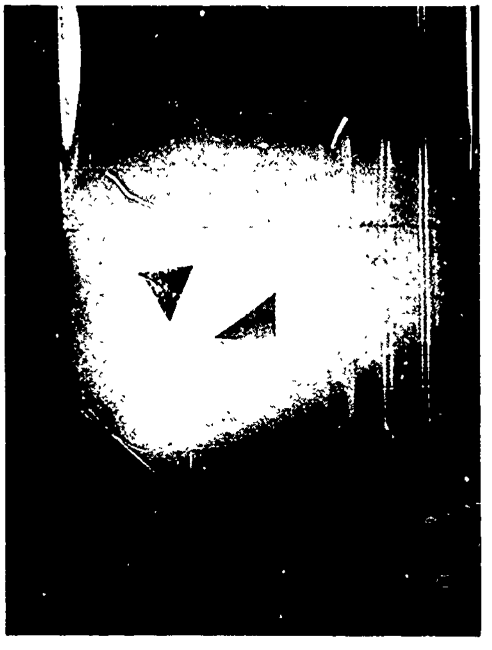
During the reporting period, hundreds of unique, potentially useful, crystalline materials were prepared, most of which were analyzed and tested in the Laboratory. But the Laboratory also supplies custom synthesized crystals for other AFCRL laboratories—to the Microwave Physics Laboratory (Chapter IX) for microwave acoustics research; to the Optical Physics Laboratory (Chapter IV) for laser research; and to the Space Physics Laboratory (Chapter VII) for energy conversion research.

Because of its unique skills and facilities for materials synthesis, the Laboratory often receives requests from industry and universities to grow crystals to particular specifications, usually for programs these organizations are conducting for the DOD. When AFCRL furnishes crystals to outsiders, it is always with the understanding that a full report on the analysis of the crystal (a task demanding special skills and much time) be furnished to the Laboratory in exchange. In this way, AFCRL obtains valuable data without cost. Arrangements with Lincoln Laboratory, IBM, and the Bell Telephone Laboratories have proven particularly fruitful in this respect. Such arrangements are usually made on a scientist-to-scientist basis, rather than through organizational negotiations.

GEL GROWTH OF ELECTRO-OPTIC MATERIALS: Gel growth is a method of crystal growth in which the initial conditions consist of a gel in an appropriately designed glass container. To this gel is added the solution from which the crystal will grow. Growth takes place in most cases at room temperatures, with the growth period being weeks or months. The growing crystals are clearly visible during their growth period. The method depends on the slow transport of the solution through the gel to the site of the growing crystal on which it precipitates. The role of the gel is to reduce turbulence during the slow process of diffusion and growth. The gel growth technique itself is not new but the Laboratory has introduced many extensions and refinements, and is now recognized as the leading center in the country for the development of gel growth techniques. During the reporting period, gel growth, a promising technique for many years, came of age.

With this technique, AFCRL has for the first time grown a particular crystal that is the best laser modulating crystal of any kind produced to date. Since the first laser was fired, researchers have sought methods for modulating laser light for communications. In recent years a number of modulating schemes have been announced and voice and picture information has in fact been transmitted by laser light. Like most first steps, the achievement is noteworthy but tentative.

The facets of these crystals grown by the gel growth method appear as if they have been cut and polished.



These nearly perfect cuprous chloride crystals are shown growing, suspended in the gel medium.

In 1969, AFCRL by the gel growth method succeeded in growing large crystals of cuprous chloride, a highly promising modulator material. Although cuprous chloride crystals have been grown by several others, the crystals have been too imperfect for effective laser light modulation

Most laser light modulation schemes use a transparent crystal as a modulator. The light output from the laser is passed through this crystal. If the transmission properties of the crystal can be readily altered by some external means, then one can modulate the light passing through it. The simplest way to change the transmission properties of the crystal is to change its refractive index. There are a number of electro-optical effects available to do this. By using the Kerr or Pockels effect, for example, the refractive index of the crystal can be changed by simply applying an appropriate voltage to it. By changing the refractive index, phase changes in the light passing through the crystal are induced. In this way, the laser light is modulated.

Cuprous chloride meets all the requirements of a good modulator crystal. It is transparent to light over a broad band of frequencies from 0.4 to above 20 microns and its refractive index is easily altered when voltage is applied. It has a low dielectric constant and low losses which modulation crystal must have to reduce dielectric heating during operation.

Most researchers who have tried to grow cuprous chloride crystals have used the Czochralski process in which the crystal is slowly drawn from a molten cuprous chloride solution. Large cuprous chloride crystals have in fact been grown by this method. But as the crystal cools from its 420 degree C melting point it undergoes severe strain due to a phase transformation at about 408 degrees C, and this strain produces internal fractures. The crystal cannot then be used as an effective modulator.

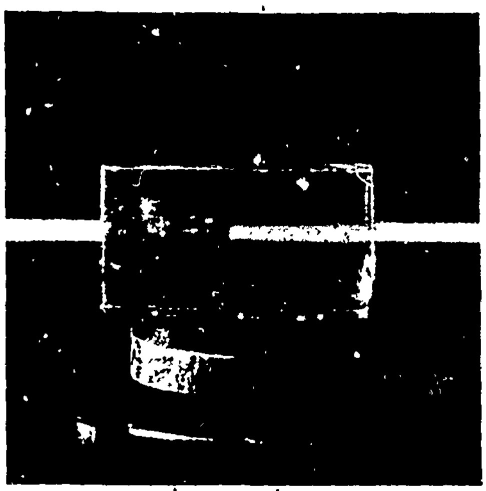
The gel growth technique has the advantage of growing the crystal at temperatures below the 408 degree C transition temperature. The largest cuprous chloride crystals grown to date are clear, transparent tetrahedrons with facets measuring 8 mm on a side.

FLAME FUSION GROWTH: The Laboratory is also the leader in the application o' ı flame fusion (Verneuil) method o. ,tal growth. In this method, fine ler drops through an intensely heated region and falls in a molten state on a seed crystal. The seed is slowly withdrawn so that the position of the liquid-crystal interface is maintained at a constant level as the seed is passed into a lower temperature region. Crystallization occurs at the interface.

During the period of this report, AFCRL scientists have introduced improvements into both equipment and technique. Foremost among these is a three-tube post-mix oxy-hydrogen burner. The design minimizes gas turbulence and produces a flame of larger diameter with lower radial temperature gradient. The importance of the reduction of the radial component of the gradient is apparent in the unique growth of 0 degree ruby boules with regular hexagonal cross section. Laue X-ray patterns at both ends of the boule indicate that these boules have an exact 0 degree orientation with the flat surfaces parallel to the prism planes of the crystal.

Experiments have been conducted to study the growth interface by alternating sapphire and ruby in the same boule. This is accomplished by an AFCRL development, dubbed the "trombone," which permits interchanging the ruby feed powder container with a container of pure aluminum oxide while the burner remains ignited. Powder drop and retraction are momentarily stopped during the interchange, but the gas feed and temperature gradients are not altered. In this way, a stable crystal growing environment is maintained.

Boundaries between the ruby and sapphire part of the boule are less than 20 micrometers thick. Laue patterns verify single crystallinity. Longer than normal crystals of a single composition have also been grown using the replenishing technique. These experiments have significance to those investigating semiconductor substrates. Laser physicists have also shown interest. A three-inch ruby crystal with sapphire tips has been provided for laser investigations. The sapphire tips have no purpose other than to serve as areas to which mounts are attached. But if the mounts are not fitted directly over the ruby material as is customary, greater laser efficiency is possible and self-damage of the ruby may be avoided.



The red fluorescence excited by an argon laser beam demonstrates the sharp gradation between sapphire and ruby sections of a sapphire-ruby crystal. White spots in the sapphire section (left) are caused by crystal imperfections.

Another technique being employed is that of seeding from a thin slab cut to a desired orientation. It is easier to cut a given plane with precision than it is to grind a cylinder with a given axis. The process permits the growth of boules having unusual orientations. Previously only three orientations were grown, with axes of 60 degrees, and 90 degrees, and sometimes 0 degree from the C-axis. Any orientation can now be grown from a properly cut slab. Boules of several uncommon orientations have been grown for testing as laser materials and as substrates.

The conventional Verneuil process introduces longitudinal gradients of over 125 degrees C per inch and this introduces considerable internal strains in the resulting crystal. To minimize the strain it is necessary before the crystal is used to subject it to an annealing cycle. While the annealing reduces the internal strains, it also often introduces undesirable chemical and structural changes. To cope with this problem, AFCRL has designed, constructed and operated an after-heating device which decreases the longitudinal gradients to levels as low as 25 degrees C per inch. Using this electrical-resistance heater as part of the growth process, it has been possible to grow 0 degree sapphire boules with extremely low strains requiring no post growth annealing treatments.

This complex maze of glass tubing and valves is an experimental vapor growth process furnace for the growth of gallium arsenide and gallium arsenide-phosphide.

GROWTH OF SINGLE CRYSTAL FILMS: This program was established to provide the Laboratory with a thin film capability, both homoepitaxial and heterotaxial, in Ge, Si, GaAs, $GaAs_{1-x}P_x$ and other III-V compounds and III-V ternaries. The primary objective of this effort is to provide thin films for the Laboratory's infrared sensor program, specifically for use in the fabrication of Schottky barrier devices. These devices have advantages over other infrared detectors in the one to two micron region, advantages which include 1) fast response time, 2) high sensitivity, and 3) minimum cooling.

For its thin film investigations, AFCRL chose chemical rather than physical deposition techniques for film preparation. After examination of the several chemical vapor deposition systems which could be used for the preparation of the materials of interest, the Laboratory chose thermal decomposition of hydrides as the chemical technique to be employed wherever possible.

For the preparation of GaAs and $GaAs_{1-x}P_x$, the system has the desirable feature of flexibility in the precise control of reactants and dopants. It is adaptable to the preparation of other III-V binary and ternary compounds.

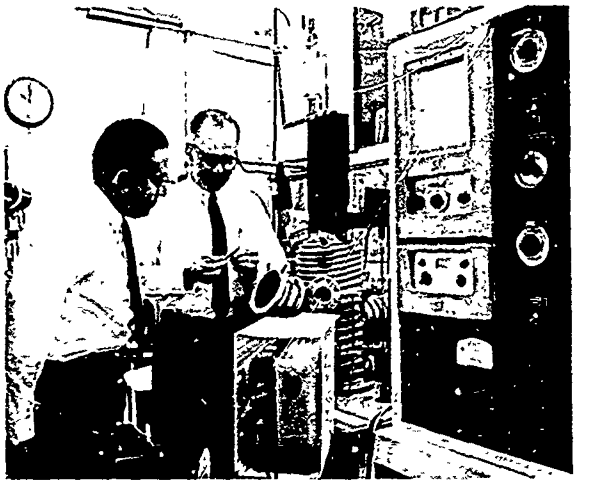
To date, the Laboratory has concentrated on the preparation of epitaxial films of germanium. Over 200 experiments have been carried out to determine the effect of reaction temperature, reactant and dopant concentration, and surface preparation on film quality, growth rate, and dopant concentration. Laue X-ray patterns and electron diffraction results show that films prepared at temperatures above 650 degrees C were single crystals with a high degree of crystal perfection. In addition, these films are mirror smooth and devoid of spurious growths, qualities necessary for photoetching and masking techniques for device fabrication.

WIDE BAND GAP SEMICONDUCTORS: Silicon is a natural choice for most solid state electronic devices. However, there are certain Air Force needs that can be fulfilled better by other semiconductors. Requirements for higher power, high current densities, higher temperature operation, and luminescence in the visible region of the spectrum, has led the Laboratory to a search for wider band gaps. Chemical and thermal stability is also needed so that the gap can be utilized. A fairly high degree of covalent bonding is also required so that crystals can be doped both "p" and "n" for the preparation of junctions and fairly simple unit cells so that mobility and resistivity can be in a useful range.

Gallium arsenide, gallium phosphide and mixed crystals of gallium arsenide-phosphide ($GaAs_xP_{1-x}$) allow a range of band gaps from about 1.4 eV to 2.2 eV, permitting luminescent devices in the red and orange regions of the spectrum. Inadequate thermal and chemical stability at elevated temperatures is likely to limit devices made from these materials to environments below 300 degrees C. A goal is to develop devices capable of operating above 500 degrees C. Another goal is to develop light emitting diodes over the full visible spectral range. For this, band gaps in the range of 2 to 3 eV are needed.

Scientists at AFCRL have investigated the band structure, defect structure and crystal growth of many of these semiconductors over the past ten years. Gradually, silicon carbide has become a clear choice for intensive investigation because of its unique combination of electrical, thermal, chemical, mechanical and optical properties. AFCRL has conducted or contracted for more than 50 percent of the research conducted in the U.S. on silicon carbide semiconductors.

AFCRL has sponsored the only two international conferences on silicon carbide, the latest being in 1968. The proceedings of this conference will be an important reference for many years.

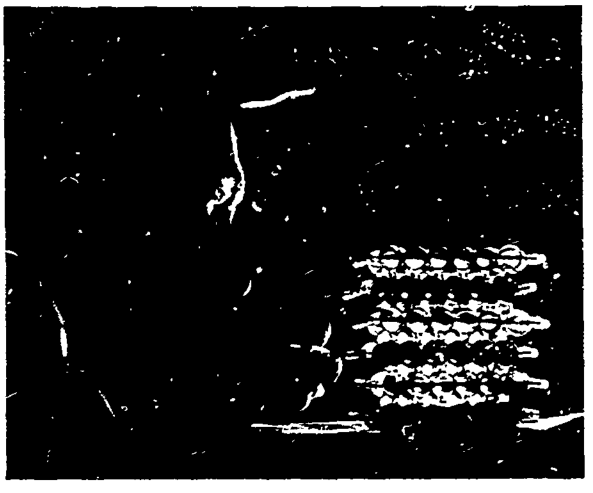


The crystal of cobalt monosilicide being examined was grown in the special high power, high pressure, inductively heated furnace, center.

A product of the Second International Conference on Silicon Carbide was the formation of the International Committee on Silicon Carbide (ICSiC) composed of experts from several countries (United States, England, Netherlands, Switzerland and Austria). The first two meetings held in New York City and Vienna in 1969 were highly successful in clarifying a number of common problems associated with the growth of single crystals of silicon carbide.

In its Laboratory, AFCRL is investigating new methods of growing silicon carbide crystals, the preparation of epitaxial and heterotaxial layers of silicon carbide, and is investigating such basic phenomena as polytypism and the beta to alpha transformation.

AFCRL is the only laboratory to date that has attempted to grow bulk silicon carbide into a conical crucible from the vapor. High temperatures are needed --in the vicinity of 2500 degrees C. With this method. AFCRL, on June 17-19, 1968, had its first successful result. In a slow sublimation run, a cylindrical boule of silicon carbide 1.9 cm in diameter, 2.5 cm long, weighing 18.1 grams was obtained. The boule was imperfect, but it was the largest ever grown. More important, the analysis of the crystal pointed up methods whereby the furnace can be modified to obtain large crystals of desired perfection.



This sample atomic model of a polytype of silicon carbide is being studied in an attempt to discern physical and chemical imperfections that arise in crystals during the growth process.

In 1970, AFCRL hopes to demonstrate two prototype silicon carbide devices. If this is successful, then a true milestone in semiconductor research will have been reached and AFCRL and ultimately the Air Force will have been rewarded for its long patience and persistence in advancing silicon carbide technology.

LITHIUM AND SODIUM GERMANATES: Of the new materials that have been announced during the period of this report, the most novel are the germanate compounds. Germanate compounds doped with rare earth ions show some promise as a new laser host material operating in the 1 to 3 micron region. These new infrared laser frequencies promise to have military application in reconnaissance and detection.

When neodymium is introduced into a sodium or lithium germanate glass, it has stronger excitation absorption bands and a fluorescence efficiency comparable to commercial laser materials. Under certain excitation conditions, neodymium-doped lithium germanate has been found to produce a strong 1.06 micron laser line with a higher efficiency than the best commercially available laser material. Also, both erbium and holmium have been introduced into sodium germanate glasses to produce, respectively, strong fluorescence lines in the 1.5 and 2.0 micron infrared regions. Optimum erbium concentrations have been determined and other ions such as ytterbium have been introduced for energy transfer studies. The strong excitation bands of these ions coupled with the energy transfer capabilities offer good possibilities for high efficiency laser materials.

ANALYSIS OF MATERIALS

Somewhat arbitrarily, this discussion of the analysis of materials is considered separately from the previous discussion on material synthesis. Quite obviously, there's a very close interaction among those who prepare and synthesize a material and those who test its performance and look at its structure. Such analysis provides the crystal grower with the essential feedback for improving quality and performance.

The Laboratory employs a range of spectroscopic, magnetic, chemical and microscopic techniques in its analytical work. Once data are acquired, they must be interpreted. Noted in the introduction to this chapter was the increasing use of computers by Laboratory members for processing and plotting these data. This is an important trend—and an essential one, because experienced technicians and physicists for analysis are seldom available in the numbers desired. Some crystals can be grown in a day; with manual procedures, their characterization may require a month of someone's time.

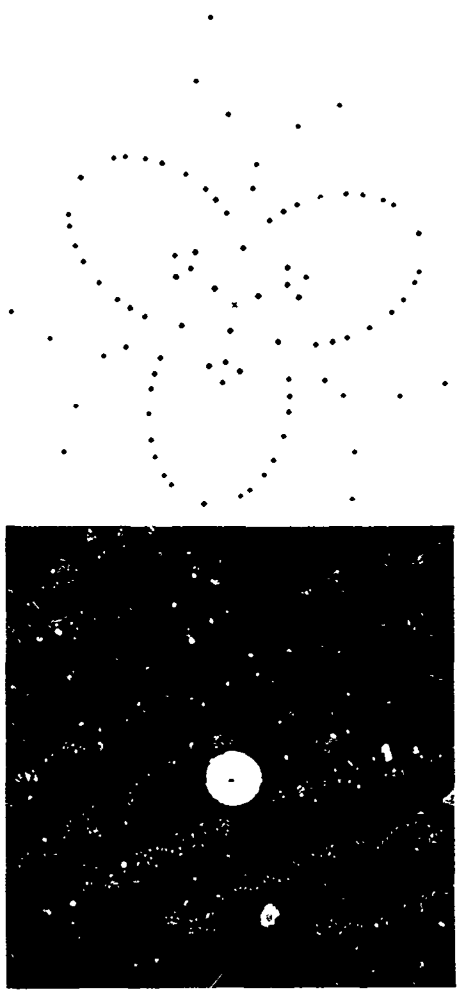
The automated X-ray diffractometric system with the X-ray goniometer is shown in the right foreground. The processor-controller is on the left.

AUTOMATION OF X-RAY DIFFRACTION ANALYSIS: During the reporting period, the Laboratory placed in operation a completely automated system for making X-ray diffraction measurements of crystals. The system is controlled by an IBM 1800 computer which can be programmed to perform all analytical operations. The computer operates auxiliary equipment for orienting crystals in any arbitrarily preprogrammed position with respect to the X-ray beam. It records data, makes a ,.-opriate calculations, and plots the re-.-ts. The system is an on-line system, and can accept information in either digital or analog form.

The AFCRL automated system is among the pacesetters in a trend toward the increasing use of automated systems for crystal analysis and characterization. X-ray diffraction is one of several kinds of measurements made by crystallographers to determine the structure and properties of a crystal. Although the automated system is presently being used only for X-ray diffraction analysis, it is capable of handling a variety of conventional analytical processes on a time-slicing basis. Planned as future inputs are such analytical methods as neutron activation, mass spectra, and Mossbauer analysis. Hall effect measurements, electron spin resonance, and many other techniques that can be incorporated into the basic system. The AFCRL automatic X-ray diffractometer can do a more complete, accurate, and versatile job in one unattended 24-hour period than could be done manually in a month.

X-ray diffraction measurements tell the crystallographer how atoms have arranged themselves in the crystal lattice network. For a particular crystal, the crystallographer may also want to know the variations in atomic ordering, or the degree of preference an atom has for unlike neighboring atoms. Often, very subtle alterations in the crystal growing process—temperature, rate of growth, minute increases in dopant materials—can result in gross changes in the crystal structure and properties.

SIMULATION OF LAUE PATTERNS: When a single crystal is used in devices, its lattice structure must be oriented in a preferred direction. The silicon substrate of the integrated circuit, the quartz oscillator of the frequency standard, and the ruby laser rod are all oriented to the particular direction that



This computer simulation of the diffracted X-ray pattern for silicon illustrates the three-fold symmetry of the atomic arrangement when viewed along the (lll) axis of the crystal. An actual Laue pattern of the same view is shown below.

provides the desirable physical property.

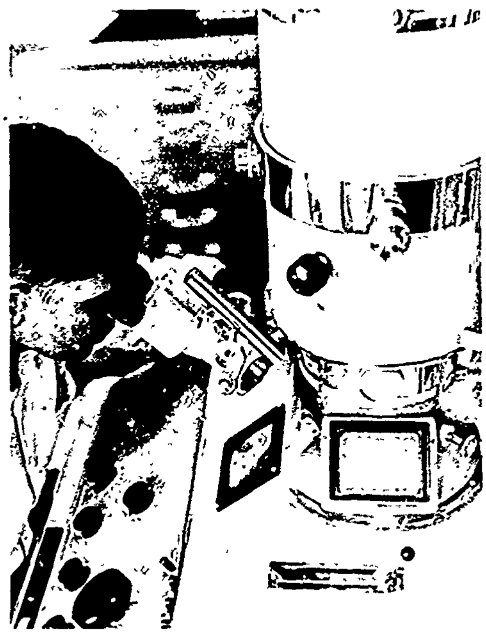
Laue patterns, a symmetrical arrangement of points showing the placement of atoms, have been used to orient single crystals since the early days of solid state electronics. These patterns are obtained by recording on film X-rays diffracted from the various atomic planes of the single crystal. The arrangement of such spots on the film reflect the orientation of the crystal. Unfortunately, the orientations of noncubic crystals, or for that matter cubic crystals of non-simple directions, are not easily identified.

As part of the Laboratory's automated laboratory procedures, a computer program has been developed that helps in the orientation of single crystals by simulating Laue patterns for any crystal system in any orientation. The simulated pattern is presented on a digital plotter. The program produces both Laue back-reflection and transmission indexed patterns as well as stereographic projections. The scientist can vary any experimental parameter and the computer almost instantaneously plots a simulated result. One can thus generate an atlas of patterns for a given crystal.

A typical simulated transmission pattern for the (III) orientation of silicon and the corresponding Laue film are shown in the accompanying figure. Such simulated patterns have also been utilized to distinguish polytypes in SiC and orientations of ruby, quartz, lithium germanate, lithium niobate, cadmium and tin crystals.

ELECTRON MICROSCOPY OF SiC: Earlier in this chapter, the growth of sizable boules of silicon carbide by the vapor method was discussed. Concurrent with this work is the study of methods for the epitaxial growth of SiC on substrates. This is of course necessary if SiC is to be fabricated into devices. The problem is that SiC does not readily bond with other materials.

Silicon carbide comes in two basic lattice configurations, alpha and beta. Beta-SiC is the structure of interest for transistor applications. Its resistance to high temperature and high radiation make it an ideal material for use in Air Force electronics hardware. One approach to the epitaxial growth of beta-SiC on substrates is to use alpha-SiC as the substrate.



The JEM-6A electron microscope is currently being used to study radiation damage in quartz and silicon.

For epitaxial growth to occur on a foreign substrate, it is important that the lattice dimensions of that material match closely those of the deposit. A further consideration is the ease of preparation of the substrate surface—whether it can be cleaned readily or etched to accommodate the deposited atoms in a way to promote single crystal growth free of impurities and faults.

Standard electron microscope and diffraction techniques were applied to the study of epitaxial beta-SiC films deposited by vapor deposition on alph-SiC substrates to determine the effectiveness of molten intermediate films in promoting single crystal growth. The electron microscope provides information on the texture of the surfaces, substrate and deposit, as well as crystallographic data which are used to identify the deposit and to determine whether it is polycrystalline or single crystal, and if it is twinned. This information, when related to deposition parameters, serves as a guide in choosing proper growth conditions.

Studies indicate that growth of beta-SiC by vapor-phase deposition on alpha-SiC can be accomplished more readily and at lower temperatures when a molten metal intermediate is used. The metals used, nickel or cobalt, were deposited as thin films on the substrates by vacuum deposition. The electron microscope showed that the metal films react with the substrate at temperatures of about 1250 degrees C to "clean" the surface. The deposit of beta-SiC is made in the same reaction tube immediately after this initial reaction.

THERMOLUMINESCENCE MEASUREMENTS: Thermoluminescence techniques are used to study the properties of defects which function as traps and recombination centers in luminescent wide band gap materials.

During the reporting period several features of thermoluminescence emission from chromium-doped lithium germanate were explored. These included thermoluminescence excitation and emission spectra, thermal activation energies for release of trapped electrons, recombination kinetics, and the behavior of thermoluminescence glow curves as functions of sample temperature during excitation and thermal bleaching.

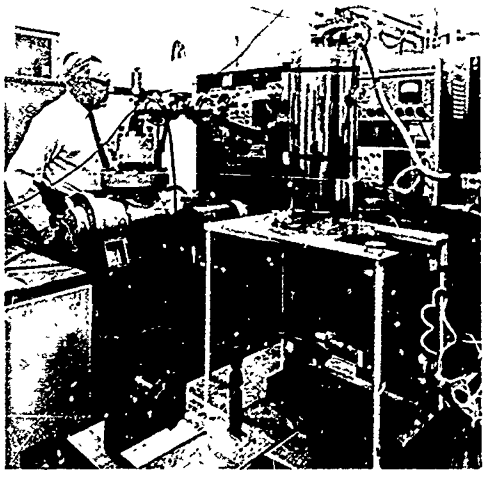
In recent experiments studies of the thermoluminescence excitation and emission spectra helped to locate energy levels associated with defect centers. Thermal activation energies provided information as to the energies required

This electron micrograph shows the texture of an epitaxial film of beta-SiC deposited on the etched surface of alpha-silicon carbide.

The otherwise smooth surface of alpha-silicon carbide is etched to accommodate a layer of beta-silicon carbide. The etching is accomplished by first depositing a layer of nickel and heating it to 1250 degrees C in hydrogen. The large textured globules are reaction products which provide nucleation sites for the deposited beta-silicon carbide.

to release electrons from traps. These ranged from slightly under 0.2 to over 2.0 electron volts. From recombination kinetics and the behavior of thermoluminescence glow curves as a function of various bleaching programs it was found that retrapping was not occurring between traps at different energy levels and that defects accounting for several of the traps appear to be physically isolated from each other.

MOSSBAUER SPECTROSCOPY STUDIES OF YiG: The Mossbauer Effect was announced in 1957. In the short time since, Mossbauer Effect spectroscopy has become a standard technique for measuring the properties of magnetic materials such as yttrium-iron-garnet —YiG. The long-pending promise of YiG for application in oscillators and filters has yet to be filled. But its properties and potential are too great to warrant the abandonment of this material for lack of success to date in finding applications. (Research on YiG devices at AFCRL is discussed in Chapter IX.)



The Mossbauer spectroscopy apparatus is used for the investigation of magnetic materials.

Many years ago, AFCRL designed and placed into use one of the first spectroscopic instruments based on the Mossbauer Effect. This involves the emission and absorption of gamma rays from a radio-isotope, with the isotope most commonly used being Fe^{57}. With Fe^{57} in the YiG bound to its crystalline environment, the effect of internal electric and magnetic fields resulting from interactions with the adjacent positive and negative ions produce characteristic sets of absorption lines. The energies associated with the position of the absorption lines can be used to reconstruct the crystalline environment of the Fe^{57}. Preferred positions and distributions of the atoms in the lattice framework can be derived.

The AFCRL 3.0 MeV Van de Graaff generator, a versatile radiation source, is used in many experimental efforts such as ion beam spectroscopy, ion implantation, and neutron damage in semiconductor materials. The analyzing magnet has a deflection capability in the one to two million gauss-centimeter range.

The object of the research on YiG materials using Mossbauer Effect spectroscopy is to establish a basis for predicting the stochiometry (relative amounts of elements in a compound) of a crystal required for a given performance. During the reporting period, this objective approached realization. The AFCRL experimental technique involved varying the composition of the YiG crystal, and of introducing certain amounts of non-magnetic ions into the crystalline structure. During the period, the gamma-ray spectra of 30 different specimen were obtained.

The most productive efforts involved the study of gallium (Ga) and aluminum (Al) ions by substituting these materials in varying quantities (8 to 80 percent of the total amount of Fe ions admissable in pure YiG). As a result of these studies, the distributions of these ions and the magnetic properties of a compound of varying compositions can be calculated in advance.

RADIATION DAMAGE AND EFFECTS

Neutrons, gamma rays and X-rays released in nuclear detonation can neutralize missile, satellite, airborne and ground electronic systems at ranges much greater than those at which actual structural damage can occur. Although vulnerability to this radiation damage can be reduced for certain circuits such as computer memories by using redundant components or with protective circuits that cut off or isolate critical components during the initial transient radiation pulse, a more direct approach is to build radiation tolerance, or hardness, into the components themselves.

This is the approach taken by AFCRL. To conduct this research, the Laboratory operates an irradiation facility which contains a Cobalt 60 cell, a 3 MeV Van de Graaff generator, a 20 MeV linear accelerator, and a 1.5 MeV Dynamitron. In 1970, the Laboratory added a high intensity flash X-ray machine. This machine has an output of 2 MeV with a 40 billion watt rating. This high intensity is delivered over a 25 nanosecond pulse length. An X-radiation dose of 200 billion rads per second is generated. (An exposure of 400 to 500 rads of X-rays would be lethal to a human being.) In addition, the Laboratory during the period tested a number of devices in an actual nuclear environment during underground nuclear test programs.

The entire Air Force research and exploratory development program on the radiation hardening of devices is the responsibility of AFCRL. The changes in the electrical behavior of semiconductor devices exposed to nuclear radiation are due to displacement and ionization effects. Ionization causes transient damage effects such as an excess electrical current surge through the circuit that decays after the radiation pulse. However, the ionizing radiation pulse may also cause permanent effects due to charge build-up in insulating layers. These ionization effects are produced by neutrons, X-rays and gamma rays. Massive, complex and permanent damage effects due to displacement of crystal atoms from their lattice sites are caused by neutrons. The extent of device degradation in both damage categories depends strongly on the device type and fabrication methodology.

AFCRL RADIATION SOURCES

RADIATION SOURCE	TYPE OF RADIATION	ENERGY	OUTPUT
Van de Graaff	Electrons, Protons & Heavy Ions Neutrons via nuclear reactions	1.5-3.0 MeV 1-14 MeV	0-500 μa
Dynamitron	Electrons	0.3-1.5 MeV	10 ma
LINAC	Electrons/X-Rays	3-23 MeV	2 amps pulsed or 0.4 ma (avg)
Flash X-Ray Sources:			
Febatron	X-Rays	300 keV	5000 amps
Pulserad	Electrons/X-Rays	2 MeV	20,000 amps
Cobalt-60 Source	Gamma Rays	1.25 MeV	20,000 curies
Positive Ion Accelerator	Electrons, Positive Ions	300 keV	

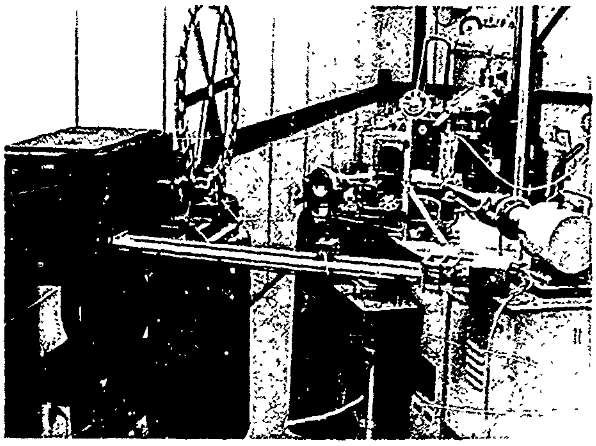
AFCRL is investigating the full range of possible radiation hardening approaches—material selection, device type, doping, geometry, fabrication, bonding, encapsulation, and so on. In this section, only those studies of the basic mechanisms of radiation damage will be reviewed. Development of radiation hardened devices will then be covered in the next section.

A remotely controlled attenuator wheel. on the left, a P-I-N diode detector system, center, and a Faraday cup on the right are used to control and measure the output of the AFCRL linear accelerator. Intense bursts of radiation from this machine are used to simulate nuclear weapons effects in electronic materials and devices.

SECONDARY ELECTRON EMISSIONS: Radiation can alter the performance of an electronic device even when no defects occur. One effort is secondary electron emission, sending a high flux of electrons surging through electronics circuitry and creating a transient noise signal This electron flux can be triggered by a high energy gamma radiation pulse from a nuclear explosion.

Almost no gamma ray bombardment studies other than those at AFCRL have been done, although there is a fairly large collection of data on low energy electron bombardment. One AFCRL study was to find out if the wealth of low energy electron bombardment data could be used to predict the effects of gamma ray bombardment. If so, much experimental effort could be saved.

In the tests, a Cobalt 60 source was used as a source of gamma rays to bombard a number of metals such as silver, gold, aluminum, and platinum. Measurements were then made of the secondary electron yield per unit of deposited energy. AFCRL found that secondary electron emission production from a surface depended only on the rate of energy deposited near the surface and not on the type of energy of the radiation. This means that the yields of secondary electrons produced by gamma radiation can be predicted



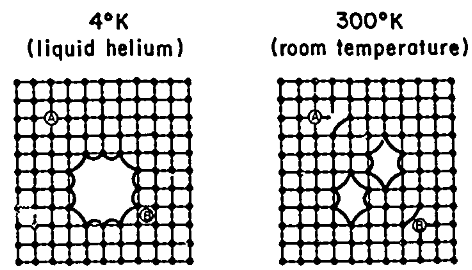
The three and one half foot thick window permits safe observation and control of experiments conducted in the Cobalt-60 cell. This cell houses a 14 kilocurie source which provides intense gamma rays for irradiating various materials and devices.

by using the lower energy bombardment data available in the literature for a vast range of materials. This research result has eliminated the necessity for an extensive experimental program on gamma ray effects. The values predicted from low energy bombardment data were within 30 percent of those obtained in the gamma ray experimental program.

DISPLACEMENT DAMAGE: Permanent damage to semiconductors can result from many kinds of radiation—high energy electrons and protons in space, neutrons, X-rays, and gamma radiation. Electron and gamma irradiations cause relatively simple defect structures. Neutron irradiations cause complex cluster-like defect structures. The nature and the extent of the damage is a function of many factors—the kind of material, its dopant, the growth method, and its electrical resistance.

One AFCRL study involves the irradiation with 1 MeV electrons of n-type silicon samples doped with phosphorus. The dominant resultant defect structures are phosphorus-vacancy and oxygen-vacancy complexes. It was shown that the damage introduction rate for both complexes decreased under continuous electron bombardment. This may be due to recombination of mobile interstitials with vacancies at defect points thereby reducing the net introduction of the vacancy-impurity complexes. This effect suggests that pre-irradiation might result in a device that would function effectively for a longer time than one having no prior damage history.

ANNEALING OF DISPLACEMENT DAMAGE IN SEMICONDUCTORS: An atom, dislodged from its normal position in a crystal lattice by high energy radiation, is not necessarily displaced permanently. Normal thermal vibrations in the crystal tend to juggle the dislodged atom back in place—or to find a new home for it somewhere else in the lattice structure. This self-repairing process is known as annealing.



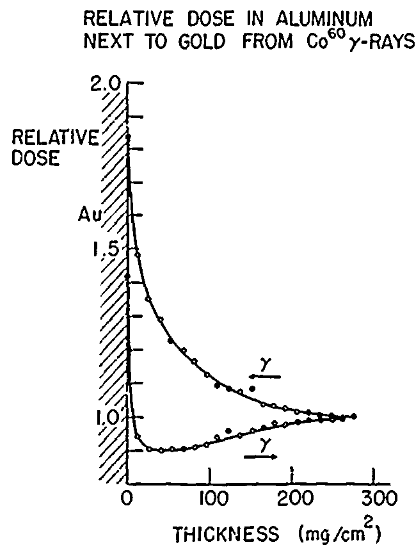
A schematic of a damage zone produced by neutron bombardment at 4 degrees K is shown on the left. This diagram is representative of the damage structure at any temperature immediately after the collision has taken place. The additional thermal energy available at 300 degrees K causes this configuration to collapse and relax into simpler, individual defects as shown on the right. A and B represent impurity atoms.

Not too much is known about how a crystal lattice goes about repairing itself after the atoms in the lattice framework have been displaced by radiation bombardment. One approach that gives insight to the process is to bombard a crystal cooled to liquid helium temperatures. At these temperatures, the defects are relatively immobile until the crystal temperature is raised. By making conductivity measurements subsequent to heat treatments at various temperatures, the temperatures at which radiation-induced defects become mobile and annealing takes place can be determined.

In this study, germanium doped with 10^{18} arsenic atoms per cubic centimeter was irradiated with 0.7 to 1.2 MeV electrons at 5 to 10 degrees K. Others had noted that two temperatures are of special importance in the annealing process. Annealing seems to take place predominantly at two discrete temperatures—35 and 65 degrees K. This suggests that two different types of defects are involved. It also suggests that the type of defect produced depends on the bombarding electron energy. The AFCRL study was undertaken to relate the defect type to electron energy. AFCRL found that the production of defects that recover at 65 degrees K increases almost linearly with electron energy. Another finding is that defects that recover at 35 degrees K are produced in greatest quantities by 0.9 to 1.0 MeV bombardment.

NEW GAMMA RADIATION ABSORPTION EFFECT: A novel effect involving gamma radiation passing through materials —an effect unaccounted for in theory —has been observed by AFCRL scientists. The effect has implications for all those conducting research on radiation hardened electronic devices. It brings into question the validity of present techniques for measuring the amounts of energy absorbed from gamma radiation in the active region of a semiconductor device. At the same time, it may be possible to take advantage of the effect to obtain additional radiation hardness by the simple procedure of orienting the devices and their associated housing in a preferred direction with respect to the anticipated radiation source, or by careful selection of the material surrounding the device.

The effect involves the energy deposition by electrons produced by absorption of gamma radiation passing through one material to a dissimilar one. When a material of low atomic number, such as aluminum, is placed in front of a material of a higher atomic number, such a gold, the amount of energy deposited in the lower atomic number material is increased by as much as 80 percent. When gamma radiation passes in the opposite direction —through gold to aluminum—the energy deposited in the aluminum is slightly increased immediately at the



This figure shows a novel absorption effect in aluminum of gamma radiation. The absorption of radiation in the aluminum is different depending on the direction of the radiation source, assuming that the facing material (in this case gold) has a higher atomic number.

interface but then drops to a value lower than it would be if the gold were replaced by aluminum. Thus it was shown that the energy deposited near an interface by gamma radiation is strongly dependent on the direction of the gamma rays with respect to the interface.

Materials such as copper, molybdenum, silver and cadmium—all with atomic numbers higher than aluminum —were investigated in conjunction with aluminum. All gave similar results, although the magnitude of the effect decreased with atomic number. Beryllium and carbon, both with atomic numbers lower than aluminum, were also tested. These caused an increase in the energy absorbed by the aluminum (which is now the higher atomic number material) near the interface when the radiation passed from the lower to the higher atomic number material, and a decrease in the energy absorbed by the aluminum near the interface when the radiation passed first through the aluminum.

Most semiconductor devices are fabricated and housed in such a way as to experience the spatially dependent effects reported by these experiments. Gold plating, high atomic number metal contacts, a support for the basic silicon chip, and the enclosure all provide interfaces which can cause large variations in dose through the active region of the device.

It should be noted that these results for gamma rays are in marked contrast to those reported at X-ray energies. At X-ray energies, the dose in a low atomic number material is always enhanced by an adjoining high atomic number material independent of the direction of the incident X-rays.

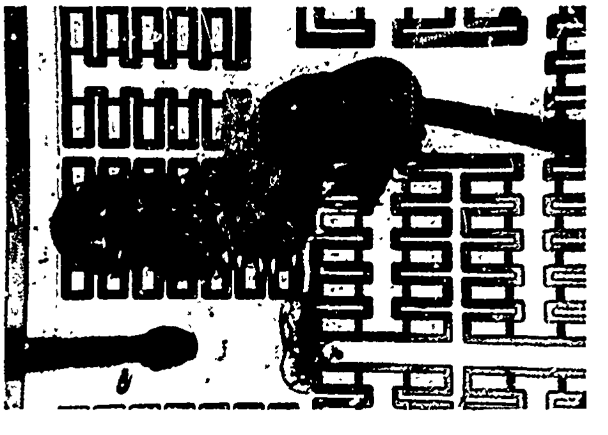
DEVICES AND TECHNIQUES

The "devices" covered under this heading are for the most part radiation hardened transistors. There's little incentive for the nation's electronics industry to concern itself with such problems as radiation hardened devices since there's obviously little demand by the commercial market. "Techniques" refers to methods for fabricating devices. One such technique is ion implantation. Although industrial concerns have taken an increased interest in ion implantation as a means for doping semiconductors, AFCRL is sponsoring ion implantation research under contract concurrent with its in-house research because the technique may prove a key to the development of radiation resistant integrated circuits.

Another device study falling into the unique-to-the-military requirement category is that of infrared sensors. During this reporting period the Laboratory, at the request of the Air Staff, initiated a new program to develop improved infrared sensors.

RADIATION RESISTANT POWER TRANSISTOR: During the report period, the Laboratory developed a bipolar power transistor which can withstand radiation levels ten times higher than the level at which the best commercially available devices fail.

The high radiation tolerance of this bipolar power transistor was achieved by applying the knowledge gained through the Laboratory's more general studies of radiation damage rather than through radical design concepts or the use of special semiconductor materials or dopants. The power device essentially consists of an array of special high frequency silicon power transistors connected in parallel. The most significant design feature is in the thickness of the silicon base, which is only about one-half micron thick. Fabrica-



This radiation hardened power transistor still functions correctly even after being damaged by the intense radiation shown here. This is the result of a design with a high degree of built-in redundancy.

tion of extremely thin layered devices, however, poses the problem of an excessively high rejection rate—or low yield—unless processing is under very good control.

Many manufacturers are also moving in the direction of thinner semiconductor layers but for reasons other than radiation hardening. Faster switching speeds of data processing circuits are achieved with thinner semiconductor layers and thus the requirements for speed and radiation resistance become the same. These high speed devices, however, do not have the requirement that the thin layers be uniform over a large area—which the power transistor must have. The AFCRL device requires special care and precision in its fabrication.

JUNCTION FIELD EFFECT TRANSISTORS: AFCRL has shown that the junction field effect transistor is the transistor type presently most resistant to permanent radiation damage, either of the ionizing or displacement type. This research has resulted in JFET designs that show virtually no degradation in electrical characteristics after an integrated neutron dose of 10^{15} neutron/cm^2. The JFET is 10 to 100 more radiation resistant than the best bipolar transistor.

In addition to the research on the permanent effects of radiation on JFET's which have led to such dramatic improvements, extensive transient effects experiments have been conducted using the AFCRL linear accelerator. Data covering a wide range of JFET designs and electrical operating conditions currently indicate that the transient ionizing effects compare to those of a bipolar transistor.

ION IMPLANTATIONS: Ion implantation consists of the bombardment of a semiconductor material—usually silicon in AFCRL studies—with ions. By shielding or masking parts of the semiconductor from the ion stream, the ions are implanted only in carefully prescribed areas of the semiconductor material. Ion implantation is an alternative technique to conventional diffusion doping techniques.

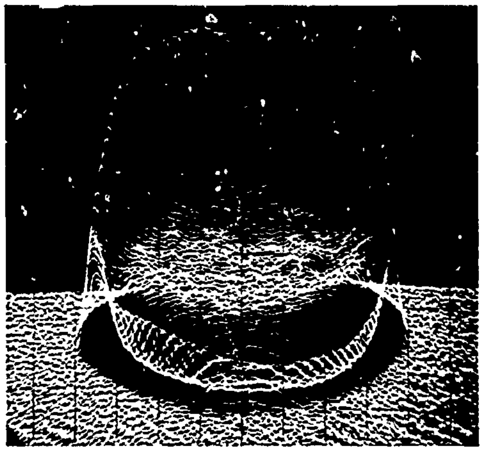
In fabricating an integrated circuit by diffusion methods, doping is distributed uniformally over the individual elements of the circuit. Ion implantation offers the possibility of varying the amount of doping from element to element by simple variations of masking. This is particularly important in the fabrication of radiation resistant circuits since it permits the designer to take advantage of radiation hardening techniques that have been worked out for individual elements. With diffusion

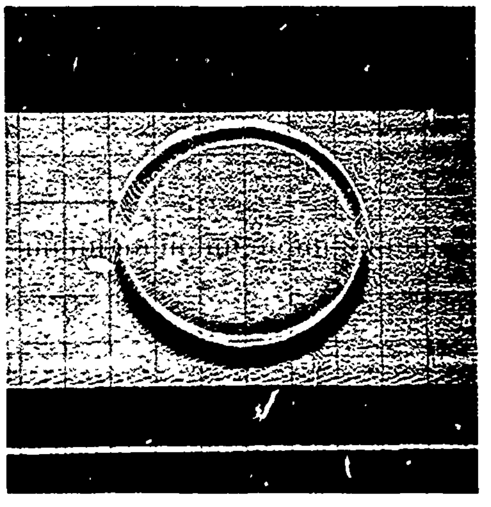
The delicate operation of attaching 1-mil aluminum wire to tiny aluminum contact pads evaporated onto ion implanted silicon devices without heating is being performed by an ultrasonic bonder.

methods, undesirable compromises must necessarily be made.

At AFCRL the emphasis has been on high energy (1-3 MeV) implantation. The results extend the findings of other investigators working at energies below 1 MeV. The high energy ions have considerably greater penetration depth. The work has yielded experimental data on the extent of large angle backscattering of light ions, such as B+ in Si, which results in considerable deviation from the gaussian distribution of implanted ions that has been generally assumed. Implantation profiles have been established for B+, N+, Al+ and P+ ions in silicon.

The annealing requirements of these implants have also been studied. Annealing of implanted samples is necessary to correct the damage to the crystal lattice caused by the ion implantation, and to permit the implanted ions to move to preferred positions in the lattice framework. Annealing can be done at relatively low temperatures so that no appreciable diffusion can occur to adjacent areas that have not been implanted. Ion implanted diodes as well as bipolar and field effect transistors have been fabricated at AFCRL.





These two figures show the phototopographical response of two Schottky barrier photodiodes as presented by a unique flying spot scanner system. The upper figure shows the local photoresponse of a uniform diode, while the lower diode shows an enhanced edge response. Both diodes are 250 microns in diameter.

INFRARED SENSORS: AFCRL's research in infrared sensors dates from a 1966 request by the Air Staff. The program centers around silicon Schottky barrier detectors. These detectors are capable of extremely fast operation and extend the useful range of silicon detectors from 0.5 to 1 micron out to 0.5 to 4 microns.

The diode is made by the evaporation of metals in high vacuum onto ultraclean silicon substrates. An internal potential barrier will form at the interface due to the Fermi-energy difference of the carriers. These diodes operate in a mode in which incident light passes through the silicon substrate and is absorbed in the metal where electrons are excited to higher energies. Those electrons that have sufficient momentum in the direction of the substrate pass over an internal barrier into the silicon where they are measured as a short circuit photocurrent. The detectivity of AFCRL experimental diodes already compares with well-known detectors and much higher quantum efficiencies—from the present limit of 1 percent to 10 percent—may be achievable.

In addition, silicon avalanche photodiodes operating beyond the cut-off wavelength have been experimentally demonstrated. At 1.3 microns the diode operates with 1 percent quantum efficiency and has an avalanche gain of 200 with a nanosecond rise time. These Schottky barrier detectors make possible the use of silicon as a photodetector beyond its normal band gap. These diodes can be fabricated in large-scale integrated circuits.

THEORY OF SOLID STATE

Complementing some of the larger programs described in the preceding pages of this chapter are theoretical efforts of a general nature in which a more complete understanding of the behavior of materials in the solid state is sought. The studies cited in this brief section were carried out by three different individual scientists.

One of these scientists is Dr. Johannes N. Plendl who for the past ten years has investigated the properties of solids. Dr. Plendl will retire from AFCRL in 1970. During the past decade he has published a score of papers on his research and has gained wide recognition for the new insight he has brought into the behavior of matter in the solid state.

LATTICE DYNAMICS: The problem that Dr. Plendl has investigated for ten years is the classic one of characteristic energy absorption spectra of solids and the meaning of these spectral properties in terms of thermal expansion, bond strengths, specific heat, compressibility, hardness and phase transformation processes. In past years, his studies have involved simple dielectric compounds. More recently, his attention has turned to metals.

The properties investigated by Dr. Plendl were the properties that were of concern to the chemists and physicists of the late 19th and early 20th Centuries. But with the exciting new world of quantum mechanics of the 1920's, physicists were led to a new way of investigating the nature of matter, with the focus on energy states and rules of quantization.

Dr. Plendl's work is based on the hypothesis that the absorption and emission spectra of a solid can reveal much more about the properties of the material than has been assumed. He asks, for example, if the characteristic spectra of a material can yield information on the hardness of the material, on compressibility, on the bonding between atoms, and so on? Can unifying, general formulas be found for dealing with these properties? The very asking of these questions was to go back to re-explore a domain that had largely dropped from fashion.

The approach was essentially empirical. It required that reflection and transmission spectra be obtained on scores of single crystal and thin film specimens. These spectra are combined to derive the fundamental absorption spectra. Once the fundamental absorption spectra are obtained, it is possible to calculate, using new formulas derived by Dr. Plendl, vibrational modes of solids, temperature effects, damping characteristics, nonlinear effects of atomic binding and much else. To check the validity of derived values, emission, laser-Raman and cold neutron scattering techniques were used.

With his retirement in 1970, AFCRL will terminate these investigations and leave their exploitation and extension to the scientific community at large.

INTERNAL FIELDS IN MATTER: This study concerns the behavior of matter in applied electric or magnetic fields. The properties of matter depend on the details of the fields in its interior. These fields, which are due in part to the microscopic dipoles that make up the matter, are irregular and rapidly fluctuating over small distances. Conventionally, they are taken account of by introduction of the well-known vectors D and H of classical electromagnetic theory. Because these vectors are not precisely defined, considerable ambiguity and even controversy surrounds them.

A new approach has been undertaken to clarify this subject. The theory of internal fields has been reformulated on a postulatory basis in which all the definitions and assumptions have been clearly spelled out. It has then been shown that this well-defined postulatory system is equivalent to and clarifies the usual theory. In this way, ambiguities and even errors in the classical theory have been noted. With the present approach, this important branch of solid state theory has been put on a firm basis.

THE THREE-PARTICLE SCATTERING PROBLEM: The previous *Report on Research* discussed a new method for viewing the bound-state, three-body problem. The method consisted of writing the total wave function for the problem as a sum of three parts. Appropriate expansions were developed for each part, expansions which converge rapidly for several important three-body atomic problems. Good results, for example, were obtained for several energy levels of the helium-like atom, the H_2+ molecule ion, and the p/p mesic molecule.

In addition to making these bound-state calculations, the method was extended to treat the three-particle scattering problem. In treating three-particle scattering for the zero-range pair potential, the method produced the standard result. Studies of electron-hydrogen scattering in the limit of zero incident energy resulted in a cross section which agrees quite well with experiments and the best calculated value using variational techniques.

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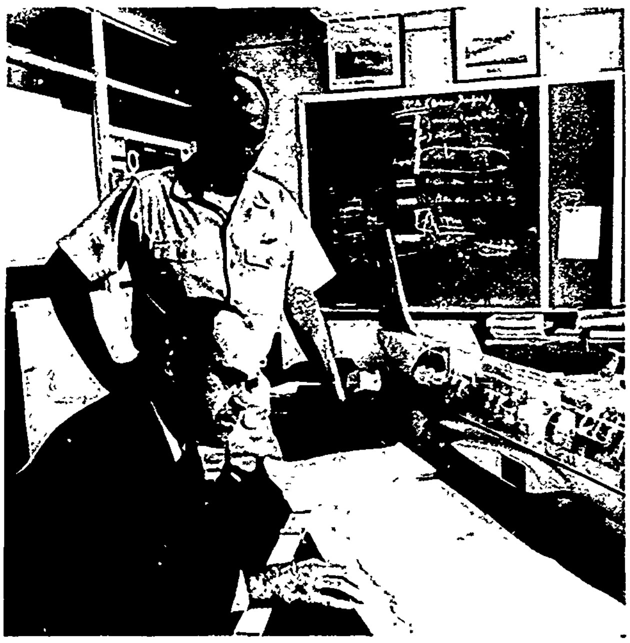


Two Optical Physics Laboratory scientists examine infrared emission spectra. On the table is a model of the Laboratory's KC-135 flying laboratory.

IV Optical Physics Laboratory

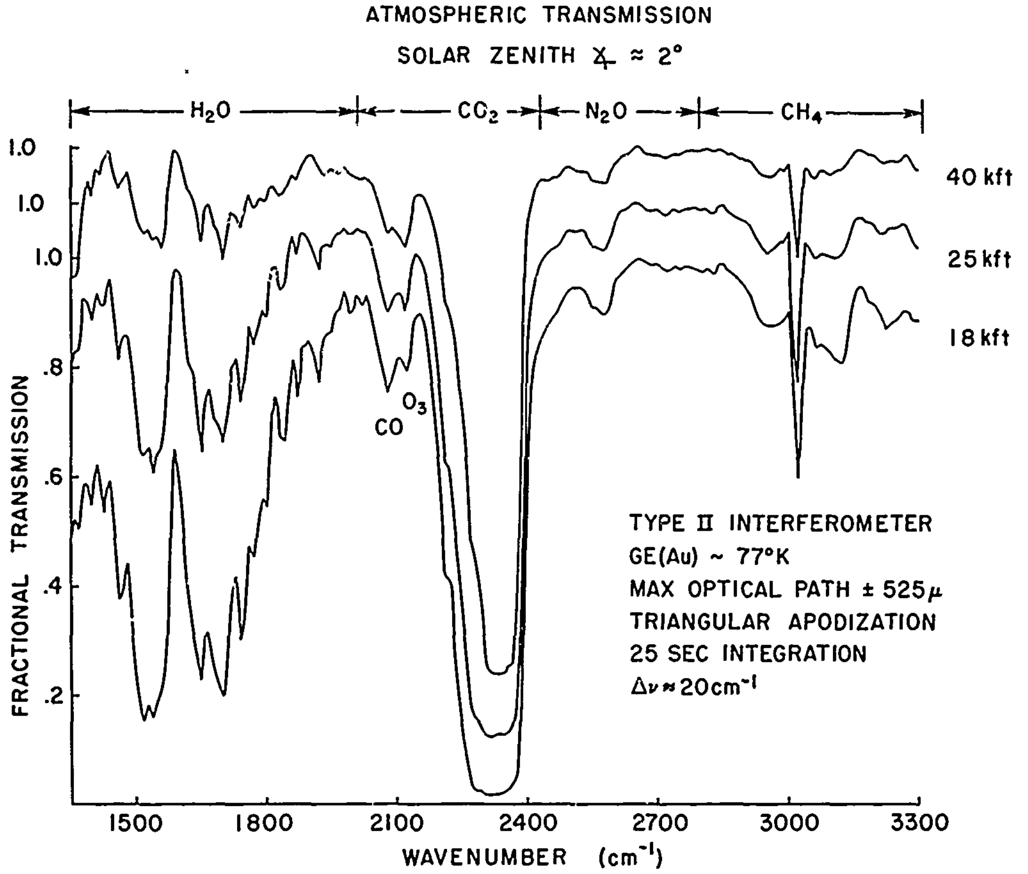
The Optical Physics Laboratory is concerned with ultraviolet, visible and infrared radiation—with that portion of the electromagnetic spectrum that extends from about 2000 angstroms in the ultraviolet to about 1 millimeter where the far infrared blends into the microwave radio spectrum.

The atmosphere interacts powerfully with this radiation. A major class of problems under investigation by the Laboratory centers on the atmospheric attenuation of the radiation—the transmission properties of the atmosphere, its transparency. Atmospheric molecular species absorb this optical/infrared energy selectively at discrete wavelengths. So one of the objectives of the research of the Laboratory is to locate transmission "windows," including those exceedingly narrow wavelength regions through which radiation such as from lasers passes with a minimum of attenuation.

Through thermal and chemical processes, the atmosphere emits radiation as well, with the intensity of emissions varying along the spectrum. Such emissions represent interfering background noise superimposed on weak optical/IR signals that a surveillance system may be trying to detect. Another atmospheric obstacle is light scattering. The result in the case of photoreconnaissance, for example, is loss of contrast in the targets one is trying to observe. Scattering is why the sky is blue, and why no stars are seen in the daytime sky. The atmospheric molecules responsible for this kind of scattering—Rayleigh scattering—are small in size. Larger molecules, dust particles and water droplets in clouds produce yet another scattering effect—Mie scattering—that tends to block or shield the radiation and which must be analyzed by different sets of calculations.

The interaction of optical/infrared radiation with the atmosphere has a direct bearing on the development of Air Force optical/infrared sensors for reconnaissance, surveillance, homing and tracking systems and on the operation of these systems. All optical/infrared systems that operate in or above the atmosphere must either look through the atmosphere or must look into the optical/infrared background noise of the sky and space.

For this reason, the Laboratory conducts considerable research on the chemistry and physics of the atmosphere. Studies of atmospheric chemistry provide essential insights into the absorption or emission mechanisms. Related atmospheric research, but research having other objectives, is conducted by the Aeronomy Laboratory (Chapter



Atmospheric transmission at various altitudes measured by the Laboratory's KC-135 optical infrared research aircraft is plotted. The sun was used as the radiation source.

III) and by the Space Physics Laboratory (Chapter VII). In addition, the Terrestrial Sciences Laboratory (Chapter V) is a developer and user of optical/infrared sensors in its work on remote sensing techniques.

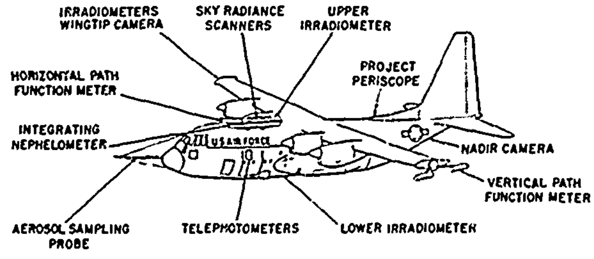
Historically, the Laboratory's focus of attention has been on the infrared spectrum. It is here that the greatest potential for Air Force applications lies. Specifically, the kind of problem for which the Laboratory seeks solutions is this: What is the effect of the infrared properties of the atmosphere and environment on the detection of a missile at long ranges?

An inseparable part of the Laboratory's atmospheric studies is the development of more sensitive infrared sensors and spectral instrumentation. Signals of interest are often so weak and so buried in background noise that special processing is often required to extract them. One such processing method is that of Fourier spectroscopy, a field to which AFCRL has contributed much. In March 1970, the Optical Physics Laboratory sponsored the first international conference devoted exclusively to this new field. This conference, for the first time, brought together the world's leading scientists in this field.

During the three years of this report, the Laboratory launched four rockets and instrumented one satellite (the OV1-86) in connection with its research. Fifty-five instrumented balloons were also used. But the vehicles on which the Laboratory basically relies on are two instrumented aircraft. Two of AFCRL's five flying laboratories are instrumented exclusively for research by the Optical Physics Laboratory. During the reporting period, these aircraft made observations all over the world. The C-130 aircraft made two lengthy expeditions to Thailand to examine the tropic atmosphere. The KC-135 aircraft made extensive studies of atmospheric transmission and emissions at widely spaced geographical locations.

AFCRL's laser research program is centered in this Laboratory. Laser research is concentrated on high-powered, pulsed, solid state lasers, although some work is done also on ultrashort pulse generation and on tunable lasers.

Among the new important facilities placed in operation by the Laboratory during the period were computerized instrumentation for real-time Fourier spectroscopy, two new molecular beam



The Laboratory's C-130 flying laboratory was photographed soon after its arrival in Thailand to investigate atmospheric transmissions in the tropics. Placement of instruments for measuring sky radiance, atmospheric transmission, aerosol distribution, terrain reflectance, and other parameters are diagrammed in the drawing.

generators for studying chemical interactions, and an updated calibration facility for calibrating spectroscopic instruments prior to installation in balloons and rockets.

FIELD OBSERVATIONS

With the mobility provided by the Laboratory's KC-135 and C-130 instrumented aircraft, the Laboratory has the capability for making observations all over the world. Ready access to the AFCRL balloon launch facility (Chapter XII) provides another observational platform for measuring scattering, absorption, transmission and emission at various altitudes in the atmosphere. Laboratory personnel and contractors conducted experiments on 55 different balloons during the period.

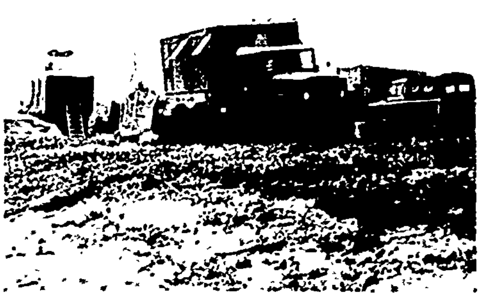
Four instrumented rockets were launched from widely spaced geographical locations—Brazil, Ft. Churchill, Canada, and the White Sands Missile Range in New Mexico. Three of these rockets were instrumented to look at and define the infrared horizon, in connection with satellite navigation and stabilization systems. Launched in July 1967 was an infrared satellite package for measuring the infrared background of the earth and clouds.

In addition to observations made by Laboratory personnel, an informal cooperative program for photographing the twilight sky (using procedures specified by the Laboratory) at locations extending from Northern Canada to South America was established. The purpose of this program is to measure aerosols in the stratosphere, the concentrations of which are directly correlated with twilight intensity.

The field observation program has many purposes, obvious ones that hardly need restatement. They are checks on theoretical calculations, they provide empirical data from which a better theoretical understanding evolves, they test the performance of new instruments and the effectiveness of new observational techniques, and all of these, in a feed-back arrangement, provide the basis for new detection schemes and new instrument design.

THE C-130 THAILAND EXPEDITIONS: Just how well infrared and other optical instruments for guidance, surveillance, reconnaissance and target acquisition perform often depends on the atmospheric conditions at a specific time and place. In Vietnam, for example, atmospheric transmission properties are not the same during the dry season as they are during the monsoon season. The visibility properties of terrain features also differ during the wet and dry seasons.

These are the reasons behind the Laboratory's C-130 expeditions to Thailand. The first was made during the monsoon season in September and October 1968, and the second during the



The Thailand experiments required as an adjunct to the airborne measurements considerable ground equipment and instrumentation which were transported to the various regions.

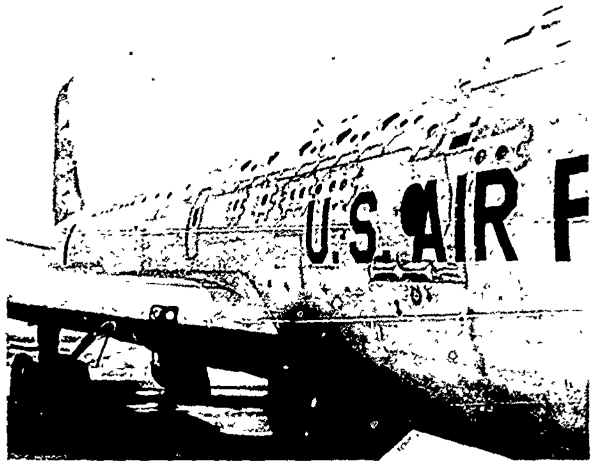
dry season for a ten-week period beginning February 14, 1969.

Participating in the program were 16 scientists and engineers from AFCRL and the Scripps Institution of Oceanography. The C-130 operated out of the U-Tapao Air Field. Instruments aboard the aircraft observed the same geographical areas during both expeditions, areas selected for distinct terrain features. These are the Khorat Plateau, a region of forest and relatively high elevation; Lop Buri, with its rice paddies and delta region features; the Rayong area, with its typically heterogeneous vegetation on the southeast coast of Thailand.

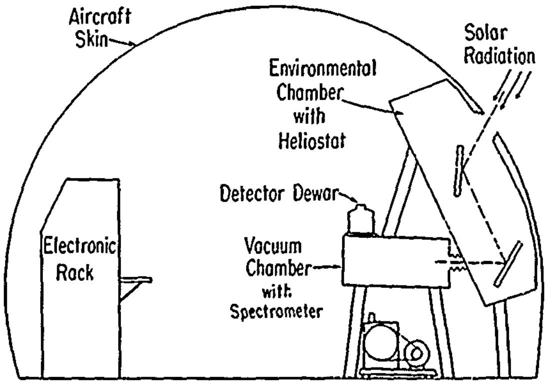
Instruments aboard the aircraft included 12 optical and several meteorological subsystems all mated to a high-speed data recording system. In addition to the airborne system, a complementary mobile ground station was used, operated with support from the Thais. The ground station served as a control for the data collected by the aircraft and had a duplicate set of instruments to observe targets at close range without the background interference of the atmosphere. Differences in target resolution between the airborne instruments and ground-based instruments can be attributed to atmospheric masking. The airborne and ground instrumentations were fabricated and installed at a cost of about one million dollars, instrumentation that in itself greatly expanded the state of the art in photometry.

Low light level measurements were made over a range of altitudes during both expeditions. From the computer analysis of these data, prediction criteria for the performance of optical sensors in the SEA environment will be established, giving answers to the following kind of question: "What will be the level of contrast between a particular target and its background as a function of sensor wavelength, altitude and atmospheric condition?"

KC-135 OBSERVATIONS: The Air Force requirement can be stated simply. It is to detect infrared emitting targets or sources at the greatest possible distance. However, the atmospheric environment seems deliberately designed to obstruct this goal. The approach is

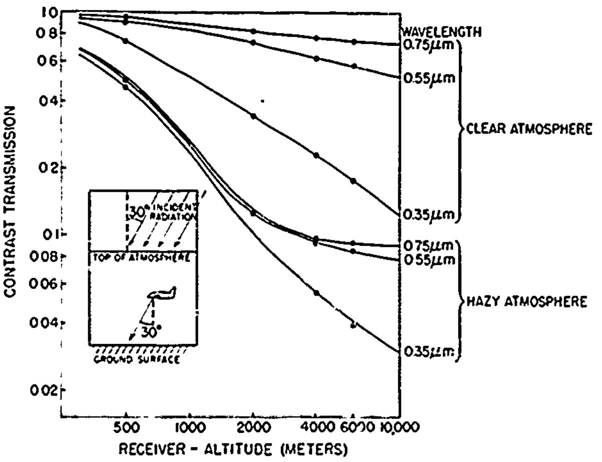


The KC-135 flying laboratory has many observing ports. One port, diagrammed below, provides an opening for the aircraft's far infrared spectrometer and heliostat.



to locate those wavelengths—"windows"—in which the infrared radiation is not absorbed by some molecular species and in which another molecular species does not emit radiation that would make the infrared target of interest undetectable.

The flights made by the KC-135 flying laboratory during the three years of this report were in one way or another concerned with the problem of atmospheric transmission or emission. Atmospheric transmission data can be obtained by simply observing the sun at various flight altitudes and angles. Most observations were made with two interferometers aboard the aircraft to obtain data in the 1 to 8 micron spectral regions. These instruments have a resolution of approximately 15 cm^{-1}. Using the sun as a source, data were acquired at various altitudes between 18,000 and 40,000 feet as a function of solar elevation angle and latitude between 90°N and 55°S.



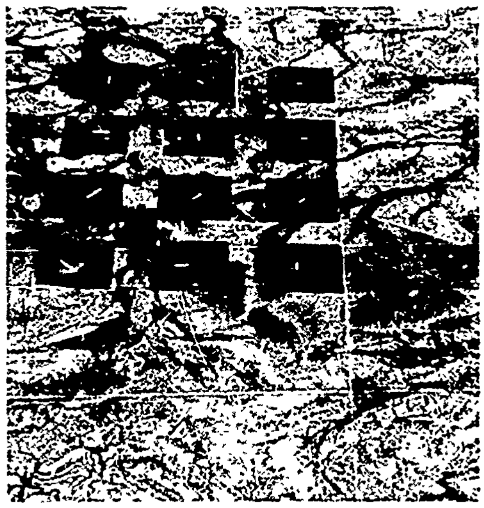
· Many flights by the Laboratory's aircraft are concerned with atmospheric transparency as a function of wavelength. In this diagram, an optical path looking down from an aircraft to the ground at an angle of 30 degrees with the incident illumination also at 30 degrees is depicted. The clear atmospheric model has a ground visibility of 25 km; the hazy atmosphere has a 3 km visibility.

The airborne program to measure atmospheric transmittance is being extended to the far infrared—50 to 300 microns. The instrumentation, when completed, will consist of a heliostat in an environmental chamber open to outside air, a Michelson Fourier spectrometer, mounted in a vacuum chamber; and a gallium doped germanium detector operated at 2°K. The principal absorber of far infrared radiation in the atmosphere is water vapor. Water vapor distribution in the lower stratosphere is being studied in particular detail.

The KC-135 is also used to observe atmospheric emissions. The aurora and airglow can provide an intense infrared masking background. Both are subject to diurnal, seasonal and geographic variations. Using instruments aboard the KC-135, the Laboratory is compiling the best data available on the spectral, spatial and temporal features of these backgrounds, data which are essential to the systems designer.

With respect to airglow, the emission from the hydroxyl radical (OH) dominates the night sky in the short wavelength infrared (1 to 4 microns). A major effort has been devoted to observations of the OH emission during sunrise and sunset when changes in the emission are expected due to the solar influence on the ozone. Although the sunrise/sunset variation in OH emission has been observed it has been sufficiently irregular to preclude formulation of OH chemistry. The hydroxyl radical has been observed to have large diurnal intensity variations and has also shown major seasonal changes.

Measurements of the type touched upon here were made during scores of flights that took the KC-135 from its home base at L. G. Hanscom Field to

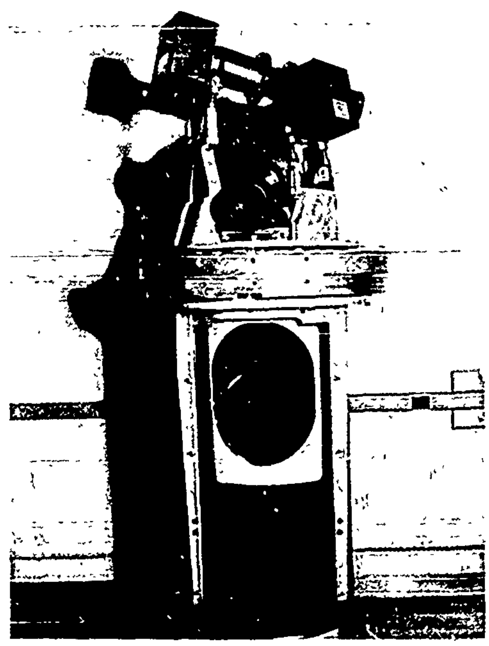


One method used to measure sensor efficiency is to place white strips on the ground and to observe the contrast between the strips and the dark background as a function of solar incidence, look angle, and altitude.

observing points over much of North America. The most publicized single flight of the aircraft during the period, however, was one made during the March 7, 1970 solar eclipse. During the eclipse, observations were made over the Pacific, southwest of Acapulco, Mexico. By following the sun, five minutes of total eclipse were observed. The flight was made primarily to observe atmospheric chemical processes resulting from the sudden cessation of solar energy.

ROCKET OBSERVATIONS: Three of the four rockets launched by the Optical Physics Laboratory during the reporting period were instrumented to measure the infrared radiance of the earth's atmosphere near the horizon. The fourth rocket launched from Ft. Churchill, Canada, was instrumented to measure infrared auroral emissions. The three rockets—all Aerobees—designed to obtain an accurate observational description of the earth's limb radiance (as a reference for space vehicle attitude determination) also carried spectrometers for obtaining data on atmospheric emissions.

The first, launched from Ft. Churchill, Canada, in August 1968, observed emissions from the rotational water vapor band (19 to 35 microns), the carbon dioxide band (14 to 16 microns), the ozone band (9.6 microns), the atmospheric and earth continuum in the "window" region (10 to 12 microns), the near infrared electronic transitions of hydroxyl (1.4 to 2.4 microns) and transitions of oxygen at 1.28 microns. The second rocket was launched from Natal, Brazil, in March 1968. This probe observed the emission from the rotational water vapor, carbon dioxide, the near

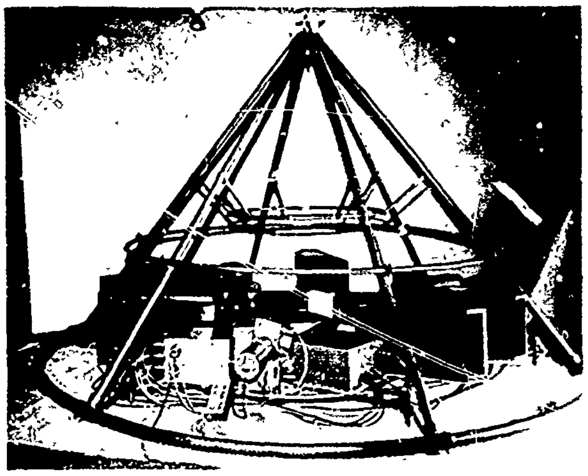


The primary instrument flown aboard rockets for measuring the infrared horizon is this assembly containing a radiometer (lower section) and star mappers above. The Cassegrain mirror of the radiometer can be seen reflected in the scanning mirror.

infrared hydroxyl bands, and the 1.28 micron oxygen band. The third rocket was launched from White Sands Missile Range, N.M., in February 1970. A new liquid helium cooled detector was used on this flight and this precision radiometer provided excellent records of the 15 micron carbon dioxide, the 9.6 micron ozone, and the 6.3 micron water vapor horizon profiles.

In addition to direct measurements of the infrared horizon, the rocket experiments produced other information —mixing ratios for H_2O and O_3 in and above the stratosphere, the limits of validity of atmospheric models, and the altitude regime where the concept of thermodynamic equilibrium is no longer valid.

OBSERVATIONS FROM BALLOONS: From July 1, 1967 through June 30, 1970, the Laboratory launched 55 balloon-borne experiments, all from the AFCRL balloon launch facility at Holloman AFB, New Mexico, and reaching an average altitude of 100,000 feet. Most of these flights carried multiple instruments for several types of observations.



To determine light scattering properties of the atmosphere as a function of altitude, this balloon-borne nephelometer measures scattered intensity and polarization at five angles for visible and near infrared wavelengths. Measurements up to 100,000 feet have been made.

One series of flights carried as its primary observing instrument a nephelometer for observing the polarization and angular light scattering properties of the atmosphere for altitudes up to 30 km. The instrument consists of a pulsed xenon light source which projects a beam providing a uniform intensity distribution throughout the volume being measured. Five observation telescopes view the projected beam at scattering angles of 25°, 45°, 90°, 130° and 155°. The volume defined by the intersection of the source and observation beams contains the air and aerosol sample whose scattering properties are measured. The series of balloon flights with this instrumentation yielded data which are unique because of the variety of controlled parameters, spatial resolution and altitude range.

More typical of the balloon observational program was the launch and successful recovery of a 650-pound payload which reached a floating altitude of 94,500 feet. This flight involved four different experimental units. The keystone for this flight was the performance of a biaxial sun pointer. This instrument, in spite of swinging and rotating motions of the flight platform, continuously points to the center of the sun. Performance of the experiments depended upon the accurate orientation with respect to the sun.

One of these experiments was designed to measure the amount of water vapor distributed in the atmosphere by measuring the direct sun radiation at 1.87 microns at which wavelength there is also an absorption band due to water vapor. Another instrument measured the sky radiation very close to the sun for determination of the vertical distribution of aerosols. The final experiment consisted of two instruments (spectropolarimeters) for measuring the intensity and polarization of light coming from the earth and its atmosphere.

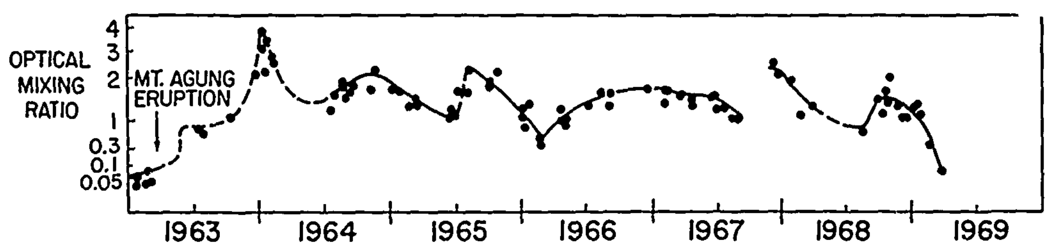
ATMOSPHERIC AEROSOLS: Aerosol particles are found throughout the lower atmospheric strata and possibly in the mesosphere above 50 km as well. Haze layers in the stratosphere (above about 18 km) have been reported by pilots and evidence of stratospheric dust has been reported by astronauts from space. These dust particles set limits upon how well airborne and satellite instruments can observe the ground.

The Laboratory has gathered a considerable amount of data on vertical aerosol profiles up to 35 km altitude by means of searchlight backscattering experiments conducted in New Mexico. An analysis of these measured aerosol profiles has yielded good correlations with general atmospheric circulation and structure patterns. For example, the 18-20 km dust layer, found in almost all measurements, is directly related to the altitude of the tropopause.

Concentration variations in stratospheric aerosols by month or year can be studied by observing sky radiance during twilight. Twilight is primarily the product of aerosol scattering, and twilight brilliance, intensity and duration are governed by concentrations of stratospheric aerosols. Measurements of the spectral radiance and polarization of the twilight sky can therefore provide information on the light scattering properties and thus on the dust particle content of the upper troposphere and stratosphere.

Twilight measurements are made routinely by photometers. To obtain a continuing record of the distribution of aerosols at widely spaced geographic latitudes, arrangements have been made with photographers at locations extending from Northern Canada to South America to photograph the twilight sky under a set of procedures specified by AFCRL.

A by-product of the Laboratory's aerosol research is that of measuring levels of pollution in the atmosphere. In recent years investigators at AFCRL and elsewhere have started to use laser probes routinely for measuring aerosol concentrations at various altitudes. As in the case of AFCRL's earlier searchlight experiments, a laser beam is projected upward and concentration of aerosols can be derived from the amount of light that is scattered. When



Long-term variations in concentrations of stratospheric aerosols are shown in this plot. These variations are directly correlated with volcanic activity.

many independent investigators enter a new field, an initial consequence is lack of uniformity in measurement procedures, making it difficult to correlate results obtained by the different observers.

This led to an AFCRL proposal for the establishment of uniform standards to be adopted by all observers based on considerations arising from AFCRL experience. If these uniform procedures are adopted, investigators can begin to collect a consistent body of data. In time, those using laser probes to monitor upper atmospheric pollutants will be able to plot long-term trends in aerosol (pollutant) levels.

The intensity of twilight illumination is a measure of stratospheric dust. By photographing the twilight sky at a given solar depression, aerosol concentrations in the stratosphere can be derived.

A study undertaken by the Laboratory in the spring of 1970 concerned the amounts of pollutants injected into the stratosphere by SST operation. Considerable press commentary at that time indicated a high injection rate. In one of the most complete studies undertaken up to that time, AFCRL determined that the increases in stratospheric aerosols resulting from a large worldwide fleet of SSTs would be minimum.

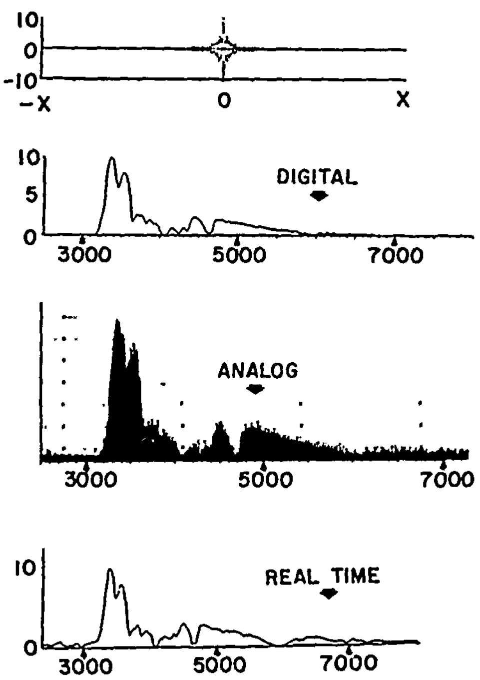
To obtain data on maritime aerosols in the lower atmosphere, Laboratory personnel in the summer of 1969 made field expeditions to St. Croix in the Virgin Islands and to Puerto Rico. Observations of the maritime air pointed up the long distance transport of aerosols in the lower atmosphere. Dust arising from a storm in the Sahara Desert was measured in ocean air off the Caribbean region. Analysis of aerosol data from all over the world pointed up the marked day-to-day variation in aerosol distributions at any given location. However, the study also showed that, except for major metropolitan areas, aerosol distributions all over the world, on the average, are much the same.

LABORATORY INSTRUMENTS AND TECHNIQUES

Most of the programs of the Optical Physics Laboratory involve spectroscopic instruments in one or another of their many forms. Much of the total Laboratory effort is spent in the design and development of these instruments and related analytical techniques. The instruments designed and developed initially for the acquisition of more refined scientific data can often be adopted with little design modification for Air Force operational use.

Data collected by the Laboratory's two research aircraft, from its other research vehicles and from field expeditions are usually returned to the Laboratory for analysis and this often requires special analytical techniques. Or sometimes phenomena of interest cannot be observed in the natural environment and it's necessary to set up controlled environments in the Laboratory. In developing new instruments, their performance must be precisely calibrated. This need has led the Laboratory to maintain a special calibration facility.

The several new instruments and analytical facilities that were placed in operation during the reporting period are reviewed in this section.



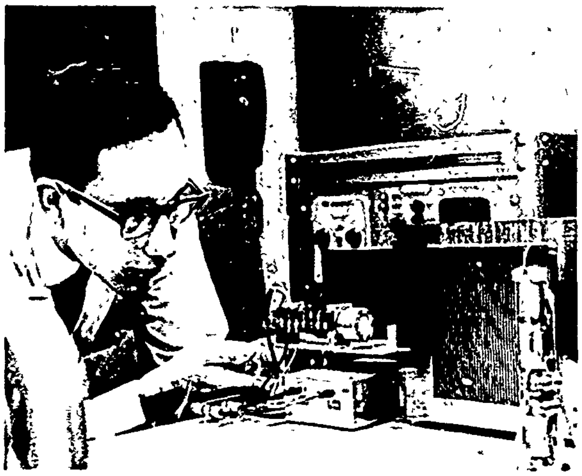
The results of three techniques for transforming the interferogram (top) is shown. The second plot was made by a digital computer; the third plot was made by an analog computer, and the bottom plot by the AFCRL real-time spectral synthesis computer.

REAL-TIME FOURIER SPECTROSCOPY: Of the many contributions made by AFCRL to science and technology over its 25-year history, its contributions to Fourier spectroscopy must rank among its more significant. Fourier spectroscopy is a powerful technique for obtaining spectral data. Its capabilities are unique and so attractive that it becomes quite worthwhile to devote many hours of computer time to obtain a Fourier spectrum.

For AFCRL's real-time system, the Fourier spectrum is obtained by synthesis rather than by analysis of an interferogram. The interferogram is produced by a simple interferometer, which splits an incoming wavefront into two beams and introduces a delay into the path of one of them. The beams are then recombined to produce the interferogram. A Fourier transform is done on the interferogram.

Fourier spectroscopy has two advantages. First, the interferometer, compared with the conventional spectrometer, views a source with a much larger aperture and this allows more energy to reach the detector. Next, the interferometer has what is called the "multiplex" advantage, which gives an improved signal-to-noise ratio. These advantages, particularly in the far infrared where sources are weak and detectors are insensitive, lend great attraction to Fourier spectroscopy.

The disadvantage of Fourier spectroscopy was the time that it takes to obtain a spectrum—as much as a day on a digital computer. During the period, the Laboratory developed the means for displaying a Fourier synthesized spectrum on an oscilloscope immediately after the interferogram is obtained. This AFCRL real-time system is one that substitutes a highly specialized spectrum synthesizer for the computer. The entire system is small



On the right is a variable groove depth lamellar grating which serves as the beam splitter in an interferometer-spectrometer. The electronic package immediately to the left of the grating is the detector system used to determine the position of zero path difference between the two interferometer beams.

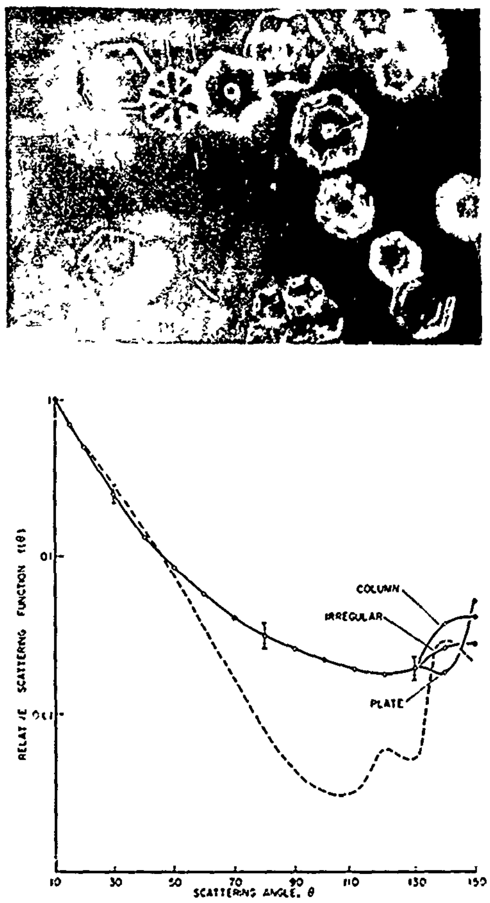
enough for easy transport to remote field sites or for use aboard aircraft. The system can also be designed in a package small enough to be carried aboard balloons or satellites.

With this technique, only selected points on the interferogram are sampled and these sampled points are located at equal increments of path difference. The spectrum is synthesized by the successive summation of a series of harmonic functions (cosines) whose amplitudes are controlled by the value of the interferogram at the sample points and whose frequencies are related to the path difference at the same sample points. Since an additional cosine function is added to the spectrum synthesis each time a sample is taken, the final spectrum is ready for study as soon as the interferogram has been taken.

AFCRL has also applied Fourier spectroscopy to the measurement of optical constants. Channel spectrum fringes (also known as fringes of equal chromatic order) arise when collimated heterochromatic radiation is passed through any plane parallel homogeneous sample. The fringes are revealed when the radiation is dispersed, appearing as a wavelength dependent modulation of the intensity in the spectrum. These fringes, closely related to those observed in a Fabry Perot interferometer, arise from interference between beams produced by reflections internal to the sample. The spacing of the fringes depends on the refractive index alone while the amplitude depends on both index and absorption coefficient. This makes it possible, in principle, to derive both optical constants from a single spectrum. This method is applicable not only to solid samples but also to gases which may be studied by using a sample cell with plane parallel ends. The Laboratory has measured the optical constants of numerous plastic, crystalline and sintered materials.

LIGHT SCATTERING BY ICE CRYSTALS: Clouds are the most obvious obstacle to the transmission of optical/IR energy in the atmosphere. Calculations of transmissivity of clouds must include parameters on light scattering of the cloud particles. The scattering properties for spherical water droplets can be reliably computed from existing theories. Considerable difficulties, however, arise in the case of nonspherical ice crystals of the type found in cirrus clouds.

Ice crystals were formed in a laboratory cold chamber and a nephelometer was used to measure the light they scatter. The nephelometer measures the amount of light scattered at different angles by the small volume



Above is a photomicrograph of ice crystals grown in a laboratory cold chamber at a temperature of minus 17 degrees C. The plot below shows the relative angular scattering functions for ice crystals (solid curve) compared with that of water droplets (dashed curve).

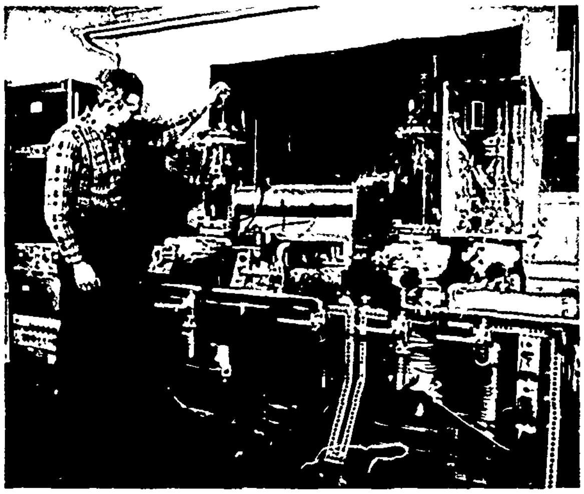
containing many ice crystals. Ice crystal size and shape can be controlled by changing the temperature of the cold chamber.

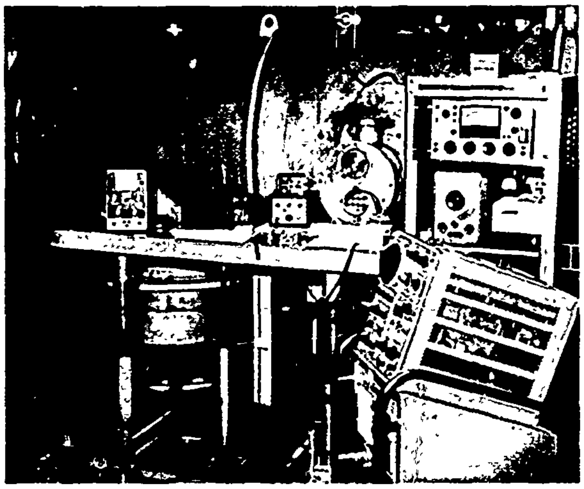
The results show that the way in which light is scattered by ice crystals is significantly different from the way in which it is scattered by water droplets. Instrumentation is now being developed that will enable these measurements to be extended into the near infrared spectrum. The objective of this study is to find a way to calculate optical properties of cirrus clouds in the same manner that is now possible to calculate the optical properties of water clouds.

MOLECULAR BEAM GENERATORS: For a chemical reaction to take place between two atmospheric molecules, the molecules must collide. Not only must they collide, but the collision must take place at specified velocities. If relative velocities are either too small or too great, no chemical reaction will take place. Velocities are expressed in terms of electron volts, and in these terms the electron volt range within which most chemical reactions take place is relatively low—1 to 10 eV.

While charged particles can be accelerated to billions of electron volts, the problem of accelerating a concentrated beam of neutral particles to a few electron volts is extremely difficult. Only in recent years—during the 1960's—have techniques evolved for creating a concentrated beam of molecules in this energy range. During the reporting period, two molecular beam generators were placed in operation at AFCRL. They are based on different principles. The smaller of the two first accelerates ions and these ions are passed through a charge exchange cell where they pick up electrons and are neutralized. The other generator is much larger and more versatile because beams of almost any species can be generated. In this generator high pressure gas is released through a supersonic nozzle into a vacuum. An aperture in front of the nozzle blocks all particles except those traveling in an axial direction.

This second facility is sizable, centering around a large evacuated chamber (10^{-8} torr) having the general volume and shape of a railroad tank car. Intersecting this evacuated tank to form a T configuration is another cylindrical chamber where one of the beams is generated. This beam collides with a second gas in a large spherical chamber and the interactions and products of the collisions are then measured.





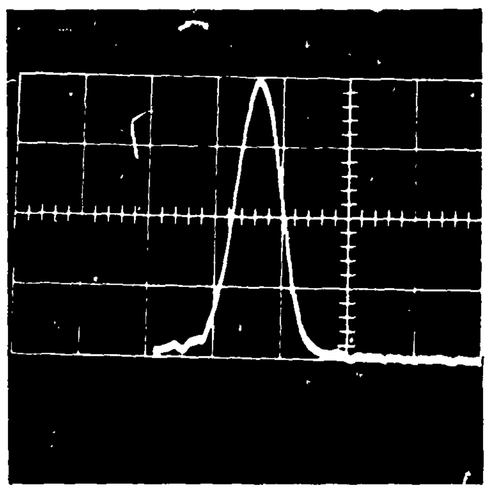
Two of the Laboratory's molecular beam generators are shown. Above is the charge exchange molecular beam apparatus; below is a portion of the supersonic molecular beam generator.

Most of the effort during the period was concentrated on checking out the two generators—understanding the mechanism of the beam production and beam diagnostics. Of the actual experiments conducted using the larger of the two generators, one involved the collision of $CO_2 + A \rightarrow CO_2^{*} + A$, a collision leading to infrared radiation. The second molecular beam apparatus, when fully in operation, will be used in high energy collision experiments that produce optical radiation. The objective is to obtain optical excitation functions for these collisions.

CALIBRATION FACILITY: In the Laboratory's calibration facility, optical systems can be calibrated in the spectral region from 2000 angstroms to 15 microns on absolute radiance and irradiance bases, including spectral, angular and temporal responses. In mid-1970, the facility was being modified to extend the coverage to 30 microns. The expanded facility will include the addition of a liquid nitrogen cooled collimator and a three by seven foot vacuum chamber. The chamber will be used to calibrate radiometers, spectrometers and interferometers to be flown on balloons, aircraft and rockets. An important capability of the calibration facility is a system for measuring the transmittance of filters in the 4 to 25 microns region at temperatures of 5 to 300 degrees K.

LABORATORY EXPERIMENTS, THEORY AND MODELS

The goal of research—any research—is to understand and explain observed phenomena. Field measurements can produce some data on the operational limits of Air Force optical and infra-



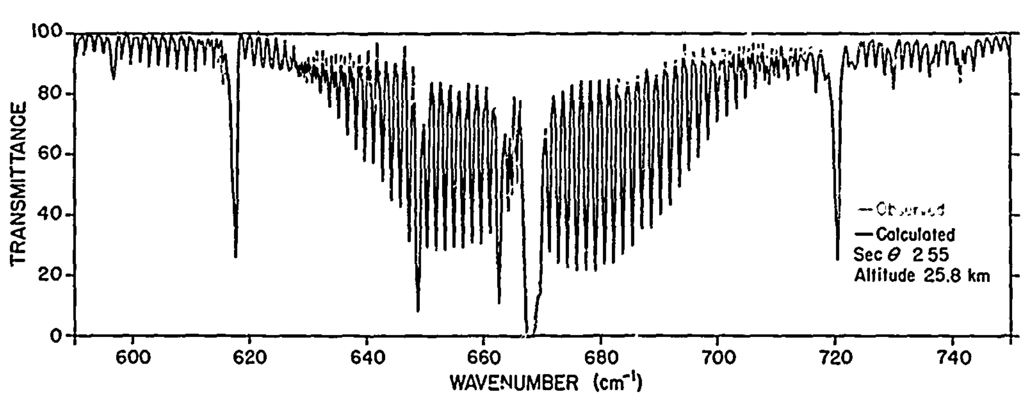
This oscilloscope trace shows the time of flight distributions for an argon beam obtained from the supersonic molecular beam generator. Each vertical line represents a time interval of 200 microseconds.

red systems, but such measurements alone cannot provide data for all situations and do not provide the insights into fundamental mechanisms for predicting these effects. Nor do they, except by inefficient step-by-step elimination processes, indicate optimum approaches toward the development of new systems.

The Laboratory's theoretical program provides the foundation on which the field measurement and instrument development programs rest. It has many parts, but basically, it is concerned with the energy exchange and radiative mechanisms of atmospheric gases. Atmospheric transmission, emission, absorption and all the factors that affect the operation of Air Force optical/infrared systems have their origins in the radiative properties of atmospheric atoms and molecules.

ATMOSPHERIC TRANSMISSION-EMISSION MODEL: A model of the transmission and emission properties of the atmosphere is being developed. Using this model, the transmission of the atmosphere along any conceivable path can be calculated with a high degree of accuracy. The spectral region covered in the model is from the ultraviolet (about 0.3 microns) to the far infrared.

To attempt a calculation program of this sort it is necessary to compile

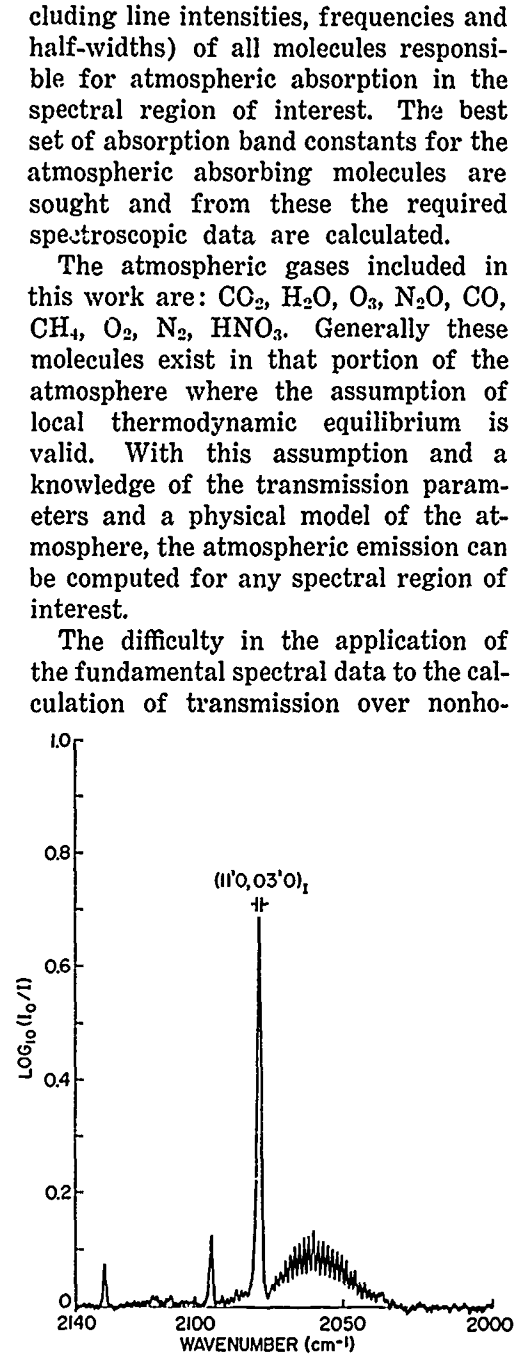


Shown here is a comparison between theoretically predicted atmospheric transmission in the 15 micron CO_2 region and that observed with a balloon-borne spectrometer using the sun as a radiation source.

the fundamental spectroscopic data (including line intensities, frequencies and half-widths) of all molecules responsible for atmospheric absorption in the spectral region of interest. The best set of absorption band constants for the atmospheric absorbing molecules are sought and from these the required spectroscopic data are calculated.

The atmospheric gases included in this work are: CO_2, H_2O, O_3, N_2O, CO, CH_4, O_2, N_2, HNO_3. Generally these molecules exist in that portion of the atmosphere where the assumption of local thermodynamic equilibrium is valid. With this assumption and a knowledge of the transmission parameters and a physical model of the atmosphere, the atmospheric emission can be computed for any spectral region of interest.

The difficulty in the application of the fundamental spectral data to the calculation of transmission over nonhomogeneous paths such as those traversed by radiation in the real atmosphere is a knowledge of molecular abundances and the distribution of abundance with height. All of the molecules listed above except H_2O, O_3, and HNO_3 are assumed uniformly distributed for this purpose.



The 4.8 micron region of CO_2 at a pressure of one atmosphere is shown here. Note that the rotational structure of the band is clearly defined.

A significant source of uncertainty in these calculations results from uncertainties in line shapes which are a function of pressure, temperature and a number of other parameters. In addition to these there are uncertainties related to departures from the usually accepted Lorentz shape in the far wings of lines which result in uncertainties in continuum absorption in some of the "window" regions. This latter problem will be solved for the present by direct use of experimentally determined absorption coefficients.

The model will also include the effect of both molecular and aerosol scattering on atmospheric transmission at all wavelengths of interest.

VIBRATION-ROTATION INTERACTION: The complete development of atmospheric models, as described above, requires a great amount of fundamental data concerning the molecules of interest. Spectral line positions and intensities must be measured, as well as line shape and vibration-rotation interaction parameters. A quantity of particular importance is the integrated band intensity, A, defined as the integral of the spectral absorption coefficient taken over the entire vibration-rotation band.

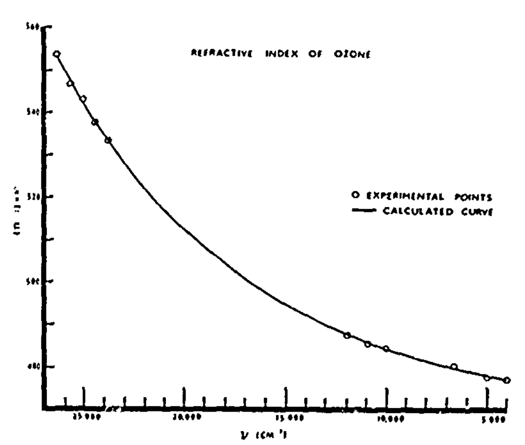
A concentrated effort was directed toward measuring the intensities of weak infrared bands in the CO_2 spectrum. Because these bands do not completely absorb over long paths, values for their intensities are important for transmission calculations through these path lengths in the earth's atmosphere.

The measurements have been carried out in absorption using the high-pressure, self-broadening techniques which had been previously developed for the Laboratory's studies of CO and NO. Measurements at 1.4, 1.6, 2.0, 4.8, 5.2, 9.4 and 10.4 microns were completed at pressures ranging from 1-50 atmospheres, path lengths from 0.5 to 100 cm and spectral bandwidths from 0.5 to 2.0 cm^{-1}.

The pressure broadening technique is not applicable to studies of water vapor or ozone, and for these molecules an asymmetric Michelson interferometer was constructed. With this instrument, refractive indexes were measured in the 4000 angstroms to 2.5 micron region.

Another source of absorption data is derived from the study of the energy levels and transition probabilities of small molecules. Included among these are the asymmetric rotors O_3 and H_2O, the linear molecules CO_2, CO and NO, and the spherical rotor CH_4.

Calculations of the absorption coefficient as a function of frequency for a wide range of thermodynamic conditions may be obtained directly from the results of this research. Such calculations are required for horizon definition investigations, atmospheric transmission studies, and radiative transport problems.



A near perfect matching of the calculated curve and experimental data for the refractive index of ozone from 0.38 to 2.5 microns is plotted.

AIRGLOW AND CHEMILUMINESCENCE: Airglow, the faint luminescence of the sky seen on a dark, clear night, is the conversion of chemical energy into radiation. The process is called chemiluminescence. Strong sky luminescence produced by similar mechanisms is also induced by nuclear detonation in the atmosphere. This natural, or nuclear-detonation induced, luminescence represents background noise to optical instruments which may be used to detect and track targets. The spectral domain of airglow radiation extends from the visible well into the infrared.

Airglow illumination—chemiluminescence—is produced by the emission of molecules during rotation and vibration. Vibrations that produce radiation occur only in those molecules having a dipole moment—or an arrangement of atoms that can be pictured as electrically charged weights at either end of a highly flexible balance. These weights oscillate with periods characteristic of the molecule. The oscillations or vibrations are described in terms of dipole moment.

The interpretation of chemiluminescence requires knowledge of the dipole moment function of all radiating molecular species. Following certain reactions, large amounts of energy are released into vibrational and rotational states of the product molecules. Some of the more important reactions leading to chemiluminescence studied by the Laboratory are:

$$H + O_3 \rightarrow OH + O_2$$
$$NO + O + (M) \rightarrow NO_2 + (M)$$
$$NO_2 + O \rightarrow NO + O_2$$
$$N + NO_2 \rightarrow N_2O + O$$
$$N + NO_2 \rightarrow NO + NO$$

All of these reactions leave the products vibrationally excited, and from analysis of their infrared emission spectra the dipole moments of OH, NO_2, NO and N_2O can be determined. The Laboratory's extensive study of the OH dipole moment function is of special interest. The fundamental and first overtone vibration-rotation bands of this hydroxyl radical were obtained from the first reaction listed above. The AFCRL analysis showed that the accepted value of the ratio of the radiative transition probabilities of these two bands are seriously in error. The correct value must be six times higher. This experiment is the first observation of the fundamental band of OH in the ground electronic state.

VIBRALUMINESCENCE: In addition to chemical reactions, another process whereby molecules are vibrationally excited is called "vibraluminescence." By this process, vibrational energy from a molecule which cannot radiate (due to lack of a dipole moment) is transferred to a molecule which can radiate. Since the last reporting period there has developed an increased awareness that in the ionospheric E region $N^{\ddagger}_2$ is an important atmospheric constituent in its own right.

50 keV electrons interacting with nitrogen at 80 millitorr produce an intense luminescent beam. The center of the beam is N^{+}_2 emission produced by primary electrons. The diffuse emission outside the primary beam is due to N_2 excited by low energy secondary electrons.

In addition to providing excitation to radiators like CO, N_2O, and CO_2, the vibraluminescence experiments make available valuable information on the quenching of $N^{\ddagger}_2$ molecules. There has often been speculation that atoms and molecules in an excited electronic state may react with other species with a rate constant greatly different from that of their ground state. Because of the great difficulty of experiments testing this notion, there are few data available to support it. Laboratory investigations have shown that oxygen molecules in the a $^1\Delta$ and b $^1\Sigma$ states both react with nitrogen atoms with rates about 100 times faster than the reaction involving oxygen in the $^3\Sigma$ ground state. These results provide support for the postulate that the reaction, $N + O_2\ (^1\Delta) \rightarrow NO + O$, is a principal production mechanism for NO in the 70-110 km region.

The importance of O_2 (a $^1\Delta$) and O_2 (b $^1\Sigma$) to defense systems concerns their roles in the determination of optical and radar backgrounds in both the normal and nuclear disturbed atmosphere. For instance, in this case the molecule NO is an important atmospheric species which participates in the prominent airglow reaction $NO + O + (M) \rightarrow NO_2 + (M) + h\nu$, and is a precursor of the species NO^+ whose spectrum was first observed by this Laboratory in the airglow accompanying high altitude nuclear detonations.

ELECTRON INDUCED EMISSION: As an energetic electron is slowed and stopped in the atmosphere some fraction of the initial kinetic energy is dissipated by populating excited electronic states of atmospheric molecules. The excited electronic states, in turn, may decay spontaneously with the emission of characteristic radiation. The fraction of the incident electron's kinetic energy radiated in a given transition as the primary and higher order electrons are stopped in a gas is defined as the electron-induced luminous efficiency. This latter process is a principal mechanism in auroral excitation and in the production of atmospheric luminescence by detonation of nuclear weapons. To interpret both auroral and nuclear-induced atmospheric emission, electron-induced luminous efficiencies must be known.

During the reporting period, the electron-induced luminous efficiency of four important band systems of nitrogen has been determined as a function of collision frequency in nitrogen and air. When the mean time between the collisions approaches the radiative lifetime of an excited state, the state may be depopulated by collision in which neither colliding partner emerges in the precollision states. The effectiveness of this collisional depopulation process, called collisional deactivation or quenching, may be expressed in terms of a cross section in some cases.

Electron-induced luminous efficiencies and the collisional deactivation cross sections of ground states of nitrogen and oxygen have been determined for the first negative and Meinel systems of N^+_2 and the first and second positive systems of nitrogen. These four band systems radiate strongly in the wavelength range of 3000 to 11,000 angstroms and constitute a significant fraction of the atmospheric emission within this wavelength interval for excitation by energetic particles.

LASER PHYSICS

Laser research at AFCRL, except for diode laser studies and laser crystal synthesis in the Solid State Sciences Laboratory, is concentrated in the Optical Physics Laboratory. (Excluded from this discussion are lasers used in a multitude of instrumentation applications throughout AFCRL.) The Laboratory's laser research program is confined to a limited number of studies particularly germane to potential Air Force use. Avoided are areas where significant research is already being done by industrial laboratories and universities.

A scientist in the Laboratory's Laser Physics Branch prepares an experiment to test damage mechanisms in laser rods.

The program focuses on high-powered, pulsed, solid state lasers. One large study involves laser rod damage as a result of repeated firings and high laser beam power operation. The phenomenon of ultrashort laser pulses is being investigated from the standpoint of an optical radar with extremely high resolution—as low as 0.06 cm. Ultrashort laser pulses also have the potential for application in high data rate PCM optical communications systems. More recently attention has turned to the prospect of tuning lasers by means of parametric conversion processes. These programs are reviewed in the following sections.

AFCRL's mode-locked ruby laser is capable of producing a pulse train of 25 millijoules of energy in a single subnanosecond pulse. The dye cell and the apparatus for switching out a single pulse are in the foreground; the Brewster-angle ruby rod and flashlamps are at the rear.

DEGRADATION OF RUBY LASER OUTPUT ENERGY: After a ruby laser rod has been fired several hundred thousand times (a relatively short operational lifetime), it changes color—usually from pink or red to orange or brown. With this color change comes a loss in laser efficiency. The output energy decreases, and a stronger light pulse must be used to energize the laser rod. The efficiency loss is gradual rather than sudden or catastrophic. In operational ranging systems, long-term sustained efficiency is obviously desirable.

The Laboratory study indicates that color changes result largely from trace impurities in the ruby rod—and, most important, from residual impurities on the surface of the rod itself. These impurities remain on the surface even after the rod has been cleaned with great care. The contributions of surface impurities to color center formation were demonstrated most dramatically in tests made with one rod that had been seriously degraded by repeated firings. When a thin outer layer 0.5 mm thick was ground off the surface of the rod, the energy output of the rod increased twentyfold. In addition, the rod's threshold energy—a measure of light intensity needed to energize it—also dropped back to initial values. After grinding, the rod regained most of the pinkish color typical of a new ruby, although a small residual orange coloration remained throughout the bulk of the rod.

Electrons associated with trace impurities in the ruby lattice structure, when subjected to the energy from the pumping lamp, are probably dislodged from their original positions to fall into minute defects (traps) in the lattice framework. This combination of an electron captured in a trap is called a color center. That this might be the case was shown by annealing experiments. If a degraded ruby rod is heated for 24 hours at 900 degrees C, the color centers can be annealed out and the rod largely (but not completely) restored to its original efficiency. This would indicate that the electrons, during the high temperature annealing process, are given sufficient mobility to reassume their original sites in the lattice framework.

The most important result of the study from an applications standpoint was the confirmation that color center formation is induced primarily by the UV and visible blue radiation from the xenon light pumps used to energize the rods. By filtering the lamp's UV radiation, the efficiency of ruby lasers can be maintained for prolonged periods of operation.

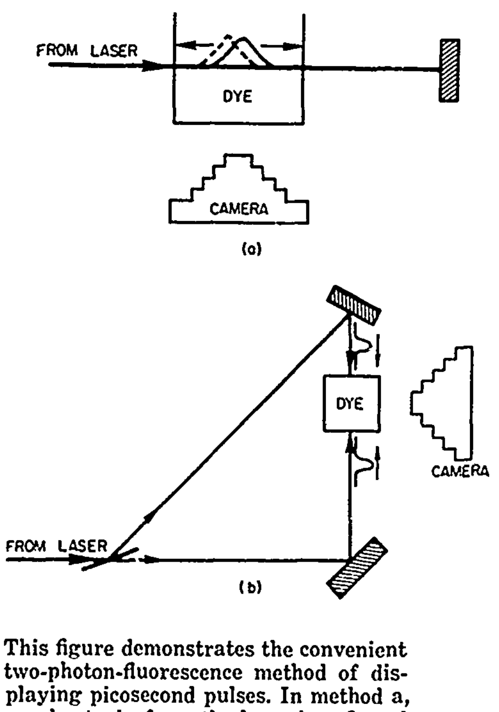
MODE-LOCKING AND ULTRASHORT PULSES: Mode-locking in lasers resulting in ultrashort (10^{-12} second) pulses were first observed (not at AFCRL) in 1967 and since then several laboratories have been seeking to exploit the properties of these pulses. The pulses are contained within the overall envelope of the main laser pulse. The ultrashort pulse is a stream of light only about a tenth of a millimeter long. Pulses occur in evenly spaced sequences at a rate of more than 100 million a second.

Such pulses have potential application to efficient frequency conversion, to high temperature plasma production, to high resolution optical radars and to PCM optical communications system. In addition they may prove extremely valuable in scientific instrumentation.

Mode-locking is the situation that exists when a preponderance of the several hundred modes or frequencies comprising the output of a laser become locked with well-defined phase relationships. When the energy traveling back and forth in the laser cavity becomes mode-locked the laser pulse is, in effect, reduced in time width to a very short pulse which propagates back and forth between the mirrors forming the cavity. The time separation between successive pulses leaving the laser cavity is given by the cavity round-trip time.

Internal modulation of a laser will tend to produce short pulses when the modulation frequency is near the difference frequencies between adjacent cavity modes. The modulation required to produce the pulses can be provided by a driven modulator which periodically changes the index of refraction or cavity length. A saturable-absorber dye in the cavity can also serve as a passive modulator.

Predicting theoretically whether one expects short-pulse formation under given conditions and what the charac-



This figure demonstrates the convenient two-photon-fluorescence method of displaying picosecond pulses. In method a, a pulse train from the laser is reflected back on itself through a cell containing a dye which absorbs two photons and then fluoresces. Method b, employing a beam splitter, is similar, but allows one to look more easily at the correlation of a pulse with itself rather than with other pulses.

teristics of the pulses will be is a complex question. The question is being attacked by computer simulation, which follows the pulse as it builds up from the spontaneous-emission noise in the cavity and approaches a steady state. An experimental program is underway to study the temporal behavior of the power emitted by a ruby laser with an internal passive modulator, as well as the time-resolved spectra of emission.

One of the main problems in studying picosecond pulse formation is the lack of techniques for making direct measurements of pulse widths and shapes since no standard electronic detectors of terahertz bandwidth exist. The Laboratory is considering several measurement approaches.

PARAMETRIC OSCILLATORS: An optical parametric oscillator is a device for converting laser radiation efficiently into continuously tunable radiation at longer wavelengths. The heart of the device is a nonlinear crystal in which polarization currents are quadratic in applied optical electric field strengths. This polarization radiates at harmonics and sum and difference frequencies. In general, due to dispersion, radiation from different parts of the crystal interferes destructively and little total radiation is produced. By making use of the crystal birefringence, applied and generated radiation can be made to propagate in phase and efficient conversion obtained. This procedure is called phase matching. The signal frequency is tuned by heating, rotating or applying voltages to the crystal, all of which change the dispersion or birefringence.

Proustite (Ag_3AsS_3), a material with a large nonlinearity is used in these experiments. This material, pumped with ruby or YAG lasers, should permit tunable lasers to be constructed operating over a range from 0.8 to 11 microns. Other techniques for providing visible and IR tunable coherent emission are also under investigation.

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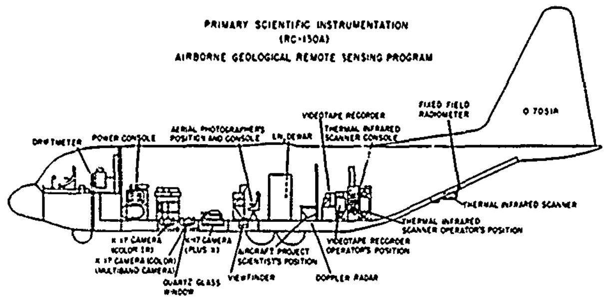
A basic AFCRL mission is the preparation of state-of-the-art surveys. Such a survey, prepared by the Terrestrial Sciences Laboratory and published in 1970, is "Earth Sciences Applied to Military Use of Terrain," which reviews present and potential methods for the remote sensing of terrain features and for monitoring varying conditions of terrain where military operations may take place. The author is shown here with a copy of the study.

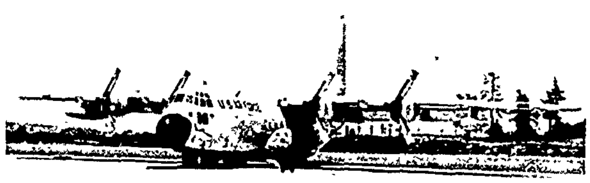
V Terrestrial Sciences Laboratory

The Terrestrial Sciences Laboratory conducts research in seismology, geology, geodesy and gravity. An intrinsic part of the research in each of these five areas is the design, development and testing of new sensors and instruments. Much of the Laboratory's total effort goes into the collection, correlation and interpretation of data. This data collection aspect takes Laboratory scientists on field expeditions that are sometimes worldwide in extent. The research program also includes the formulation of mathematical models and a search for a theoretical understanding of particular phenomena.

The reporting period saw the completion of two new Laboratory facilities. One of these is a lunar-laser observatory in Arizona, a facility constructed to conduct experiments involving reflector arrays placed on the moon by the Apollo astronauts. The second new facility is the Haskell Gravity-Seismic Observatory built at the main AFCRL Laboratory complex at L. G. Hanscom Field. From the heavy concrete piers of this facility, the Laboratory will test new seismic and gravity instruments and will continuously monitor seismic events.

Among the new instruments placed in operation during the period is a laser-interferometer apparatus for measuring the acceleration of gravity. This is perhaps the most important new gravity measuring apparatus to be developed during the past decade. New and more sophisticated gravimeters for airborne surveys were also tested.





The Laboratory acquired during the reporting period an RC-130A (as a replacement for an older JC-130) for airborne remote sensing of surface conditions.

The aircraft used for these gravity surveys was the Laboratory's JC-130. This same aircraft was instrumented for the Laboratory's airborne geological surveys. During the period several major geological surveys were made—to Iceland, to Yellowstone National Park, and to Puerto Rico. This particular aircraft has seen service with AFCRL since 1959 and was first used as a transport to ferry men and equipment to remote arctic regions. Later it was converted to a flying laboratory. During the summer of 1969, it was replaced by an RC-130, an aircraft better suited for AFCRL as a flying laboratory.

The period saw several shifts of emphasis in the Laboratory program. The Laboratory's research program on playas—dry lake beds that can serve as natural landing areas—was completed. Under this program, most of the US playas were surveyed and their characteristics catalogued. From playa research, Laboratory geologists turned their attention increasingly toward geologic remote sensing employing airborne and satellite techniques.

Both seismologists and geologists in the Laboratory expanded their studies of the earth's crustal features. These studies were motivated by problems of missile siting and guidance and inertial component testing. One question to be answered is the extent of damage that a particular silo, set in terrain of certain characteristics, will suffer as the result of a nuclear explosion of a given yield at a given distance. In addition to nuclear alterations of terrain, subtle shifts in the earth's crust can occur which, if undetected and corrected for in the missile directional control system, can impair targeting accuracy.

SEISMOLOGY

The Nuclear Test Ban Treaty of 1963 moved nuclear testing underground. To detect underground nuclear detonations, new techniques were required. The technique given most attention was that of identifying characteristic seismic waveforms, the assumption being that the waveform of a nuclear detonation would differ from that of an earthquake.

Seismic research at AFCRL, historically, has been directed almost exclusively at problems of detection, location, and identification of underground nuclear explosions as part of the Defense Department's Project VELA UNI-

FORM. But with the decline of the VELA UNIFORM program, there has been a corresponding increase in more general seismological research. The Laboratory's seismic research programs can be grouped under the headings of: source characterizations, source identification, rock mechanics and environmental seismic noise.

All underground nuclear tests at the Nevada Test Site nevertheless remain events of major interest to AFCRL seismologists. These periodic tests serve as a check on the more general theoretical and analytical studies and the tests themselves point the way to possible new investigative approaches.

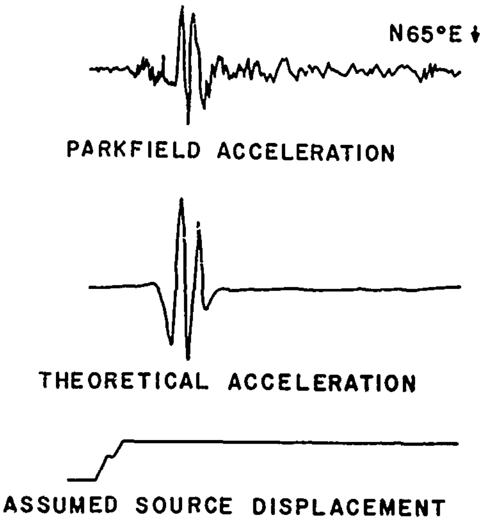
During the reporting period, a new seismological station was placed in operation at the AFCRL main laboratory complex at L. G. Hanscom Field. In addition, the Laboratory continued to maintain, under contract, the Weston Seismological Observatory in Weston, Massachusetts, one of the most complete seismological observatories in the country.

Earthquake prediction and control have come more and more to occupy the attention of the nation's seismologists. This has presented a need for a more general theoretical understanding of earthquake mechanisms. In line with this need, a growing proportion of the total AFCRL effort in seismology is concerned with the development of more detailed quantitative theories of the earthquake focal mechanism and with direct measurement of the deformational behavior and strength of minerals of various kinds under extreme pressure and temperature.

SOURCE CHARACTERIZATION: If the seismic source (explosion or earthquake) is more thoroughly understood, success in isolating and identifying unique signal characteristics radiating from each source should be enhanced. The Laboratory is pursuing this hypothesis through theoretical work with the goal of developing a theory applicable to seismic energy radiating from both faults and underground nuclear explosions.

Data from an array of acoustic sensors to detect extremely minute disturbances near the earth's surface are recorded on these instruments.

Although little is known about the actual spatial and temporal distributions of displacements along a moving fault, rather plausible assumptions by AFCRL scientists about certain average properties of the fault motion have been applied in their theoretical work on source characterization. This has led to the development of a quantitative focal mechanism theory for the computationally difficult region very close to the source. The accelerations to be expected near an earthquake for longitudinal shear faulting have been calculated and compare favorably with the limited observational data available from accelerometers. Direct waveform calculations for other types of faulting continue.



One of the many contributions by Dr. Norman Haskell, an internationally honored AFCRL scientist whose death occurred during the report period, was a near field longitudinal shear fault theory permitting the seismic waveform of a source displacement to be derived theoretically. The upper trace shows an actual recorded seismic waveform compared to the waveform produced by theory, assuming a source displacement of the type shown in the lower trace.

Experimental observations of ground motion measured in a region near underground nuclear explosions in several different media (hard rock, soft soil, etc.) have been fitted quite closely to a family of analytic functions. By using these functions it has been possible to calculate the total energy of the elastic wave radiation and its frequency spectrum. The calculations provide a useful basis for comparison between the source energy spectra of underground nuclear explosions and earthquakes.

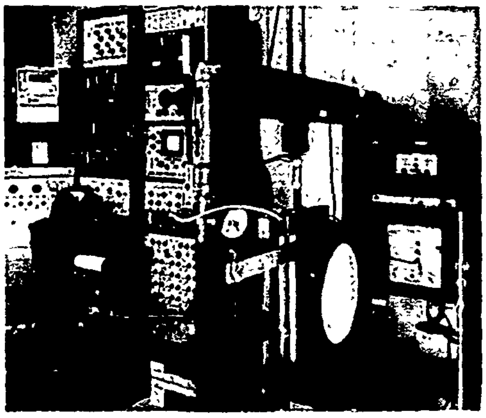
Horizontally polarized shear waves (SH) that show up in data recorded from distant underground nuclear explosions greatly complicate the problem of explosion discrimination. To help explain the generation of these waves, an AFCRL seismic modeling program was initiated to examine the radiation from explosions detonated in biaxially prestressed and unstressed static fields under laboratory conditions. The propagating wave, initiated by the explosion of a length of mild detonating fuze, has been recorded in the near-source region by means of the photoelastic effect and an ultrahigh speed camera, and in the far field by means of strain gages. Results to date suggest that the explanation may lie in the tectonic stress release caused by the explosion.

SOURCE IDENTIFICATION: Under AFCRL contract, an investigation was made of the unique characteristics of short-period (SP) and long-period (LP) seismic waves in an attempt to use the characteristics to distinguish between earthquakes and underground nuclear explosions. The original development of a set of SP diagnostics led to the preparation of a computer softwear package capable of near-real-time, routine, automated seismic event classification. The original SP identification parameters represent three measurements of the P-coda complexity by different methods and one measurement of the spectral content of the P wavelet. To these SP parameters have been added LP measurements of the relative excitation of surface waves. Four pattern recognition techniques are applied: class-clustering, class-separation, linear discriminant and adaptive algorithm. On-line computer evaluation of this automated approach to seismic event classification was in progress at the conclusion of the reporting period.

ROCK MECHANICS: The extreme pressures and strains (the release of which induces earthquakes) which minerals deep within the earth undergo are simulated at AFCRL using a large shear press. Deformation equipment employed in the AFCRL high-pressure facility now includes: an opposed anvil shear apparatus, two Birch-type shear squeezers, and a Griggs-type 20 kilobar solid pressure medium apparatus. Maximum pressures of 150 kilobars, temperatures to 2000°C, and strain rates as low as 10^{-8} sec $^{-1}$ can be achieved providing AFCRL scientists with the capability to simulate earth depths to 450 km. Within the region between the earth's surface and this 450 km depth, most important tectonophysical phenomena such as volcanism, ocean floor spreading, mountain building and earthquakes, have their origins.

Shear measurements on Nevada Nuclear Test site tuffs revealed weakening induced by dehydration of associated hydrous minerals. The water weakening effect occurred at temperatures as low as 300°C and has immediate application to strength studies in underground nuclear explosions at the Nevada site.

In another series of deformation tests, the shear strength of grossly deformed metals including tungsten, germanium, nickel, beryllium, uranium, copper, gold, aluminum, magnesium, bismuth, and tin was measured in the opposed anvil apparatus up to 150 kilobars at 27°C, and for the noble metals to a maximum temperature of 920°C. The shear data agree with independent measurements at low pressure, but differ significantly from high pressure measurements made by other investigators. The data for the



To evaluate the effects of stress on various types of materials, the Laboratory uses the apparatus shown in the upper photo. The resultant pattern of one type of stress is shown in the lower photo.

The extreme pressures and shears to which earth crustal materials are subjected during tectonic movement are simulated in the Laboratory. The above pattern was produced in enstatite and shows two phases of the minerals under strain.

noble metals fit a simple empirical formula relating the temperature and pressure dependence of shear strength.

A third major study was one in which the deep earth materials, amphibolite and hornblende, were deformed on the shear and the Griggs-type apparatus. Over 300 tests were run to maximum test conditions of 80 kb and 1200°C. These hydrous materials exhibit anomalous weakening above 800°C.

The theoretical and experimental shear deformation work on both metals and rocks has led to the derivation of a simple empirical formula by which deformation of a wide variety of solids may be predicted. The formula helps the geophysicist understand the mechanical properties of materials at conditions not obtainable in the laboratory.

Minor artificial seismic noise is characteristic of an urban environment. Subways, trucks and pedestrian traffic all contribute to this noise. One Laboratory study of urban seismic noise was conducted in Cambridge, Mass., near MIT and entailed the placement of seismometers at varying depths beneath the surface of the ground.

ENVIRONMENTAL SEISMIC NOISE: The earth's environmental seismic noise field consists of all vibrations, however small, detected at the earth's surface. Sources of these vibrations are many—weather, heavy surfs, vehicular traffic, and of course seismic. Environmental seismic noise can degrade the operation, test, and calibration of many motion-sensitive equipments which require a relatively vibration-free environment. Inertial components for guidance systems, optical benches, and laser beam analytical work are among these. Seismic background noise also governs the placement of seismic detection equipment and arrays.

To test the environmental seismic noise levels at particular locations, the laboratory developed a highly sensitive portable seismic array. Associated with the array is a high-speed data reduction capability. The data collecting portion consists of a 21-element portable seismic array system developed to measure both spatial and temporal characteristics of seismic waves. It is characterized by ruggedness, flexibility of aperture and channel response, transportability, operational simplicity, unattended operation, and ability to withstand climatic extremes.

Because noise from jet aircraft is coupled to the earth and registered as a seismic noise, the array can be used to monitor noise patterns generated by operations at Air Force bases and commercial airports. This has led to an AFCRL program for documenting the environmental noise pollution resulting from the operation of Air Force aircraft at various bases. This program will continue for the next few years.

GEOLOGY

During the 1950's the AFCRL geology program was concentrated in arctic areas, particularly in Greenland and

Northern Canada where extensive field and photographic surveys were made of natural aircraft landing sites. The best publicized arctic program however was that conducted on the floating ice island, T-3, where AFCRL established a semi-permanent field installation. Arctic research was superseded during most of the 1960's by a comprehensive study of playas (dry lake beds) in the southwestern U.S., the Middle East, and elsewhere that could serve the Air Force as natural landing areas. The weight-bearing properties of broad, flat terrain, the geomorphology, and the seasonal variations, have been catalogued for potential emergency use by the Air Force.

The present reporting period saw only a small residual of the once-extensive dry lake bed program still in progress. Emerging in its place is research in geologic remote sensing instrumentation, remote sensing techniques, and the evaluation of remote sensor data obtained from airborne and satellite surveys. Also coming into prominence are studies that relate to missile siting. This latter work falls under the general heading of crustal studies research. The crustal studies program is focused primarily on the deformation and plasticity of the earth's crust. Only recently have small-scale movements of the earth's crust (which vary widely in magnitude with location, but which usually go unnoticed) been fully appreciated. Such microscale movements can affect the azimuth control systems (and thus targeting accuracy) of missiles.

REMOTE SENSING: The Laboratory's geologic remote sensing research involves photographic and thermal infrared imaging techniques for use in making airborne or satellite surveys. By surveying an area simultaneously in a number of narrow spectral regions in the infrared, visible and UV, one can derive information on rocks and minerals, morphology and thermal properties of the earth below.

AFCRL's C-130 flying laboratory figures prominently in the remote sensing program. One of the many remote sensing instruments aboard the aircraft is a multispectral camera system for taking nine simultaneous aerial photographs at different narrow-band regions from the near-ultraviolet across the visible and into the near infrared. Other instruments aboard this well-equipped platform are conventional cartographic cameras, an infrared scanner, and a radiometer.

The effectiveness of any remote sensing technique depends ultimately upon the effectiveness of analysis and interpretation. Ideally, a geologic analyst should have extensive field experience. The analyst must know the reflection, absorption, polarization and emission characteristics of minerals and materials in all their many forms. This latter knowledge is acquired by field observations and by bringing soil and rock samples into the laboratory for measurement under controlled conditions.

C-130 FIELD EXPEDITIONS: Proper assessment is also required of the effects of composition and particle geometry on spectral signatures received by remote sensing systems. A theory of reflectance, which accounts for particle size effects, has been developed. A computer program, based on this theory, allows simulation experiments to be conducted. During the reporting period, the C-130 flew a number of geologic field expeditions to Puerto Rico, Yellowstone National Park, and Iceland.

Shown here are nine aerial spectrophotographs acquired of the Middle Sambo Reef Area, Florida, by AFCRL's nine-lens multiband camera. The same scene is recorded simultaneously in nine discrete narrow bands between 3850 A (upper left) and 8800 A (lower right). Note the varying water penetration characteristics of Bands 1-6 (Plus-X film) and lack of penetration in Bands 7-9 (IR film).

The exceptional transparency of the water around Puerto Rico makes the location an outstanding one in studies of water penetration. The AFCRL study was undertaken to define optimum spectral regions for achieving maximum water penetration. Numerous aerial photographs using color, color IR and specially filtered black-and-white films were taken for analysis.

Bottom terrain 30 meters below the surface is clearly visible in the 4500 to 5500 angstrom wavelength region. These studies point to the feasibility of using airborne remote sensing for geomorphic mapping of ocean bottoms near coastal areas.

The C-130 expeditions to Iceland and to the Yellowstone National Park both involved geothermal surveys with the observing instrument being a thermal IR scanner. The Iceland program was conducted cooperatively with the US Geological Survey, the Iceland National Energy Authority and the University of Michigan. Iceland surveys were made in 1967 (field) and 1968 (field and airborne) and were a continuation of a field and airborne program begun in 1966. Iceland is the most active volcanic and geothermal area in the world, and is particularly suited for thermal infrared research. Thermal IR surveys of the Yellowstone National Park were made in 1969 primarily for the purpose of testing the IR scanner in this active geothermal region.

Closer to the C-130's home base at L. G. Hanscom Field, surveys were made of the New England coast. The thermal IR scanner aboard the C-130 and cameras were used to observe coastal estuarine and harbor areas. IR imagery clearly presents the thermal gradients. The AFCRL geological sensors not only vividly displayed the dispersion of thermal effluents, but chemical and waste pollution as well.

A thermal IR image of the volcano Surtsey off the Iceland coast (above) is compared to a regular photo of the volcano (below). The dark areas in the IR image are the cold waters of the Atlantic Ocean; the large white area denotes the intense heat radiated by the volcano, while the other white areas are underground lava channels visible only to IR instruments.

CRUSTAL STUDIES: Instability of the earth's crust has important implications for Air Force ballistic missile systems. Minute crustal movements can influence the azimuth control networks of missile installations. The nature and rate of deformation of the earth's crust at a particular point is not easily specified ..antitatively. Yet measurements of crustal de:ormation are needed for optimum missile siting and for gauging possible targeting errors.

The interests of the Laboratory's seismologists and geologists merge in these studies. Much research emphasis is placed on the crustal and mantle rocks. The rate and nature of the deformation of these materials are being studied, using the high pressure-high temperature apparatus discussed earlier in connection with the Laboratory's seismology program.

Reflectivity of soils of various types and at different angles of the light source are measured in the Laboratory using the above experimental apparatus.

One study revealed a possible origin of some earthquakes, one having to do with a polymorphic change that takes place in the crystal lattice structure when a material is subjected to high pressures. Of the many materials subjected to the 150 kilobar pressure of the AFCRL high pressure apparatus, the pyroxene mineral, enstatite, was shown to be highly sensitive to shear stress, inverting almost instantaneously to a smaller volume polymorphic form. The inversion is accompanied by a large energy release. Calculations show that an inversion of 0.01 percent of a cubic kilometer of enstatite could release energy equivalent to an earthquake of intermediate magnitude.

AFCRL geologists, however, are less concerned with phenomena of earthquake proportions than with subtle crustal movements—movements only detected by the most sensitive instruments. Among these movements are the less violent tectonic forces, and the periodic vertical movements and deformational strains that result from tidal forces of the moon and the sun. Local deformation also results from atmospheric pressure systems, seasonal snow load, and the filling of reservoirs.

The magnitude of some of these minor displacements may range up to a few centimeters per day for solid earth tides. Geodetic triangulation is being examined as a possible way to measure the amount of horizontal displacement in several areas of the western United States. Realistic earth models for evaluating the effects of various loads—moving atmospheric pressure systems, for example—are being developed. To measure local instability, a prototype tiltmeter is being built, which will be installed in a 30-meter borehole.

DRY LAKE BEDS: Under its highly productive playa research program, most of the dry lake beds in the US that might be suitable for contingency operation by Air Force aircraft had been catalogued with respect to weight bearing properties of soils, the amount of preparation needed before operation, and the seasons during which the playa could be used.

Two studies made during the latter stages of AFCRL's playa research program are noteworthy. One relates to the monitoring of the playas using Nimbus satellite TV and infrared photographs. Playas, when viewed by a satellite, have good contrast separation from adjacent terrain. The effects of rainfall are clearly apparent in satellite photographs—and this is very important because even small amounts of rainfall can produce profound changes in the weight bearing properties of a dry lake bed. A dry lake bed catalogued as potentially capable of supporting aircraft could be quickly rendered unsuitable.

The other study concerns the rapid changes that can take place from year to year in a particular playa. Vegetation can intrude upon the barren lakebed in a few years time or can rapidly recede. Giant fissures can develop on the surface, some being three feet wide and 15 feet deep, and a vast array of mounds up to 10 feet high can form over hundreds of acres. Such mounds are often the results of the root structure of plants holding the soil while adjacent soil erodes away. The surprisingly rapid changes in playas suggest the need for periodic surveys to obtain current information on their condition.

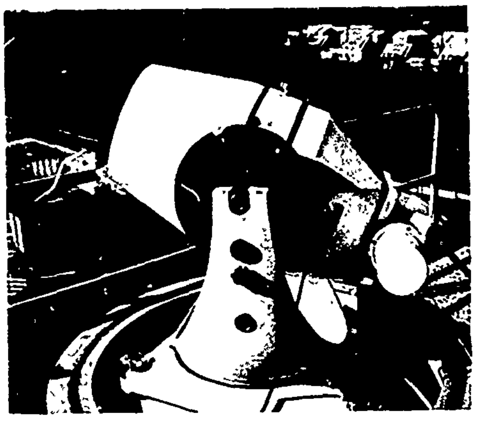
GEODESY

A limiting factor to targeting accuracy is the uncertainty of launch site position and the distance and direction to target area. A part of AFCRL's geodetic program is directed toward eliminating such uncertainties.

For many years, the Laboratory has evaluated for the Air Force use of dry lake beds as emergency runways for aircraft. Early studies involved B-52 aircraft. In 1970, the Laboratory assisted in similar studies involving the much heavier C5A. These studies were made at Harper Dry Lake in California.

To an increasing extent, satellites are used for long distance measurements. These satellites serve as aerial beacons for three-dimensional triangulation and trilateration. Much of AFCRL's current geodetic research program involves refinements in satellite geodesy techniques, a field in which AFCRL pioneered.

AFCRL has continued its participation in the National Geodetic Satellite Program, together with NASA, ARMY, NAVY, other USAF agencies and civilian observatories. This program is directed toward the positional relationship of a world wide geocentric network of stations to 10 meter accuracy. Camera observing techniques developed by AFCRL are now being used by geodesists all over the world.



The Laboratory's 600-mm geodetic stellar camera with moving plate back for photographing faint sunlit satellites (above) is housed within the smaller of the two domes at AFCRL's main laboratory complex (below).

COMPUTER SOFTWARE: Two computer software programs were developed during the period:

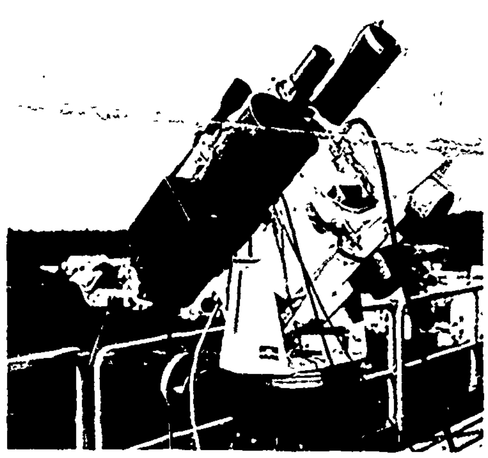
1) The Geodetic Analysis Computer Program involves geometric error analysis. It is presently being used by AFCRL and other Air Force agencies for the reduction and analysis of geodetic satellite observations from simultaneous estimation of positions on the surface of the earth and the trajectory of an observed satellite using measurements of topocentric right ascension, declination and range from the positions to be estimated.

2) The Short Arc Geodetic Adjustment Computer Program is one of the most advanced reduction programs yet developed for precise geodetic positioning by means of satellite observations. The program can handle any combination of electronic and optical directional and/or ranging observations. The program exploits multishort arc orbital constraints, dynamic scaling and error model recovery in the adjustment of a large-scale geodetic network.

INSTRUMENT DEVELOPMENT: An electro-optical theodolite has been developed for use in geodetic astronomy and spatial geometric triangulation. For many years, geodetic astronomy has used the tracking micrometer for detecting star transits. The tracking is done manually by the observer and requires personal judgment. The electro-optical theodolite detects star transits electrically and has the capability of recording the data for direct input to a computer. The basic theodolite is a WILD T-4 astronomic theodolite. A large telescope has been added and the eyepiece micrometer has been replaced by vertical and horizontal slits and photo sensors. The theodolite has increased accuracy and automatic data reduction plus a capability to observe satellite and aircraft borne light sources.

Although there are several hundred satellites and pieces of satellite debris in space, only a few are bright enough and have the proper configuration for detection by the USAF PC-1000 stellar camera. An image motion compensation system has been developed which, in effect, permits longer photographic exposure. With this system, many of the smaller satellites can be used for satellite geodesy. The image motion compensation (IMC) device drives the film in the direction and at the angular speed predicted for the satellite and the light intensity integrates over a longer period to form the satellite image. The IMC has been designed for use with both the normal USAF PC-1000 and PTH 600 cameras. The plate drive is operated by a precise phase lock speed control and runs on air bearings.

The Laboratory is sponsoring research at the Environmental Science Services Administration (ESSA) on multiwavelength baseline measuring systems. The principal limitation, at present, to the accuracy of distance measurements is the uncertainty in the average propagation velocity of the radiation due to influence of the atmosphere. Accuracies to within a few parts per hundred million are the present objectives. Through the use of the dispersion method, simultaneous measurements of optical path length at two widely separated wavelengths are used to determine the average refractive index over the path length thus giving a better measure of the true geometrical distance. The use of lasers as light sources has greatly extended the range, and recently a microwave frequency has been added to provide data on the water vapor density of the air. The development of a passive receiver for one end of the baseline eliminates the two way transmission and extends the range to approximately 60 km.



Located on the laboratory rooftop is this pulsed laser for measuring satellite ranges. The first successful long-range test was a daylight range measurement of a satellite in December 1967.

LASER RANGING SYSTEM: Several years ago, AFCRL first reflected a laser beam from satellite-borne corner cubes.

A unique dual laser system is employed by AFCRL scientists in geodetic satellite studies. A ranging short pulse laser is housed in the lower left side of the mount while a long pulse photographic laser is seen in the upper right. High voltage and receiver components are also viewed.

To obtain a detectable reflection, the experiments were conducted at night.

AFCRL has developed a technique that permits daytime observation of reflective satellites. The first daytime observations were made in December 1967. The technique involves the production of several very short laser pulses, each precisely controlled as to length and separating interval. This precise control of duration and spacing of pulses greatly enhances the ranging accuracy of lasers.

With this technique, AFCRL has recorded photomultiplier detections of the reflected image many times, even on bright days. The return is photographed as a series of spikes on an oscilloscope presentation, each spike representing the reflection of one precisely timed pulse.

When two such laser systems are used to reflect light from the corner reflectors simultaneously, the distance between the observing sites can be derived by triangulation.

TIME SYNCHRONIZATION SYSTEM: AFCRL is working with the National Bureau of Standards, U.S. Naval Observatory and Lincoln Laboratory in a country-wide experiment using synchronous satellites to disseminate and synchronize precise time and time interval to widespread geodetic observing sites. (A requirement for this capability is set forth in AFLC ROC 4-67.) This technique will give world-wide geodetic field teams the precise synchronization of time and frequency that now require the complicated, time consuming and expensive transporting of clocks for the calibration of time at widespread observing sites.

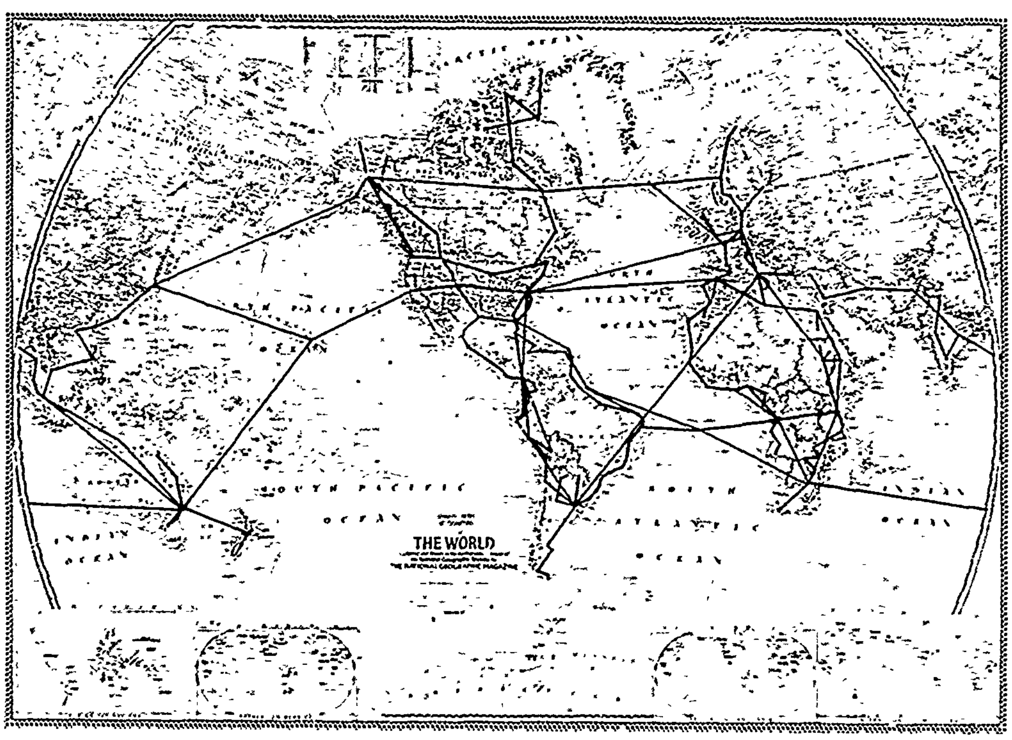
This time dissemination experiment uses one-way radio propagation at VHF or UHF relayed from the master reference station to user stations by a transponder on a geostationary communications satellite. Tests are being conducted using the ATS-1, LES-6 and TACSAT-COM satellites as transponding units. The reference frequency signal is transmitted from either Lincoln Laboratory at Bedford, Mass. or Bureau of Standards at Boulder, Colo. to the satellites and down to the receiving stations.

Throughout the Winter of 1969-70, a considerable amount of data has been collected by the AFCRL receiving site in this program. By using this technique to establish a reference frequency, AFCRL is maintaining the frequency and real time of its reference oscillator to within one microsecond of the standard at Boulder, Colo.

If the results from the tests continue as well as they have been to date, this technique will be a valuable contribution to the National Geodetic Satellite Program in that it will offer a very inexpensive and very simple way for all observing sites to synchronize their time and reference frequency. Another experiment is also testing the use of commercial television as a transfer medium of precise frequency to widespread sites. If successful, this method has the advantage of simple, low cost field equipment.

GRAVITY

The Laboratory's gravity program is directed toward obtaining more precise gravity values at all locations on the earth's surface and in its external field. In addition to its gravity measurement program, the Laboratory develops theories and mathematical methods for the description of the earth's gravitational field, for the determination of gravity dependent earth constants and for the prediction and interpolation of gravity values at locations where no measurements have been made. An intrinsic part of gravity research is the development of gravity instrumentation of greater sensitivity and efficiency. To test and calibrate new instruments, AFCRL scientists transport them to widely spaced geographical areas. For



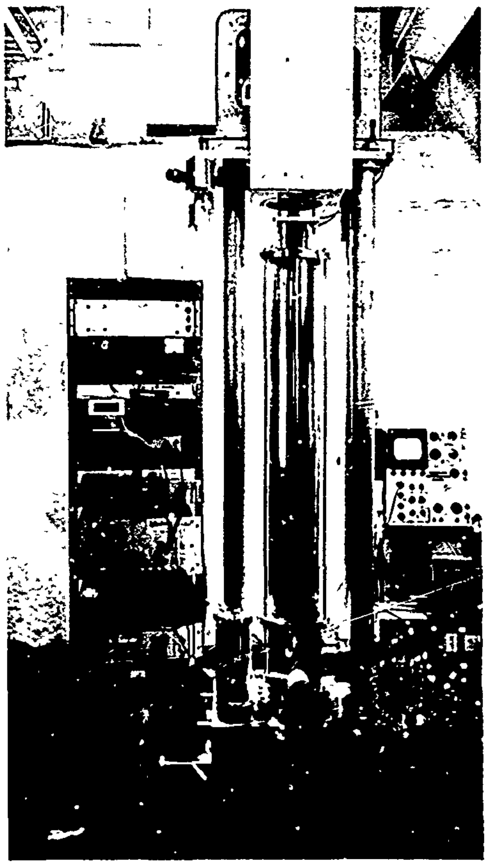
The Laboratory has been a principal participant in the development of the First Order World Gravity Net since 1962 when the international project was initiated. Lines on the map are paths along which gravity values have been carefully measured. Status of the Net in 1970 is shown, with the final adjustment of all values due to be completed in early 1971.

airborne gravity surveys, the Laboratory used its C-130 aircraft.

Three airborne gravimeters were installed in this aircraft during the period and tested over several different areas of the U.S. Also placed in operation was a new gravity measuring system employing modern technological methods. This is the laser interferometer absolute apparatus, which is discussed in the following section.

THE LASER-INTERFEROMETER APPARATUS: A new gravity measuring apparatus was tested and placed in operation during the reporting period. The measuring technique, in principle, is simple. An object is dropped and the experimenter clocks its rate of fall. In doing so, he is using the method used by Galileo who made the first gravity measurements more than 300 years ago.

Instruments for measuring gravity (actually the acceleration of gravity is measured) haven't changed much in principle since then. The rate of fall of a free-falling body is timed, or a free-falling body whose motion is constrained is timed. In the latter category is the pendulum which was first used to measure gravity in the 17th Century. The pendulum has been greatly refined over the years, and accuracy is approaching theoretical limits.



A new absolute gravity measuring apparatus tested in 1969 at AFCRL was this laser interferometer device in which a laser beam produces an interferogram to obtain a precise measurement of the rate of fall of an object within an evacuated chamber.

The new gravity apparatus is a free-fall instrument and was developed for AFCRL and the National Bureau of Standards by James E. Faller of Wesleyan University. The apparatus, which has a vertical length of nine feet, consists basically of a Michelson-type interferometer, with a helium-neon laser light source. It is called the laser-interferometer apparatus. The heart of the system is the four foot drop chamber, evacuated to 5 x 10^{-7} torr to reduce drag on the falling body. Associated with the apparatus is an array of electronic timing gear plus a seismometer which senses and corrects vibrations.

To measure gravity by the interferometric method, one mirror of a Michelson interferometer is dropped in free-fall. This produces a rapidly varying fringe pattern. To obviate the problem of misalignment of the mirror during free-fall, a mirrored corner cube is used. Light from such a falling cube is always reflected in the same direction, even if the cube tilts slightly during its one-meter fall.

The output from the interferometer is a sinusoidally varying intensity which increases in frequency during the free-fall of the corner cube. The light and dark oscillations produced by the rapidly changing fringe pattern are detected by a photomultiplier and counted by an electronic timer with a timing accuracy of about one nanosecond. The instrument is capable of precisions of a few parts in a hundred million. By comparison, the accuracies of pendulums are a few parts in a million.

To establish gravity values for a particular location, many measurements must be made and an average obtained. The site then becomes a standard to which relative gravity measurements are referred. There are only about ten sites in the world where gravity values are known with sufficient accuracy to serve as standards or absolute base stations.

AIRBORNE GRAVITY INSTRUMENTS: New, extremely sensitive airborne gravity measuring instruments were installed in the Laboratory's C-130 aircraft. During the reporting period, a series of flight tests were made to evaluate these instruments against the known gravity fields of two different gravity test ranges in the United States.

From Ellsworth AFB, South Dakota, the C-130 made measurements over the North Range covering the states of Washington, Oregon, Montana and South Dakota. Later, the South Range covering Colorado, Texas, Kansas and Oklahoma was covered with Forbes AFB, Topeka, Kansas, serving as the staging base.

AFCRL has greatly improved airborne gravity instrumentation survey techniques and data reduction programs since beginning the program in 1958. The three airborne gravimeters are a La Coste-Romberg, an Askania-Graf, and a Pendulus Integrating Gyro Accelerometer (PIGA). Associated with the PIGA meter is an AJN-10 Inertial Reference Unit. All of these instruments are mounted on highly stabilized platforms.

The instrumentation complex also includes an airborne profile recording unit for monitoring vertical aircraft ground clearances and relative deviation from planned flight level; a Doppler radar; a navigational computer; an Astrotracker for navigational purposes; and a T-11 camera system for identifying landmarks along the flight paths which are used for obtaining position data.

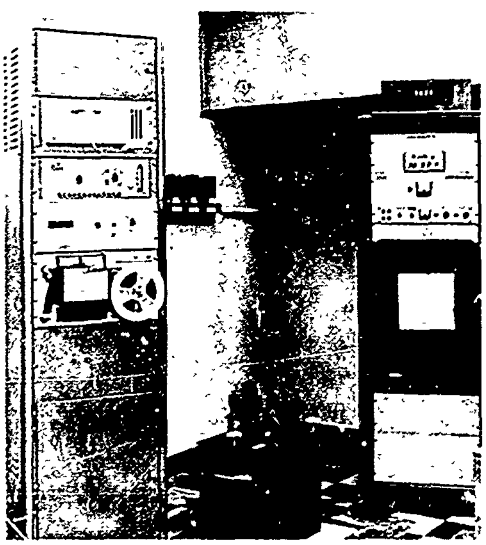
OTHER GRAVIMETER DEVELOPMENTS: A cryogenic gravimeter with a sensitivity of 0.025 microgals is under development. The gravimeter will be used to measure the free modes of the earth but also has potential for measuring wandering of the earth's polar axis and possible secular variations in gravity.

A LaCoste and Romberg earth-tide gravimeter is in continuous operation at AFCRL's new gravity-seismic observatory. Variations of the vertical component of gravity are measured to an accuracy of one microgal.

A rotating gravitational gradiometer for measuring gravity gradients has been developed and tested under laboratory conditions. A gradiometer for measurement under moving conditions is now under development.

THE EXTERNAL GRAVITY FIELD: The external gravitational field of the earth refers to the gravitational attraction of the earth at various distances from its surface. This attraction varies with the mass distribution of the earth. If the earth were a smooth sphere of homogeneous composition, gravity calculations would be relatively easy. Given a few data points, it would be simple to calculate gravity fields with great precision. Because the mass distribution is irregular, the gravitational field varies in a manner not easily predictable. The mascons of the moon (publicized during the Apollo flights) are an example of inhomogeneous mass distribution.

AFCRL hopes to develop techniques for deriving information on gravity values all over the earth and at all altitudes based on limited measurements. Several methods are being investigated for doing this. The problems concerning the "upward" continuation of gravity values to high altitudes from the anomalous field observed at the surface have been solved and various methods, including computer programs for handling a large number of points, have been tested and results published. Theoretical and practical solutions for the "downward" continuation problem are also available. This means that measurements made with AFCRL's airborne gravimeters can lead to the computation of surface mean values from gravity profiles observed at various altitudes. Correlation studies and development of statistical methods for estimation of gravity anomalies in unobserved or inaccessible areas are continuing.



A basic instrument in the Laboratory's new Haskell Gravity Seismic Observatory in this LaCoste and Romberg earth tide gravimeter which measures variations in gravity produced primarily by the attraction of the moon and sun.

The harmonic coefficients (describing the external potential) derived from satellite solutions have been evaluated and combined with terrestrial gravity data resulting in a global gravity model in terms of new coefficients, mean anomalies and geoid undulations.

WORLDWIDE GRAVITY SYSTEM: AFCRL is a major participant in the International Gravity Commission, whose principal objective is a worldwide gravity standardization program. Until 1962, when work on the worldwide gravity system got underway, the critical problems were the lack of uniform standards for calibrating gravity measurement instrumentation, and the lack of a worldwide network of base stations needed to integrate various local gravity measurements into a single uniform net.

The starting points of the worldwide gravity system are three north-south calibration lines, along each of which are eight or nine primary standardization stations. These are the American calibration line, extending from Point Barrow, Alaska, to the southern tip of Argentina; the Euro-African calibration line, extending from Norway to South Africa; and the West Pacific calibration line, extending from Fairbanks, Alaska, to New Zealand.

The relative pendulum measurements along the calibration lines and gravimeter fieldwork were completed in the fall of 1967. The reduction and analysis of the new measurements, the analysis of pre-1963 measurements for possible use, and the data preparation for final adjustment has been completed.

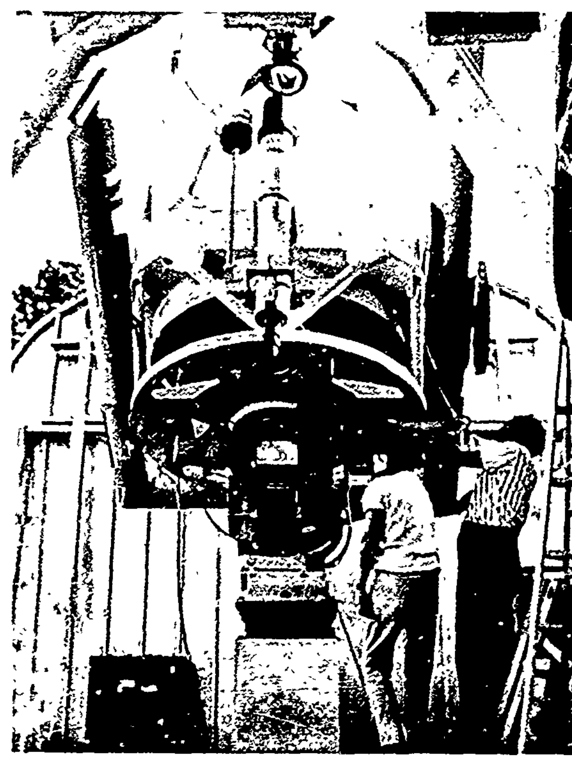
Absolute measurements necessary for the establishment of the scale for the new network and for the new absolute reference were completed in 1969.

THE LUNAR LASER OBSERVATORY: On July 20, 1969, when the retroreflector array was placed on the moon by the Apollo 11 crew, there were four observatories in the U.S. equipped with a laser telescope and associated timing equipment for reflecting a light signal from the array. AFCRL's Lunar Laser Observatory, located 60 km north of Tucson, Arizona in the Catalina Mountains, was one of these. The others were the Lick Observatory in California, the McDonald Observatory in Texas, and the ARPA-University of Michigan Observatory in Hawaii.

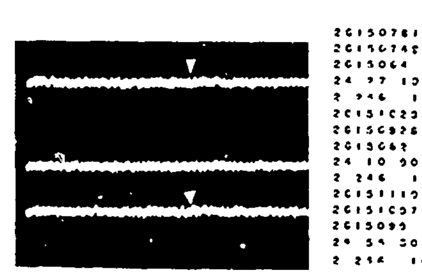
On September 2, 1969, AFCRL received return signals from the reflector, and on the following day the first actual measurements were made.

Following is a description of the optical system at the AFCRL Observatory: Transmitting-receiving optics of the telescope consist of 1.5m primary and 28 cm secondary mirrors to form an equatorially mounted special purpose telescope of Cassegrain design with an f/14 focal ratio. Both mirrors are constructed of Tenzaloy aluminum, nickel coated by the Kanigen process, and aluminized. The primary is an f/2 spherical mirror, and the aspherical secondary mirror is corrected to give the optical system an on-axis narrow field resolution of less than one arc second. The ruby laser transmitter is placed at the Cassegrain focus of the optical system.

The ruby laser is of dual-mode design. For ranging experiments it operates in its Q-switched mode. Here [illegible] joule pulses of 10 nanoseconds can be transmitted at a repetition rate of 12 pulses per minute. In the normal mode the output energy of the ruby laser is designed for



Partially funded by NASA, this 60-inch Cassegrain telescope is used for lunar ranging experiments involving retroreflectors placed on the lunar surface by Apollo astronauts.



Signals of interest (arrows) shown on this oscilloscope trace cannot normally be discerned by visual examination. Range data are therefore derived through computer processing.

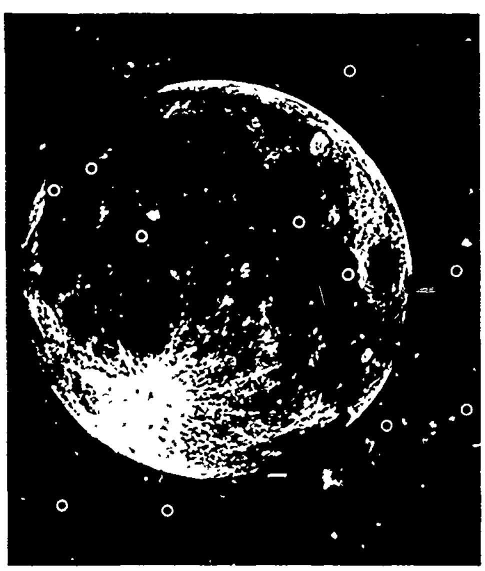
40–120 joules per millisecond pulse duration, which is more suitable for photographic experiments. The transmitting optics also serve to receive energy. Earth-moon distance resolution is about 1.5 meters.

The net divergence at the moon of a transmitted ruby laser pulse from the earth depends on collimated laser divergence, telescope optics, and atmospheric conditions during the event. At the moon a transmitted Q-switch pulse from this system may be visualized as a thin disc of ruby light, a few meters thick due to pulse length, and a few kilometers in radius due to divergence.

Because transmitted ruby laser signals from this system have a narrow beamwidth, it is difficult to aim such signals at pre-selected lunar targets. To solve the aiming problem, an offset guiding technique was developed, where observers can track an identifiable lunar feature by electro-mechanically offsetting the required pre-computed offset angle and rate required to acquire and hold a retroreflector target. A guiding error of less than 1 arc second is possible with this technique.

The retroreflector target is comprised of one hundred 3.8 cm aperture, solid, uncoated cube corners. Ten rows of 10 retroreflectors each form a square panel (one-half meter on a side) that is affixed to a metal platform, which rests on the lunar surface.

When used for optical ranging with the AFCRL ground station this target provides a scattering cross section of several hundred km^2 within 1 arc second of the center of its far field diffraction pattern. With the target array properly oriented towards the earth and the ground station ranging signal properly aimed, each transmitted Q-switched, ruby pulse will cause a detectable return of several photoelectrons.



One method of determining distances between points on the moon is by a double exposure process. First the stellar background is photographed and later the moon is exposed on the same plate.

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VI Ionospheric Physics Laboratory

The state of the ionosphere at any given time defines the limits of Air Force capabilities in communications, radar surveillance, and navigation.

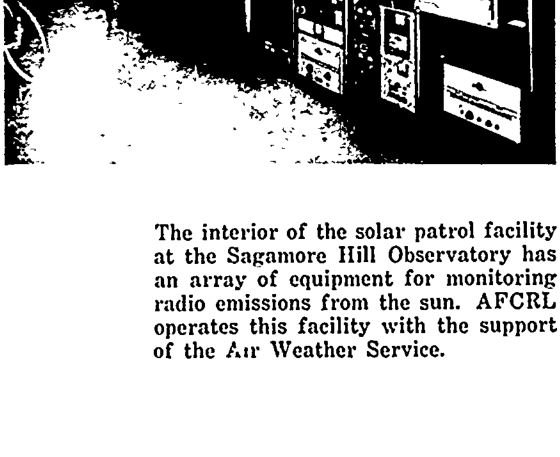
The ionosphere extends from a lower boundary of about 50 km outward to several thousand km. The charged particles—the ions and electrons—that form the ionosphere are a small minority among the dominant population of neutral atoms and molecules of the upper atmosphere. Only one particle or less in a thousand is a charged species, and typically it will be short-lived. Within a short time period, it will become neutralized through collision with another particle. But in its stead, and just as quickly, another charged particle will be created by an ionizing x-ray or ultraviolet photon or by other collisional processes.

Since 1945, the ionosphere has been a major AFCRL research field. Over-the-horizon detection is a product of AFCRL ionospheric research. Other products have been the definitive models of the effects of nuclear detonations of various yields on the ionosphere, and propagation data basic to the design of military and commercial satellite communication systems.

Solar radio astronomy and the sun's effect on the ionosphere form a large part of the total Laboratory program. The Laboratory's Sagamore Hill Radio Observatory in Hamilton, Mass., is the most completely equipped observatory in the country for monitoring the changing state of the ionosphere and for interpreting the underlying causes of these changes. The sun modulates the ionosphere, and ultimately, the quality of radio propagation.

Several of the radio telescopes at Sagamore Hill are used exclusively to monitor the radio sun over a range of frequencies. The pattern of the intensity of solar radio emissions at various frequencies, when properly understood, serves as an index to resulting changes in the ionosphere. The Air Weather Service has established a large computer-based system for correlating and analyzing such patterns of emissions for the purpose of prediction. The Ionospheric Physics Laboratory provides basic radio data for the system. References to this new AWS forecasting system are made in several contexts throughout this report, with the most complete description given in Chapter VII.

Radio astronomy is one of many AFCRL techniques for probing the ionosphere. The Laboratory maintains other radio facilities all over the world



The interior of the solar patrol facility at the Sagamore Hill Observatory has an array of equipment for monitoring radio emissions from the sun. AFCRL operates this facility with the support of the Air Weather Service.

for observing gross changes, motions and turbulences. For many years it has monitored atmospheric transmission properties by means of a worldwide riometer network.

For *in situ* measurements of the fine structure of the ionosphere—temperatures, flux and distributions of charged particles—the Laboratory uses rockets and satellites. During the three years covered in this report, the Ionospheric Physics Laboratory placed experiments aboard 26 rockets and seven different satellites. The Laboratory's ionospheric flying laboratory—a KC-135—is the most completely equipped aircraft in the country for making ionospheric measurements.

Atmospheric scientists, beginning with the International Geophysical Year (IGY) in the late 1950's, have set for themselves the goal of understanding the relationship between solar variations and terrestrial effects. During this three-year reporting period, marked advances in the understanding of solar-terrestrial effects were made, with AFCRL's Ionospheric Physics Laboratory contributing in large measure to this new understanding. In connection with research into solar-terrestrial effects, the Laboratory mounted a large arctic field expedition during the period to map the complete anatomy of a Polar Cap Absorption (PCA) event. Several AFCRL laboratories participated in this PCA expedition which was managed by the Ionospheric Physics Laboratory.

In past years, the programs reported in this Chapter were carried out under the Space Physics Laboratory and the Upper Atmosphere Physics Laboratory. Those programs relating to the electrical structure of the upper atmosphere, to VLF propagation and to radio astronomy were brought together in March 1968 to form the Ionospheric Physics

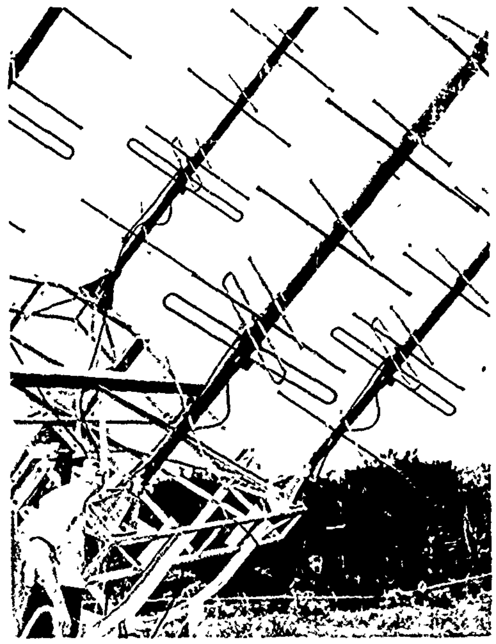
Laboratory. The Laboratory title is a resurrected one. Prior to an internal reorganization that took place in 1963, AFCRL had a laboratory entity also known as the Ionospheric Physics Laboratory.

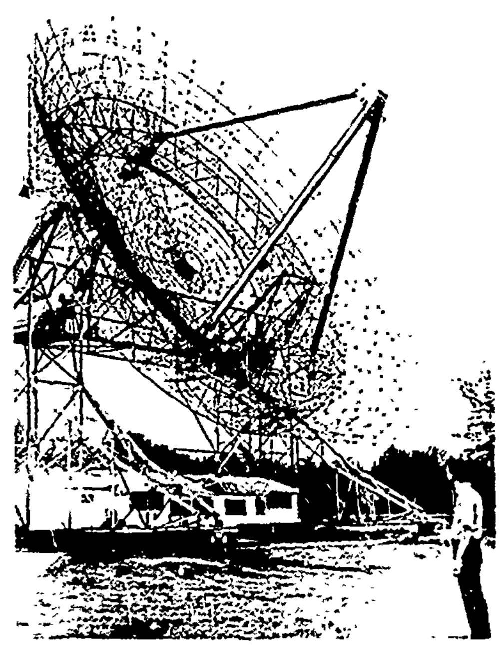
RADIO ASTRONOMY

The Laboratory's radio astronomy program is centered at the Sagamore Hill Radio Observatory in Hamilton, Mass., 35 miles from Hanscom Field. Here is located an alt-azimuth 150 ft antenna, an equatorial 84 ft antenna and three 28 ft antennas plus many simple dipole antennas. With these antennas measurements are made over a spectral range of 19 MHz to 35,000 MHz. The site itself is located at a geomagnetic latitude of 54 degrees N, a location sufficiently far north to permit auroral observations.

Radio astronomy at AFCRL is heavily weighted toward solar studies, with the goal of this research being the forecasting of solar events and their ultimate effects on the terrestrial environment. The Laboratory, through two identically calibrated facilities on the opposite sides of the earth (one at Sagamore Hill, the other in Manila in the Philippines), continuously monitors the radio sun 24 hours a day during most of the year.

Another major area of study by the Laboratory is that of ionospheric effects on radio signals from satellites including phase delay and radio scintillations (caused by ionospheric irregularities) which influence the quality of transmissions. AFCRL has developed models of scintillations as a function of season, time-of-day, and geographic position. Such scintillation models provide both the designers of satellite and

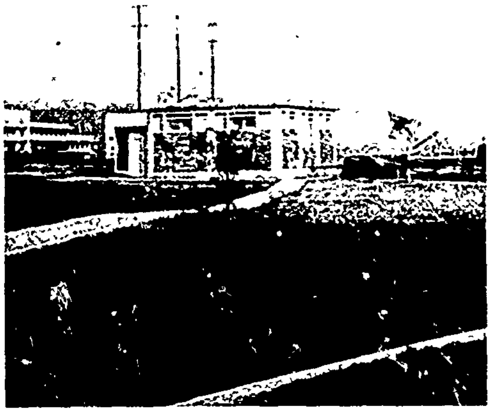




The Sagamore Hill Radio Observatory, with its many large dishes and antenna arrays, is one of the most complete facilities in the country for solar radio and ionospheric research. The dish in the lower photo has a diameter of 150 feet.

other communication systems and Air Force operational personnel with essential statistics against which to gauge system performance.

AFCRL radio astronomers conducted one satellite experiment during this reporting period. This satellite was the OV1-17 (ORBIS CAL) which carried an experiment to determine whether HF signals from the satellite could become trapped between two ionospheric layers. The satellite, launched March 18, 1969, carried two beacons—9 and 13 MHz. A worldwide network of 37 stations was set up to observe the signals. AFCRL found that the signals could indeed become trapped in a duct between the layers, and transmitted strong and clear over distances of several thousand miles. The signals were observed from Thule to Auckland, New Zealand, and from the Sagamore Hill Radio Observatory to Calcutta.



With the radio solar patrol facility in the Philippines (above) and the patrol facility at AFCRL (below) radio emissions from the sun can be monitored 24 hours a day.

PREDICTING SOLAR PROTON EVENTS: Since January 1966, continuous daily observations of the sun have been made at the following frequencies: 606, 1415, 2695, 4995, and 8800 MHz. As it became evident that the spectra of radio bursts would serve as a barometer for the warning of proton events and magnetic storms, frequency coverage was extended to 15,400 and 245 MHz in 1967 and 1968.

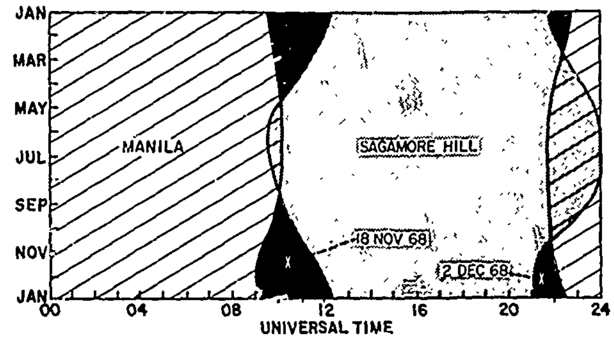
From these observations, AFCRL has uncovered clues for predicting the onset of major solar proton showers with a reliability far exceeding that previously possible. With the AFCRL prediction criteria, the false alarm rate (the prediction of events that do not occur) and the "miss" rate (a proton shower not forecast) have been reduced to a level approaching assurance—approaching, but not quite reaching.

Of the huge bursts of energy and matter that erupt from the sun during a solar flare, high energy protons have the most serious terrestrial effect. When high energy protons reach the earth's atmosphere (they are guided toward the poles by the earth's magnetic field), they create a condition known as polar cap absorption (PCA)—or radio blackout.

The forecasting of solar proton events is a high priority goal of both radio and optica. (Chapter II) solar astronomers. The approach to forecasting used by radio astronomers differs from that of optical astronomers. The optical astronomer looks for prediction clues in the size, configuration, age and growth rate of sunspots and their associated magnetic fields. The prediction methods of the radio astronomer lead to short-term prediction—warnings of three minutes to about 14 hours. The AFCRL radio prediction scheme is based largely on the analysis of the spectral characteristics of the radio bursts associated with a solar flare.

Proton-producing flares have a clear spectral signature. When signal amplitude (or flux) as a function of frequency is plotted, the result is a distinct U-shaped spectrum. The key feature of the spectrum is a null, or a minimum flux, usually at frequencies between 600 and 1000 MHz. Thus, the plot shows a strong signal at about 200 MHz, then a decrease in relative strength in the 600 to 1000 MHz range, followed by an increase in strength.

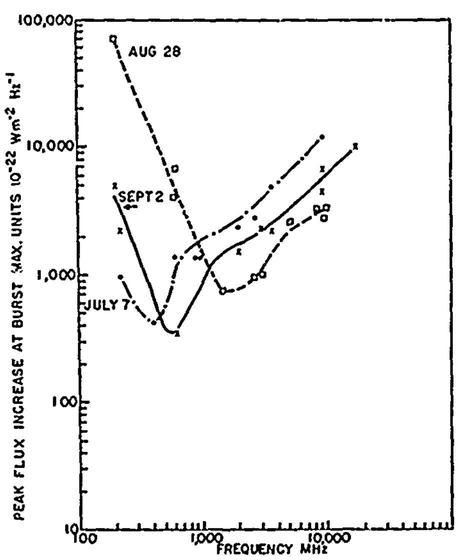
In addition to the U-shaped spectrum, AFCRL's prediction criteria call for a radio burst signal exceeding 1000 flux units (a measure of amplitude or signal strength). The radio burst itself must be of the type known as Type IV radio emission. Type IV radio emission occurs during the flare eruption across all frequencies within a time span of a few minutes. The magnitude of the flare itself, as observed visually with optical



The sun is visible to either Sagamore Hill or Manila 24 hours a day most of the year. Only during the times indicated by the dark areas on this plot can neither Sagamore Hill nor Manila observe the sun.

telescopes, has been found to be a secondary criterion—and may actually lead to a high false alarm rate if given undue weight in the ordering of prediction criteria.

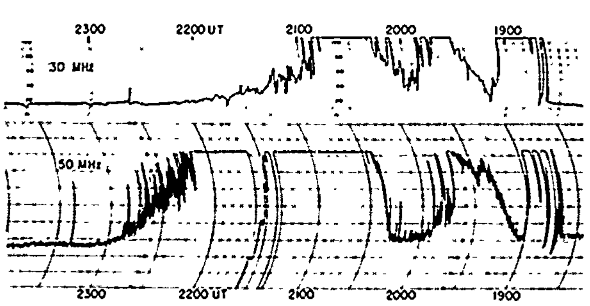
A possible model that might explain how the U-shaped radio spectrum is produced is one that postulates distinct



A basic clue to proton shower prediction was discovered at AFCRL in the U-shaped spectrum of radio emissions from solar flares.

radio emissions from two different regions of the solar atmosphere. One is synchrotron radiation resulting from acceleration of electrons in the region just above the chromosphere (15,000 km above the visible disk of the sun) to produce large radio fluxes at the higher frequencies. The second radiation source, producing emissions at the lower frequencies, results from the excitation of plasma radiation further out in the corona more than a million km from the visible disk. Between these two radio energy generating mechanisms, there's a distinct null resulting in the U-shaped spectrum.

THE GREAT BURST OF MAY 23, 1967: On May 23, 1967, there occurred one of the most violent and spectacular events ever observed in the solar system. This event was an eruption of matter and energy from the sun on a lavish scale. Intense radio energy over a broad spectrum, a dense flux of high energy protons, and a solar flare so bright that it was seen in white light were the chief features of the great burst. In the history of solar astronomy dating back to 1859, there have been only about 20 flares observed in white light.



The Great Burst of May 23, 1967, was recorded at a number of receivers at Sagamore Hill Observatory. In the above plots, the intense radio energy drove the pen charts to the limits of the scale.

The great burst reached a peak during a seven minute interval between 1947 (2:47 p.m. EST) and 1954 UT, with the higher radio frequencies reaching maximum intensity before the lower ones. The time of occurrence gave Western Hemisphere observers a clear overhead view. In addition, satellites recorded high energy proton emissions. Few solar events, other than eclipses, have been so thoroughly observed. The burst will surely be referenced in future solar research literature as a standard of comparison.

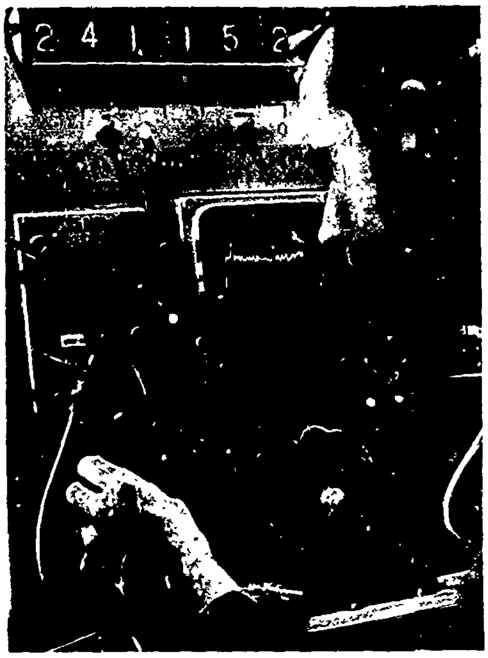
AFCRL collected more observational data on the event than any other single research organization. The optical instruments at the AFCRL Sacramento Peak Observatory in Sunspot, N.M., the radio telescopes and other radiometric equipments at the Sagamore Hill Radio Observatory in Hamilton, Mass., and the 35 GHz telescope (29 ft dish) at Waltham, Mass., were all trained on the sun at the time of the burst.

At Sagamore Hill, the burst was recorded at five frequencies, 606, 1415, 2695, 4995, and 8800 MHz. No data were lost from "off scale" or receiver saturation. Auroras were observed on May 25 as far south as latitude 32 degrees N (Georgia). A major magnetic storm associated with the great event took place on May 26. The storm was one of the largest on record.

PULSARS AND ECLIPSES: Among the more general solar observational programs during the period, programs that yielded data of interest both to the scientific community and to those engaged in the space forecasting problem, were observations of pulsars and the March 7, 1970 solar eclipse.

Using the 150 ft radio telescope of the Sagamore Hill Radio Observatory, pulsars were observed as a means of deriving electron content of the solar corona. The pulsar observing program was initiated in the summer of 1968. Observing the pulsar CPO 950, measurements of the difference in pulse arrival time between two widely separated frequencies (114 MHz and 228 MHz) were made for a period of many days before and after CPO 950's closest approach to the sun (4.7° or 17.5 solar radii, on August 20, 1969). Increases in the pulse-arrival-time difference are attributable to the additional solar coronal electrons in the line-of-sight. From the earth-sun-pulsar geometry, the radial distribution of coronal electrons may be deduced. The difficulty in this measurement is that the coronal electron contribution to the pulse-arrival-time difference is less than one percent of that caused by the electrons in the interstellar medium.

The March 7, 1970 eclipse was observed from Sagamore Hill at eight discrete frequencies between 245 and 3500 MHz. At this site, the eclipse reached 96 percent totality but totality was not essential for the study. As the moon moved across the face of the sun, it shielded each solar active region in sequence, switching off, in effect, radio emissions from the shielded regions. In this way, radio emissions from the sun were correlated with a specific active region. Radio emissions from a given active region cannot otherwise be resolved, except at extremely short millimeter wavelengths.



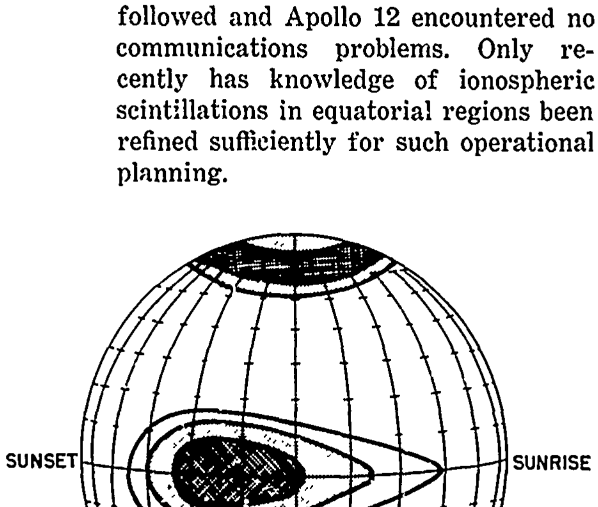
Pulsars are exploited to measure the electron content of the solar corona. To use pulsars in this fashion, the sun must pass along a line between the pulsar and the ground radio receiver so that the radio energy from the pulsar passes through the solar atmosphere.

SCINTILLATIONS AND SATELLITE PROPAGATION: Scintillation is nothing more than increases and decreases in the amplitude of a signal that is passed through the ionosphere. These variations are caused by irregularities in ionospheric density. Signal fluctuations may be rapid, with a period of a few seconds or as slow as several minutes.

The designer of satellite and other communications and navigation systems must have a knowledge of signal quality under all possible operating conditions. He wants to know the dB fading that can be expected during quiet and active magnetic periods, by season, at a given time of day, and for all geographic latitudes. With this knowledge, he can optimize trade-offs between power and weight of equipment and acceptable periods of systems blackout.

Most scintillation research outside of Soviet countries is planned, or coordinated, through the Joint Satellite Studies Group, a voluntary cooperative American-European effort, which AFCRL took the initiative in organizing in 1958 soon after the launch of the first Soviet Sputnik. Since then, AFCRL scientists have published, or presented, scores of papers on various aspects of the subject.

A practical operational application of scintillation research was best illustrated during the flight of Apollo 11. During this flight, communications between NASA's Apollo communications ships in the Pacific and the spacecraft were severely degraded during the night. NASA suspected that the reason might be the ionospheric conditions near the equator where the Apollo ships were located. This led to consultation with AFCRL which confirmed the suspicions and suggested that during the Apollo 12 flight, the ships be positioned at least 15 degrees north or south of the geomagnetic equator. This suggestion was followed and Apollo 12 encountered no communications problems. Only recently has knowledge of ionospheric scintillations in equatorial regions been refined sufficiently for such operational planning.



Until recently, it was believed that most intense ionospheric scintillations occurred in the arctic regions. Equally intense scintillations occur at night along the geomagnetic equator and degrade radar surveillance and radio communications.

In several papers prepared by AFCRL radio astronomers, simple new models have been presented regarding ionospheric scintillations on a global basis These models take into account such parameters as sunspot number, magnetic index, latitude, season and time-of-day. The data providing the basis for these models were drawn from many sources.

Satellites have been indispensable in scintillation research. VHF signals from many satellites have been used in the AFCRL studies, with the best data obtained from the LES-5 (228 MHz), the Canary Bird (136 MHz), the ATS-3 (136 MHz) and the LES-6 (254 MHz). Most studies of signal fading and scintillations have concentrated in the arctic regions and this is still the primary focus of AFCRL's program. More recently, increasing attention has been given to equatorial zone scintillations.

Ionospheric irregularities giving rise to scintillations along the geomagnetic equator during the night from about 2100 hours to 0400 hours are as severe as those found in the arctic, although mid-latitude regions are relatively free of signal degrading scintillations. Here's a description of a typical record of equatorial scintillations:

Equatorial scintillations start abruptly about three hours after sunset, frequently reaching maximum in a few minutes. The scintillations extend about 10 to 15 degrees north and south of the geomagnetic equator. Once the scintillations start, the level is maintained for several hours. However, the behavior may be different from night to night.

The nighttime irregularities are found to be in the F layer at a mean height of 306 km. The irregularities themselves are elongated, cigar-shaped electron patches, extending only about 220 meters in the east-west direction, but some 60 times longer in the north-south direction. These irregularities are moved by ionospheric winds across the propagation path of the satellite signal. By spaced-receiver methods the velocity can be measured as a function of time. The F layer drift is eastward at night with velocities as high as 140 meters a second. The drift reverses direction at about 0600 in the morning and again at about 1930 in the evening.

A clear seasonal dependence has been observed, with maximum scintillations occurring during September and March and minimum during December and June. Curiously, while solar activity (high sunspot number) tends to increase the scintillation index, it decreases the latitudinal extent of the scintillation region.

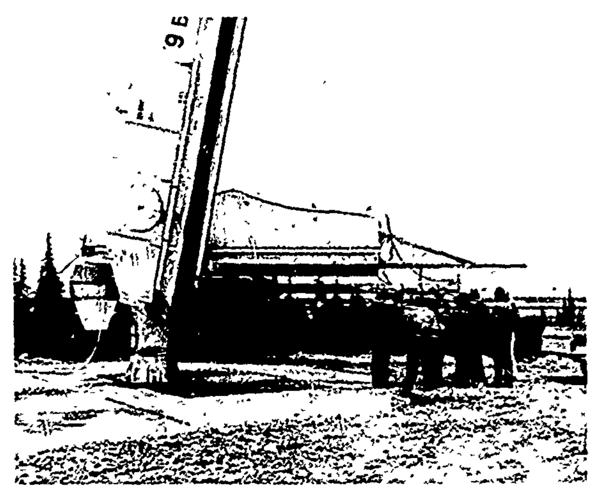
ARCTIC STUDIES

Survival in a nuclear war may well depend on how well electromagnetic sensors and systems function in the arctic environment. Knowledge of the range over which the arctic ionosphere can be modified either naturally or artificially is fundamental to operational planning.

The extensive arctic research programs of AFCRL are based on this consideration. Programs are built around rocket observations from Ft. Churchill, Canada, frequent data gathering flights by AFCRL's ionospheric KC-135 flying laboratory, ground-based radio measurements, and a permanent AFCRL observing site (operated by AFCRL's Aeronomy Laboratory) near Thule.

It is in the arctic that the ionosphere is most readily disturbed, for it is here that solar activity most directly interacts with the earth's atmosphere, producing auroras, polar cap absorption (PCA) events, auroral absorption and sudden ionospheric disturbances (SID). The aurora has been a special subject for study. It is intimately associated with the changing ionospheric densities, the magnetic storms and the ionospheric irregularities that degrade electromagnetic propagation. Auroral conditions have been shown to be directly correlated with the performance of over-the-horizon radars.

AFCRL over the years has studied PCA more intensely than any other laboratory in the country. Usually it is possible to measure only selected parameters of a given PCA event. Among the parameters of interest are electron and ion densities, temperatures and energy spectrums, light emissions, ionospheric heating and composition. During the period, however, a major expedition was undertaken to make simultaneous and coordinated rocket, aircraft, ground-based and satellite measurements of all the many related parameters. This field expedition to Ft. Churchill, planned and managed by the Ionospheric Physics

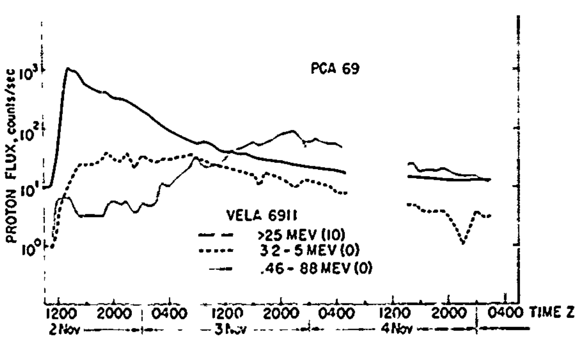


To observe the PCA event of November 2, 1969, 36 rockets, such as this NIRO, were fired from Ft. Churchill, Canada, during a 48-hour period.

Laboratory, was the largest expedition of its kind since the last atmospheric nuclear test series in 1962. In addition to the several AFCRL laboratories that participated, Canadian scientists, DASA, and the Army Ballistic Research Laboratory had major roles. The planning and effort that went into the expedition was rewarded with the PCA event of November 2, 1969.

THE PCA EVENT OF NOVEMBER 1969: A polar cap absorption event—a widespread radio blackout condition in the arctic—is not predictable. During the active period of the 11-year solar cycle, four such events on the average may occur a year. During the quiet period, none may occur during the year. Thus to make a thorough observation of all features associated with PCA, it is necessary to assemble observing equipment and then wait until an event takes place.

The equipment assembled for the observations included 36 rockets to be fired during a two-day period following the event, ground-based receivers for telemetered rocket data, radiometric equipment, and radio propagation facilities. One of AFCRL's KC-135 aircraft was prepared to leave Hanscom Field in Massachusetts as soon as the event occurred, and several satellites already in orbit were prepared to collect data. All was in readiness by July 1969. But the PCA event did not occur until November 2, three days before the deadline set to terminate the project. The event, when it did occur, was a strong, powerful one.



In the above plot, based on data from a VELA satellite, it is seen that a sudden increase of high energy protons (exceeding 25 MeV) marked the onset of the November 2, 1969 PCA event.

PCA is the direct result of high energy protons which are ejected from the sun by certain solar flares. These protons are directed to the geomagnetic polar regions by the earth's magnetic field where they enter the atmosphere near the geomagnetic poles. The resultant effects are similar to those of a nuclear detonation, one of these being the intense ionization of the entire mesospheric region between 50 and 80 km. A PCA is essentially a simulated nuclear explosion in the atmosphere.

The rockets, launched sequentially into the PCA event, were instrumented to measure light emission, ionospheric heating, ionization, atmospheric composition, neutral density, and temperature. Measurements included protons and alpha particles, and other ionizing sources such as x-rays, Lyman-alpha radiation, and energetic electrons. Rockets launched were spaced around the clock in order to observe daylight, nighttime, sunrise and sunset conditions. In addition to these 36 rockets—21 of which were instrumented by AFCRL scientists—11 certification rockets were launched prior to the PCA event. There were only three rocket failures for the total rocket program.

Satellite support for the program was an international effort with data being obtained from the VELA and Pioneer Satellite series, three European ESRO's, an ATS, the Injun V, and the Air Force OV1-18, OV2-5, and OV3-2. Instruments

In this series of photographs, the loop prominences associated with the flare that produced the November 2, 1969 PCA event were recorded optically.

aboard the satellites acquired data on magnetic fields and the energy and flux of the incoming charged particles. These satellites were in various positions and orbits, permitting scientists to plot the distribution and effects of the solar particles.

One of the AFCRL KC-135 flying laboratories (instrumented by AFCRL's Optical Physics Laboratory) was equipped to make optical measurements of enhanced sky illumination in the infrared, visible, and ultraviolet regions. Ground instrumentation consisted of riometers, ionosondes, photometers, spectrometers, and two partial reflection experiments. The results of this highly successful program were first presented on March 31 and April 1, 1970 at Boston College at a conference sponsored by AFCRL. At this conference, 34 papers were presented. A PCA symposium is planned for the spring of 1971 where more complete results will be presented.

FORECASTING THE MAGNITUDE OF PCA: Earlier, under the Radio Astronomy section, a method for predicting the occurrence of PCA was discussed. Here, the discussion is of a new scheme for forecasting the magnitude and duration of PCA once it has been initiated. The scheme provides short-term predictions up to two days, sometimes with accuracies to within 10 percent. The primary instrument for making the prediction is the riometer, automated to give data in real time. The riometer is nothing more than a small radio receiver that monitors normal background galactic radio emissions. Decreases in the signal strength of galactic background radiation are a measure of increased ionospheric absorption; absorption, in turn, is a measure of electron density in the ionospheric D region. Increased electron density is a basic PCA effect.

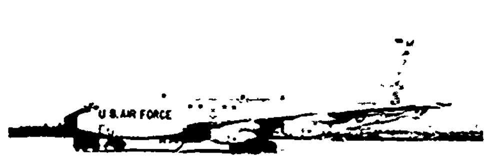
Peak PCA effects occur within hours of the onset but then trail off for the next four or five days. The first step in the prediction scheme is to make an estimate of when peak ionospheric absorption will occur. This initial estimate is derived from data provided by solar radio telescopes that detect solar radio bursts in the centimeter to meter wavelength region. These bursts herald the onset of the PCA event. Once ionospheric absorption sets in, riometer data are correlated with solar radio burst data to obtain the earliest possible estimate of peak absorption.

From the peak period of ionospheric absorption until noon the next day the predictions are least accurate, primarily because of the changing characteristics of the incoming solar proton flux. Another complicating factor is the normal diurnal variation in electron density.

The prediction scheme requires data from several high latitude riometer stations. Each riometer operates at 30 MHz and looks vertically upward. The incoming absorption values from each riometer station are extrapolated ahead in time with negative exponential weighting of the data according to the age of a data point.

FLIGHTS AROUND THE AURORAL OVAL: In December of 1967, 1968, and 1969, during the deepest part of the arctic winter, the Laboratory's KC-135 ionospheric flying laboratory departed from Hanscom Field for the arctic to observe the auroral oval. The optical auroral measurements require that the sun be depressed well below the horizon and that there be an absence of moonlight.

The most extensive of these yearly series of flights took place between December 2, 1969 and January 12, 1970. The KC-135 operated out of two different air bases—Eielson AFB, Alaska, and Keflavik, Iceland. From these bases, the aircraft made 11 flights which in the aggregate produced a dense web of flight paths covering most of the arctic above about 60 degrees latitude. Most of the flights concentrated on the auroral oval, the area of most intense auroral activity.



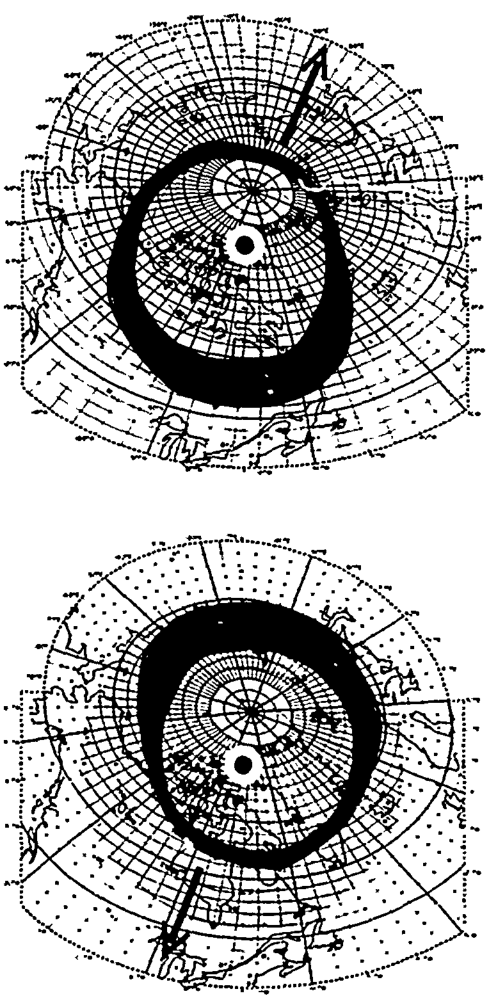
During the report period, AFCRL's ionospheric flying laboratory made four mid-winter expeditions, each consisting of several flights, to the arctic to observe the auroral oval.

The auroral oval is a belt that contains the visible discrete aurora and extends completely around the earth at high latitudes. Its position shifts as the earth rotates but it remains fixed with respect to the sun.

The inference that the auroral oval is a continuous band had never been tested until January 1970 when the KC-135 succeeded in flying completely around it. The photographic record confirmed the fact that the oval is a continuous structure consisting of auroral curtains which are approximately aligned along the oval.

The investigation of the noon sector of the oval has shown that D, E, and F region phenomena occur well separated in latitude in specific relation to the discrete auroral oval. Stable discrete aurora occur together with sporadic E while invisible diffuse auroral airglow occurs together with an E layer. The pattern stability and the detailed resolution of the phenomena observed have made it possible to infer particle energies and energy fluxes from ionospheric and optical parameters.

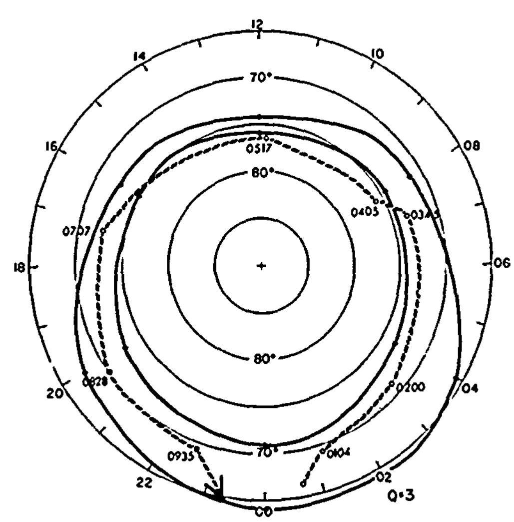
Studies of the arctic F-layer enhancement showed that it fluctuates according to universal time (UT) and appears to be controlled by the daily earth-sun geometry. The peak of electron density enhancement in the F layer is found in a ring encircling the pole located about 80 degrees corrected magnetic latitude. The enhanced F layer density is 12 hours out of phase for the Northern and Southern Hemispheres. F layer enhancement occurs at 0600 hour UT in the Southern and at 1800 hour UT in the Northern Hemisphere. The discovery that the UT control in the arctic F layer shows a strong latitudinal effect in the geomagnetic coordinate system is an exciting one and has led to a program for mapping polar F layer electron densities in the 1800 to 2200 hour UT sector. Tentative results show the replacement of the normal F layer by a very irregular F layer which is correlated spatially with a soft electron precipitation zone.

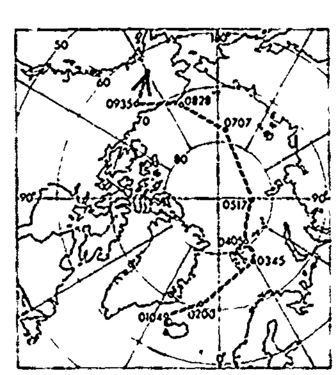


The auroral oval is the region of maximum auroral activity. The earth rotates underneath it once within 24 hours. The oval is shown in two extreme positions at 0600 UT and 1800 UT. The arrow points toward the sun.

It appears that the entire auroral oval ionosphere can be specified in real time if certain ionospheric observations in the midnight sector are conducted routinely.

MANTLE AURORA: During the December 1967 auroral oval flight to the arctic, AFCRL photographed for the first time an unusual auroral phenomenon. Although the existence of this auroral form was first suggested a decade ago, little was known of its dimensions or characteristics—and there has been





By flying east, the KC-135 can encircle the auroral oval in a 12-hour flight. One such flight path conducted in January 1970 is traced in the above map.

some uncertainty as to whether it is in fact a distinct auroral form.

There are several types of aurora, all having a marked structure—auroral curtains, rayed bands, and so on. The novel auroral form observed by AFCRL is unstructured and manifests itself as a marked brightening of uniform luminosity of the entire sky. The luminosity occurs as irregular pulsations, with each pulse lasting a minute or so. The novel aurora was too faint to be observed with the unaided eye.

AFCRL obtained its unusual photographic record by being in the right place at the right time. The KC-135 was at 30,000 feet within the auroral oval along a path off the east coast of Greenland. The time was shortly after midnight local time—0600 UT. The KC-135 carried an all-sky camera having a 160-degree view angle. For a two-and-a-half hour period, from 0600 to 0831 UT, 15-second exposures were made at one-minute intervals. Sky brightness variations were most clearly observed in a period from 0612 to 0652 UT when the last distinct pulsation was observed.

The photographic data show that after a total brightening of the sky occurred, the brightness receded toward the north, occasionally disappearing altogether. More often, the northern half of the sky remained bright after the southern half darkened. AFCRL believes that the pulsating brightness results from a fluctuating precipitation of energetic particles over an extensive area.

ELECTRIC FIELDS IN VISUAL AURORA: In the geomagnetic polar region, where the earth's magnetic field (carrying trapped radiation belt particles) dips into the atmosphere, plasma theory dictates that an electric field should be created. The electric fields should be very weak—a few tens of millivolts per meter. Until AFCRL did so, the fields had never been measured directly. Motivating the AFCRL measurements was the fact that if a model of arctic ionospheric dynamics sufficiently complete to provide a basis of prediction is to be formulated, that model must include electric field parameters.

The low values of electric fields make measurement difficult and the exact locations of the fields themselves are uncertain. Visible auroras, however, give clues as to where to look for them. Thus electric fields may extend down to the regions of auroral displays—as low as 100 km.

Four Nike-Iroquois payloads, all with identical instrumentation, were launched into fairly stable auroral displays over Ft. Churchill, Canada. One launched on December 10, 1969 served as a test round. The other three were launched in March 1970. The results

On a December 7, 1967 flight in the arctic, scientists aboard the KC-135 photographed brightness fluctuations of the overhead sky. These pulsations, an auroral phenomenon, were photographed with an all-sky (360 degrees) camera.

confirmed theory. With these instrumented rockets, the weak electric fields associated with aurora were directly measured for the first time.

Detection of the fields required careful electrical shielding of instruments. Measurements were made by two solid spheres mounted on diametrically opposed booms. Both spheres reach their respective local plasma potential, due to the high plasma conductivity. The potential difference between the sensor pair gives the electric field component along the boom direction. A 60-rpm spin was imparted to the vehicle about its longitudinal axis to enable the electric field to be measured anywhere in a direction normal to this axis. (For a discussion of inferential evidence for a general electric field corresponding to the earth's magnetic field, see Chapter VII.)

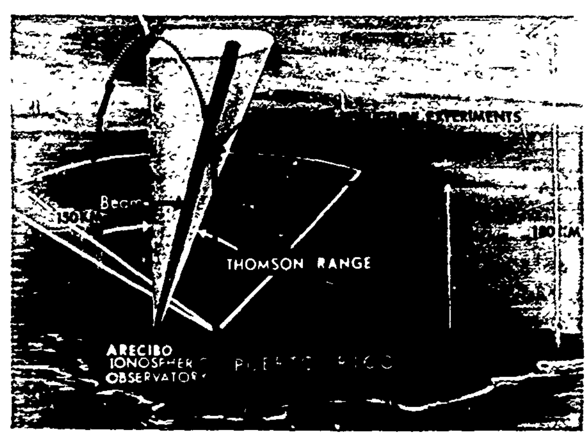
ELECTRICAL STRUCTURE

Electrical structure research is concerned with the charged particles—the ions and electrons—that make up the ionosphere. Properties of interest are flux, energy distribution, and directional vectors of the particles. The research is also concerned with electric fields, currents and conductivity in the ionsphere, the exosphere and the magnetosphere. Thus the foregoing discussion of electric fields in auroras could fit logically and comfortably into this section on electrical structure research.

The electrical structure of the upper atmosphere undergoes a regular cyclic pattern of diurnal and seasonal change as different regions of the earth's upper atmosphere rotate into and out of the direct line of exposure to solar energy. Onto this predictable rhythmical pattern is superimposed the transient change induced by solar and magnetic storms and by less violent variations in solar emissions. Nuclear detonations can create a sudden and catastrophic change over broad geographical areas.

Scientists in AFCRL's Aeronomy Laboratory whose programs are reviewed in Chapter VIII are also concerned with charged particles in the upper atmosphere, but from the standpoint of general atmospheric chemistry. But here the focus is on the formation and structure of the ionosphere.

Aircraft, rockets and satellites are used to acquire electrical structure data. These experimental programs are conducted from a base of theoretical research into the physical cause-and-effect relationships. The theoretical program is not only essential in the interpretation of experimental results, but also points the way to further experiments.



The electrical structure of the atmosphere can be measured both by rocket-borne instruments and by ground-based instruments. How well do the resultant data compare? To find out, AFCRL and the Arecibo Ionospheric Observatory made a series of simultaneous measurements.

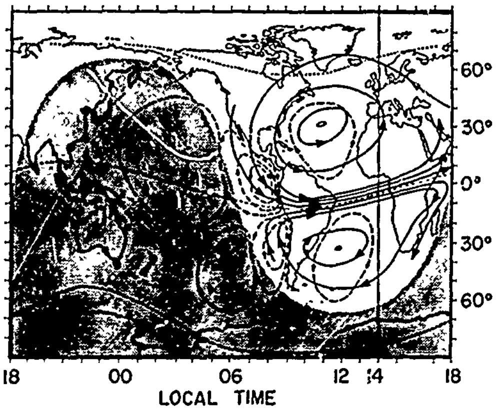
SIMULTANEOUS IN SITU AND REMOTE PROBING: Powerful radars such as the 1000-foot Arecibo Radio Telescope in Puerto Rico can probe the ionosphere remotely by detecting backscatter (Thomson scattering) of radio energy from charged particles. By this means electron and ion densities and temperatures as a function of altitude can be measured. By remote probing, data gathering costs—compared to *in situ* rocket measurements—can be greatly reduced, and fine features of the ionosphere can be monitored continuously for long periods. But to assure that the data are valid, it is necessary to calibrate the radar measurements against *in situ* measurements by rockets. Simultaneous radar and rocket measurements must be made.

In October 1967, AFCRL launched five rockets from Vega Baja, Puerto Rico, for such simultaneous measurements. The launch elevation and azimuth were set to intercept the backscatter beam of the Arecibo radar. During the same period, the Laboratory launched four additional rockets from Vega Baja independently of radar measurements.

Among the phenomena investigated were: daytime Lyman-alpha intensity, E and lower F region electron and ion densities and temperatures, small-scale charged particle irregularities, and the rate of decay of ionization in the ionosphere following sunset. Another purpose was the determination of the "near field" correction for the Arecibo radar.

These experiments showed that the electron and ion temperature data gathered by the two methods are in very good agreement. The charged particle distributions are also in agreement although there were differences in detail. Differences may be partly due to the large volume (approximately 16 km) sampled by the Arecibo radar. Spatial resolution of backscatter measurements can be improved by using different pulse widths and changing integration times.

Overall, the coordinated measurements provided a new level of confidence in both the rocket electrostatic probe techniques and in ground-based scatter systems for ionospheric investigations. The many specific experiments carried out have contributed to the solu-



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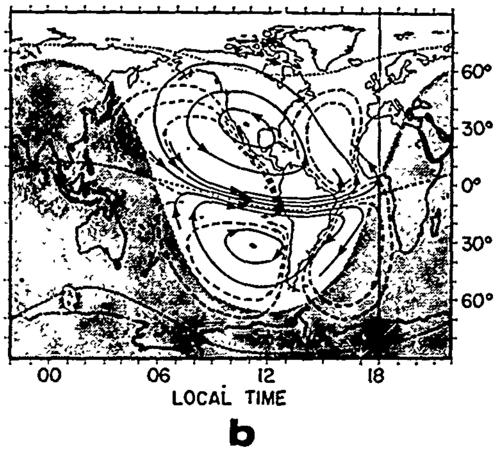

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The positions of the equatorial electrojet at two different times of the day are shown. The solid lines represent the electrical current system at about 110 km. Two loops join at the dip equator in the sunlit hemisphere and comprise the electrojet. The dashed lines represent electrical currents induced in the ocean.

tion of several problems including: daytime ionospheric E-region heating, nighttime cooling rates, and ionization production and decay mechanisms in the lower ionosphere.

EQUATORIAL ELECTROJET: The equatorial electrojet is an electric current of about 90,000 amperes found at about 110 km altitude along the geomagnetic equator during daylight hours. The whole system is stationary with the sun. It has a cross section width of about 600 to 1200 km and a thickness of ten to 20 km. The electrojet current density varies considerably from day to day and season to season and decreases with increasing magnetic activity.

The currents are driven by a dynamic effect involving the earth's magnetic field and resulting from tidal motions of the upper atmosphere. Its dynamic behavior—that is, its variations under the varying influences of solar radiation, solar wind, and so on—is poorly understood. To investigate the electrojet, AFCRL uses its instrumented KC-135 aircraft.

At an 11 km altitude, this aircraft can cross the electrojet in about 100 minutes to obtain a north-south cross section. This time is sufficiently short, except during magnetically disturbed days, to assure that temporal changes are not superimposed on the spatial changes. The obtained cross sections are therefore considered as quasi-instantaneous.

Most flights are made over the Pacific Ocean. The aircraft carries a magnetometer which records the magnetic field intensity. The recorded magnetic field intensity will, of course, not only include that induced by the electrojet current, but will include the geomagnetic field originating in the earth's interior. To separate these components, it is necessary to fly identical routes during both day and night. In addition to data on magnetic cross sections, data on electron density are obtained using an airborne ionospheric sounding system (type Granger 3900).

AFCRL has discovered the following electrojet properties:

1) During periods of high geomagnetic activity, the width and shape of the electrojet cross section changes from hour to hour while little change occurs during low geomagnetic activity.

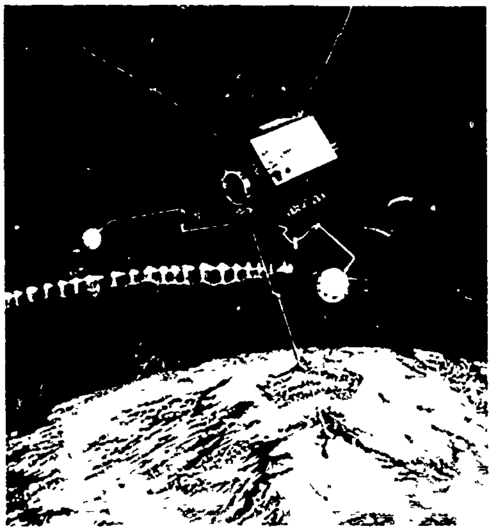
2) Striations or bands of higher and lower current density within the electrojet spaced several hundred km apart were found, and during quiet magnetic activity these did not change position for several hours. No striations in E-layer electron density were found.

3) During a solar eclipse in the Pacific when the moon's shadow crossed the magnetic equator, the electrojet left its normal position along the magnetic equator and temporarily shifted by about 300 km. A fast recovery from this anomalous position was made after the eclipse. This recovery indicates that the electric fields associated with the electrojet are able to reassemble within less than two minutes.

ATTITUDE CONTROL SENSORS: Several years ago, it became apparent to AFCRL scientists that ions at satellite altitudes could be exploited in a satellite attitude control sensor. This attitude sensor would be one that oriented the spacecraft with respect to the stream of ions through which it moved. Such a sensor was developed and it proved to be simple and highly reliable, requiring a minimum of power from the spacecraft power supply. It was flown on Gemini 10 and 12 with outstanding results. Since then both NASA and SAMSO have undertaken development programs for operational sensors.

During tne present period, the positive ion attitude system was flown on the OV1-15 satellite l unched in July 1968. In this case the sensor was flown as an operational (rather than as an experimental) device for the first time. The sensing system functioned perfectly, as it had during the earlier Gemini flights. The system can now be considered operational and can be used for automatic or manual attitude control of spacecraft for purposes such as guidance, docking, rendezvous and reentry.

INJUN V SATELLITE: On August 8, 1968, the Injun V satellite was launched successfully from Vandenberg AFB into a 666 km by 2526 km orbit with an inclination of 80.8 degrees. It carried two AFCRL plasma probes designed to measure the flux, density, energy distribution and temperature of protons and electrons with energies between 0 and 2 keV. In addition, the payload included instruments for the measurement of energetic particles between 2 and 50 keV, and low frequency electric fields.



The Injun V satellite was launched into a polar orbit in August 1968 and carried two AFCRL plasma probes to measure the flux, density, energy distribution and temperature of protons and electrons between 500 and 2700 km.

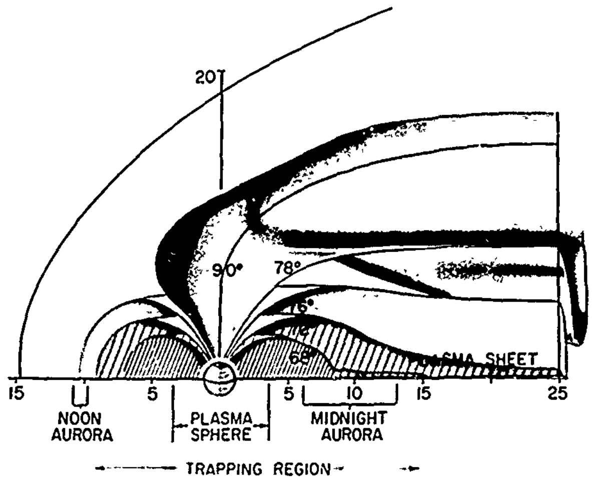
From the standpoint of those examining the electrical structure in the near-space region, Injun V proved to be one of the most productive satellites launched to date, providing new information on: the mechanism of charged particle injection in the polar regions during auroral and polar cap disturbances; the effect on the ambient electrical environment of precipitated particles entering the ionosphere; variations of charged particle temperatures on a global scale; magnetic storm effects; global morphology of ambient and epithermal charged particles in the topside ionosphere under quiet and disturbed solar conditions; relations between neutral particle temperatures and charged particle temperatures, and the relation between charged particle irregularities and VLF signals.

RESULTS FROM EARLIER SATELLITE EXPERIMENTS: Launched during the previous reporting period were the OV3-2 and the OV3-1, both carrying electrical structure experiments. The analysis of the data from these satellites was completed during the present period. Some interesting and unsuspected features were uncovered.

The OV3-2, placed in a 330 by 1620 km orbit, carried probes to measure flux, energy distribution and temperature of electrons and positive ions in the 0 to 2 keV energy range. The experiment was designed to observe day-to-day variations in the pattern of ionization over the satellite orbit. It was found that the pattern remains relatively unchanged as long as worldwide magnetic activity remains low. Even after a magnetic disturbance, the pattern is restored rather quickly. A number of persistent local features in ionization density were identified, but not fully explained. Examination of the electron temperature data has shown that there are sometimes several components to the temperature distribution of the ambient electrons. Normal temperature range is about 1500 to 4000 degrees K. But also present are electrons with temperatures of 20,000 degrees K or higher. There is apparently no preference in time or space for the distribution of these secondary electron temperature components.

The OV3-1 was placed in a polar orbit of 2000 to 5700 km. Unexpected large irregularities and density gradients were observed in the range L = 2 to L = 4. A marked depletion of the thermal plasma was found between L = 2.5 and 4.0 on about half of the 46 orbits analyzed. This depletion was found in the evening sector (15 to 20 hours local time) and at no other times. The depleted region may extend from an inner edge up to the plasmapause or it may resemble a trough several degrees in width with higher densities on either side.

Sharp density gradients often occur at the boundaries of the depletion region, similar to those at the plasmapause. At 5000 km the density typically decreases by a factor of 5 over 2 degrees in latitude. The magnitude of the decrease becomes less pronounced with decreasing altitude and is not always observed below 4000 km. Small-scale density fluctuations are often observed at the boundaries. Measurements obtained near conjugate points sometimes show the depletion occurring in only one hemisphere. The anomaly is observed on the same magnetic field lines as the evening ring current and the



This model of the magnetosphere shows the strong asymmetry of the day (left) and the night (right) sides of the magnetic field. The electrical structure of this region is of great importance in the operation of Air Force radars and communications systems.

evening increase in f_0F_2. Possible relations between these phenomena are a subject for current exploration.

MEASURING DENSITY AND MOTION

The earth's ionosphere presents itself to the radio physicist as a medium of rather substantial substance that distorts, attenuates and modulates radio signals and as such sets rigid limits on the design and operation of systems that detect and transmit radio energy. Yet physically, the ionosphere is delicate and wispy, easily modified and easily disturbed. A missile passing through it, for example, sets off a train of waves that spread out over hundreds of miles—this being the property that is exploited in over-the-horizon detection systems. Disturbances originating in the arctic are propagated southward inducing turbulences over large regions of the ionosphere.

From the research standpoint, the very fact that radio energy interacts so strongly with the ionosphere provides the basis for many techniques for monitoring and mapping the state of the ionosphere, its wave motions, turbulent drifts and changing density. Much of the research discussed under the earlier Radio Astronomy section of this Chapter was concerned with the use of radio telescopes to probe the condition of the ionosphere. This section will touch upon some of the other programs in progress in the Laboratory for studying ionospheric change.

RIOMETER NETWORK: The simplest instrument for monitoring the state of the ionosphere is the riometer (relative ionospheric opacity meter). For many years AFCRL has maintained a network of 13 riometer sites all over the world at each of which the density of the ionosphere is continuously observed. These riometers, operating at 30 MHz, are simply radio receivers that record the intensity of normal galactic background radio noise. These noise sources are assumed to be constant in radiated power output. Therefore, during periods of a quiet sun, any signal amplitude changes observed in the riometer records can be interpreted as absorption due to density changes in the intervening ionosphere.

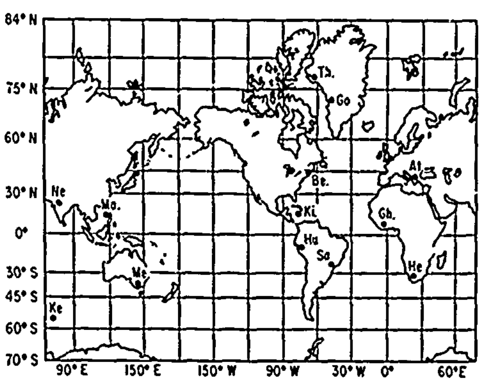
Motions, turbulences, and variations in the ionosphere can be inferred rather directly by radio techniques used by AFCRL radio physicists.

Solar flares are often preceded by radio bursts which register on riometers as a sudden signal enhancement. This enhancement is usually followed minutes to hours later by a decrease in signal strength to below normal as the effects of the flare are manifested in increased ionospheric density. It was through the analysis of such riometer data that the PCA prediction scheme noted earlier in this chapter was evolved. Data from the 13-station riometer network were used to develop the scheme.

Riometer data from the 13-station network are published each quarter in the *Geophysics and Space Data Bulletin*, a publication issued for many years by AFCRL's Space Physics Laboratory.

NEW INSTRUMENT FOR ELECTRON CONTENT MEASUREMENT: During the period AFCRL developed another instrument for measuring the total electron content—a novel polarimeter. This instrument was actually developed to overcome a problem in ranging and navigation, but has proved to be an important new ionospheric research tool as well. Here's the background on the problem it was designed to solve: A radio signal transmitted through the ionosphere is slowed down, with the amount of retardation being dependent on both the signal frequency and the density of the ionosphere. This fact must be taken into account in earth-space radio ranging schemes where distance is derived by timing the signal.

If the ionospheric density is known, corrections can be made for signal retardation. Such retardation can cause errors of several hundred meters in UHF operational radars and it degrades the accuracy of geodetic satellites using UHF timing pulses. Ionospheric density is of special concern to the de-



AFCRL operates, largely under contract, 13 riometer sites covering most of the regions of the earth.

signers of aircraft navigation systems in which signals will be transmitted from two geostationary satellites to a transponder on board the aircraft and retransmitted to the satellites. From the measured time delays, the aircraft position can be located to within a fraction of a mile, assuming no ionospheric effects. If the ionospheric effects are present and not corrected, ranging errors of ten miles or so may occur.

The electrons of the ionospheric impart a corkscrew-like twist to the signal—a phenomenon known as polarization rotation. It is possible to determine the total ionospheric density by measuring the change in signal polarization. The instrument used to make such measurements is called a polarimeter, which is nothing more than a radio receiver that processes the detected signal in a special way.

The polarimeter developed by AFCRL gives the capability for the first time of measuring the total electron content of the ionosphere on a real-time, continuous basis. It has many distinctive capabilities. The polarimeter is linear over a full 360-degree phase range, maintains phase accuracy over a long period of time, has excellent sensitivity, and is reliable, inexpensive and easy to operate and maintain. The polarimeter requires no special RF phase locking techniques or mechanically moving parts.

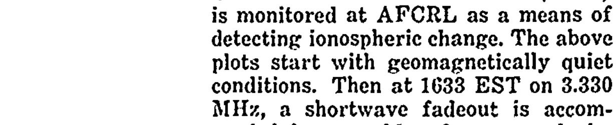
The AFCRL polarimeter design is equivalent to a single rotating antenna spinning at the modulation frequency. Two orthogonal RF signals are modulated by two orthogonal audio-frequency voltages and the resultant signals are combined, amplified, detected and phase compared with a signal derived from the modulating signal. The bandwidth of the modulators extends from 0.2 to 500 MHz. The modulators have been used at 30 and 137 MHz with no appreciable difference in results.

The polarimeter has been used to observe electron enhancements resulting from solar activity. Results to date have been exciting. In 1968, several large centimeter radio bursts occurred and an associated abrupt increase in the total electron content was observed using the polarimeter. Disappearances of electrons during severe magnetic disturbances also have been observed. One such disturbance occurred on November 1, 1968 when 60 percent of the total number of electrons in the ionosphere disappeared in 15 minutes.

CLOUD REFLECTIONS AND IONOSPHERIC DENSITY: The energy that creates and sustains the ionosphere for the most part originates directly from the sun in the form of UV and x-rays. AFCRL has demonstrated that solar energy in the visible part of the spectrum reflected from clouds or snow can enhance electron density in the lower ionosphere, the D region. This result points toward the importance of the visible light flux which must play an important role in the chemistry of ionization in spite of the fact that visible light is not energetic enough to ionize directly.

With the KC-135 ionospheric laboratory, a series of airborne ionospheric sounder measurements were conducted for the purpose of comparing the D-layer electron density over cloud-covered areas with that over cloud-free areas, while keeping other influential variables such as solar zenith angle as constant as possible. The experiment was accomplished by flying across the boundary between large areas of adjacent cloud cover and clear sky while operating an ionospheric sounder on fixed frequencies using a pulse amplitude digitizer. This equipment was developed to allow continuous digitizing of calibrated pulse amplitudes on six frequencies simultaneously.

The observed decrease of echo amplitudes due to cloud albedo was 6 percent of the amplitude value. This information translated into terms of the ionosphere at the altitude of 55 to 65 km amounted to an increase of electron density by 20 percent due to cloud albedo.



Canada's time standard station (CHU) is monitored at AFCRL as a means of detecting ionospheric change. The above plots start with geomagnetically quiet conditions. Then at 1633 EST on 3.330 MHz, a shortwave fadeout is accompanied by a sudden frequency deviation. This was produced by a solar flare that occurred at 1625 EST.

WAVE MOTIONS AND DISTURBANCES: Short-term and long-term ionospheric variations, traveling wave disturbances, and much else can be measured by ground-based remote sensing techniques. Two methods developed by AFCRL will be discussed here.

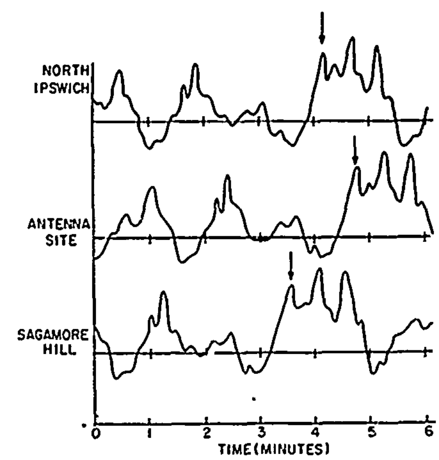
One of these is a rather complex signal processing system developed for monitoring signals from Canada's time station, CHU, located 480 km northwest of AFCRL. CHU transmits 3.330 and 7.335 MHz signals with a frequency stability of about 1 part in 10^9. To derive information on ionospheric wave motions and turbulences, the AFCRL system depends on the detection of doppler frequency shifts, modulation phase and amplitude of the CHU signal. Wave motions in the ionosphere are seen as the periodic recurrences of features in the recorded data. Typically, these periodic intervals, indicative of waves, may extend from 15 minutes to three hours.

Ionospheric waves may have a variety of sources. Certain traveling ionospheric disturbances are clearly associated with polar and auroral particle precipitation events. For observers at mid- or low latitudes, these waves are distinguishable by their advance from the polar regions toward the equator. Although these waves experience losses possibly due to turbulent damping, ion drag or leakage, long waves are seen to travel over large distances perturbing the ionosphere on the journey.

The other new system for probing of the fine structure of the lower ionosphere is one in which an HF signal is reflected from the ionospheric E region. Wave interference dominates the character of the reflected signal received at the ground station, a new receiving site in Billerica, Mass. The computer-performed analytical scheme makes use of a generalization of the more familiar ordinary correlation and spectral analysis, permitting highly complex quantities to be handled.

E-layer echoes with wavelike irregularities, too short-lived to be characterized as proper waves, have been observed. No regular period can be determined, although an average wavelength of 6 km was calculated. Occasionally, two separate wavelike motions have been observed. It is assumed that the irregularities result from wind motions of the neutral atmosphere to which the E layer is coupled.

The character of the irregularities suggest a formative stage of turbulence introduced by a large-scale atmospheric gravity wave. Presently planned are simultaneous recordings over several height strata. This and a three-dimensional recording with several frequencies planned for the future will contribute to the correct physical interpretation of the data. It is expected that the development will lead to a practical instrument and analysis technique for continuous monitoring of various motions in the upper atmosphere.



The velocity of ionospheric drift motion can be measured by using spaced receivers. Scintillations of the signal from the ATS-3 satellite were recorded at three stations in a triangular configuration separated by 10.1, 8.6, and 3.8 km. Time delays between identifiable features (arrows) allow ionospheric drift to be measured.

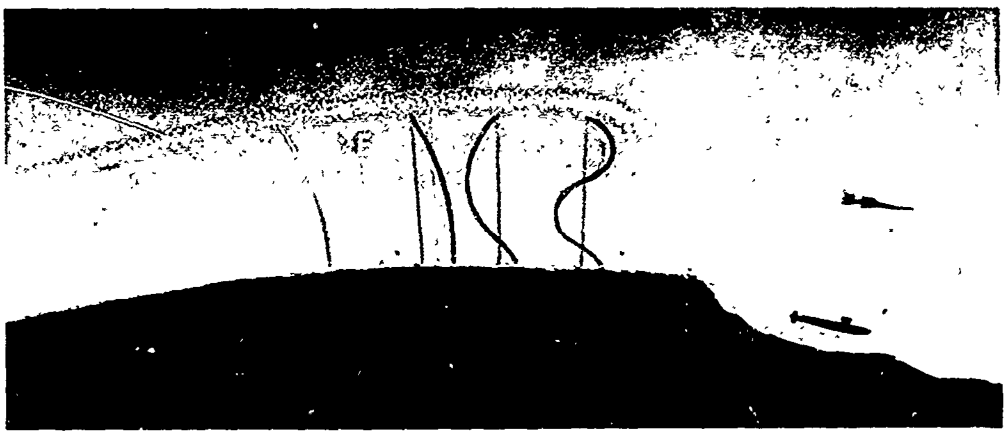
EARTH-IONOSPHERE CAVITY

The earth's surface and the lower ionosphere form the boundaries of a cavity in which low frequency (30-300 kHz) and very low frequency (3-30 kHz) radiation is trapped. The cavity serves as a waveguide within which LF and VLF signals can be propagated with minimum losses over thousands of miles. Most important from the Air Force point of view, communications within the waveguide are generally immune to the natural and nuclear ionospheric disturbances that so profoundly affect higher frequencies.

LF AIRCRAFT COMMUNICATIONS: Air-to-ground communications at LF pose unique antenna problems. An efficient airborne system at 60 kHz, for example, would require a vertical antenna 8000 feet in length. It would seem out of the question for an aircraft to support such an antenna. Nevertheless, the Ionospheric Physics Laboratory has tested a system that will provide aircraft with an LF transmission capability. It is known as SCAT (Self-Contained Automatic Transmitter).

AFCRL's idea is for the plane to carry a battery-powered transmitter which is dropped from the aircraft with a pre-recorded message. A large parachute is deployed to give a long, slow descent to the ground. As the package drops, two reels of wire, each containing 4000 feet of wire, are played out with an aerodynamic braking device controlling the deployment rate. When the reels are unwound, the transmitter is at the center of a vertical half-wave dipole, which has a resistive impedance low enough (90-100 ohms) to be conveniently driven by a solid state transmitter. Electrical tests showed that with seven strands of No. 18 copper-clad cable—a standard material—the radiation efficiency is about 80 percent. When dropped from 45,000 feet, transmission times in the order of 30 to 45 minutes and a radiated power of 3 kW should be obtainable in a package with an overall weight of 300 pounds.

EXPLORING THE EARTH-IONOSPHERE CAVITY: Although the earth-ionosphere cavity is a highly efficient waveguide at VLF, there is still some leakage of energy into the ionosphere. But how much and in which geographical regions does the greatest leakage occur? AFCRL has launched rockets from Eglin AFB, Florida, (60° N geomagnetic latitude) and Natal, Brazil, (geomagnetic equator) which have measured VLF signals at altitudes up to 500 km. As predicted by theory, it was found



The earth's surface and the lower ionosphere form the boundaries of a cavity in which VLF (3-30 kHz) radiation is trapped. The cavity serves as a waveguide within which signals can be propagated with low losses over thousands of miles, and with minimum effects due to nuclear detonations.

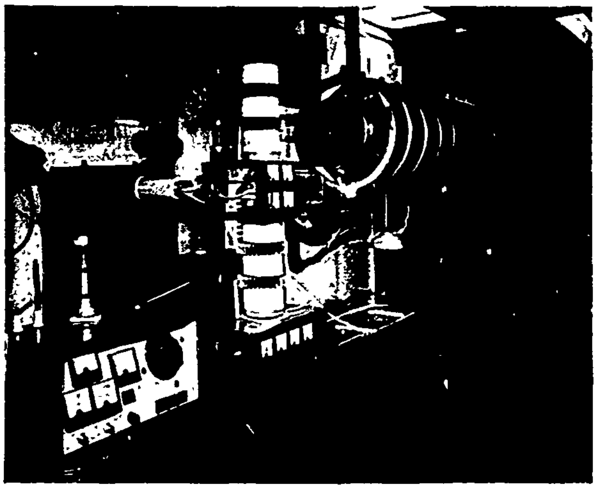
that less VLF energy leaks into the ionosphere at the geomagnetic equator than at 60° N latitude.

To acquire data on ionospheric reflections at LF and VLF frequencies, AFCRL has developed a short-pulse ionosounder capable of measuring reflection coefficients at a number of frequencies simultaneously, from 100 kHz down to 6 kHz. Short pulses, each consisting primarily of one cycle of a 15 kHz wave, are radiated from a 3000-foot vertical, balloon-supported antenna. At the receiving station, the ground- and sky-waves arrive as discrete pulses separated in time, and hence can be processed independently. The vertical antenna has a uniform azimuthal radiation pattern which allows measurements to be made in any or all directions. The equipment is mobile and has been operated aboard ship.

SCHUMANN RESONANCE PHENOMENON: When one speaks of a cavity, including the earth-ionosphere cavity, it is assumed that the cavity will resonate at some frequency proportionate to its size. The resonance frequency of the earth-ionosphere cavity is about 8 Hz. The constant background 8 Hz radiation is known as Schumann resonance. Schumann resonance could have many sources, one of these being EM radiation from lightning discharges from all over the world. From the broad spectrum of EM radiation generated by lightning strokes and other sources, the 8 Hz waves are extracted because of the earth-ionosphere cavity dimensions.

During the period, the Laboratory undertook a program to measure Schumann resonances by establishing two contractor-operated field sites. One is located at Kingston, Rhode Island, the other at Brannenburg, Germany. Widely spaced observatories were necessary because resonance phenomena near 8 Hz involves a large portion of the earth-ionosphere cavity. The two sites have identical equipment.

Two large, shielded coils, which measure the H-component of electromagnetic noise in the ELF range, are oriented perpendicularly to each other.



During the reporting period, the Laboratory measured VLF and LF ionospheric reflection properties from a field site in California. To obtain a uniform azimuthal radiation pattern, a balloon-supported antenna several thousand feet long was utilized. The high voltage portion of the transmitter, located in a trailer, is shown in the lower photo.

A short but thick electric monopole with pre-amplifier is mounted nearby and used to receive the E-component of the electromagnetic noise in the ELF range.

Analysis involves the comparison of the temporal behavior of the ELF noise from both stations, as recorded in several narrow frequency bands, in order to study the spectral similarity, the relationship to terrestrial and extraterrestrial sources, and the effects of solar and geophysical phenomena on the resonance structure of the cavity. It is hoped that the analysis of this resonance phenomenon may also lead to a numerical index (earth-ionosphere cavity resonance index) characterizing the worldwide state of the lower ionosphere.

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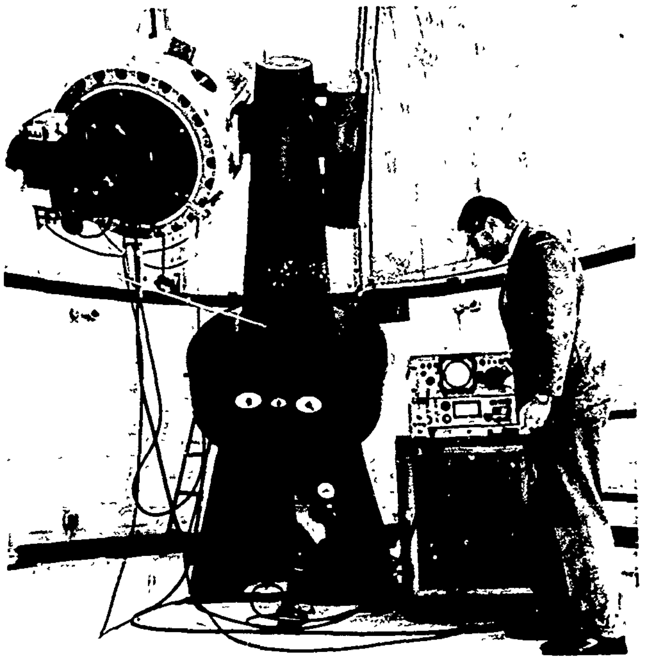


During the reporting period the Laboratory's lunar research program was curtailed and the observatory housing this 24-inch telescope located in Concord, Mass., was closed. A by-product of the lunar research program was the development of an extremely sensitive infrared scanning system (attached to the telescope) later tested for use in airborne surveillance.

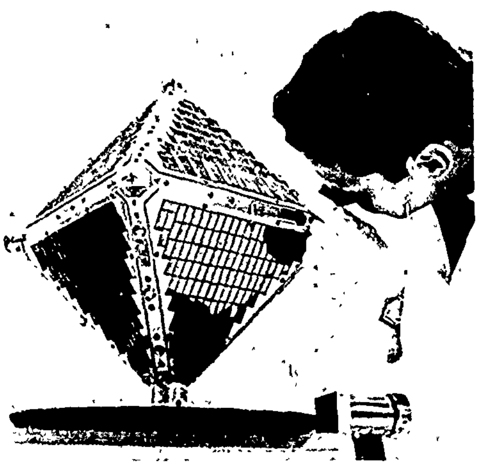
VII Space Physics Laboratory

Much of the research of the Space Physics Laboratory has the purpose of defining the effects of variable solar emissions on the earth environment. Such studies include solar flares and related energetic particle emissions, the solar wind, and the magnetosphere which surrounds the earth. Also involved are studies of electrons and protons trapped by the earth's magnetic field and of the precipitation of such particles into the ionosphere in the polar regions. Finally, a considerable amount of effort is devoted to an attempt to develop forecasting programs to predict solar activity and its effects on the near-earth space environment and on the ionosphere.

Also within the scope of the program of this Laboratory is the search for more efficient methods for converting energy, primarily the sun's radiant energy, into electrical power, and spectroscopic studies of nonstellar celestial background radiation.

This research is conducted through laboratory experimentation and through a range of facilities for making direct observations and measurements. Among the laboratory facilities available to Space Physics Laboratory scientists are shock tubes for studies of plasmas as related to solar flares and to energy conversion research; a simulation chamber for studies of materials exposed to the space environment; and a clean room for analyses of samples obtained in the meteor physics research.

The Laboratory operates two observatories, one in Massachusetts and the



The Space Physics Laboratory is a large user of satellites, rockets and balloons.

other in Hawaii, both with 24-inch telescopes for infrared studies of the non-stellar celestial background radiation. During this reporting period, the Laboratory sent instrument packages aloft on 12 high altitude balloons, 17 rockets and three satellites.

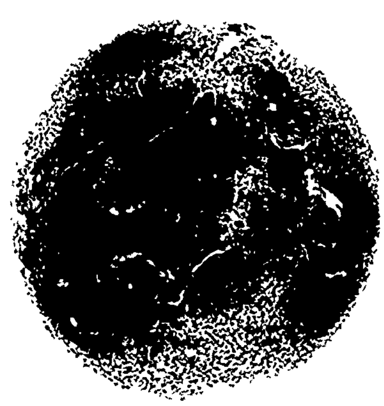
During the latter part of 1969, as the result of a general cutback in funding leading to a review of Laboratory programs to assure that all research is related to Air Force capabilities, immediate and projected, three long-standing AFCRL programs were marked for termination. A decision was made to immediately curtail further research in stellar astronomy. This meant that no further observations at the Cerro Tololo Inter-American Observatory by Space Physics Laboratory scientists would be made. The meteor physics research was scheduled for support only through the end of Fiscal Year 1970, and lunar and planetary research at AFCRL also would terminate at the end of Fiscal Year 1970.

SPACE FORECASTING SYSTEM

The Space Forecasting System will be placed in operation in the summer of 1970. The system is designed to predict bursts of radiation and energetic particles from the sun, and the effects of these bursts on the earth's atmosphere.

The system draws on most of the environmental sciences, the product of which forms a complex matrix of causal interrelationships involving radio and optical solar astronomy, astrophysics, radio propagation physics, and the physics and chemistry of the upper atmosphere. The phenomena that these scientific studies deal with have a direct and sometimes profound influence on a range of Air Force electronic and optical systems. Radars, delicate satellite sensors, radio communications, and navigation systems are all influenced by events that originate on the sun. Consequences of these events are absorption of radio waves in the polar regions, geomagnetic disturbances, auroral activity, enhanced airglow levels, variations in atmospheric density, and ionospheric fluctuations and inhomogeneities. It is of obvious concern to the Air Force to know well in advance expected degradation of its electromagnetic operational systems. These environmental effects are triggered by bursts of electromagnetic radiation and by energetic particles from the sun.

If the magnitude of bursts of particles and EM radiation from the sun can be predicted, then some ultimate effect on Air Force operations can also be predicted. This presupposes an understanding of the relationship between a particular solar event and a particular terrestrial effect. At present, these relationships are unknown except coarsely and qualitatively.



The Space Forecasting Program, a joint AFCRL-Air Weather Service endeavor, is one that attempts to predict changes in the earth's upper atmosphere and near-space environment by monitoring by radio and optical means the changing dynamic features on the face of the sun.

Two needs must be met if the Space Forecasting System is to be effective: a more thorough knowledge of the dynamic processes on the sun, and a better understanding of solar-terrestrial relationships. As knowledge and understanding increase, so will the accuracy of predictions.

The system is being developed by AFCRL and the Air Weather Service (AWS) and will be operated by AWS.

THE NATURE OF THE PROBLEM: All bursts of electromagnetic energy and high energy particles from the sun are associated with solar flares and all solar flares (with a few rare exceptions) are associated with sunspots. But not all sunspots produce flares and not all flares produce disruptive solar bursts. One problem (there are three basic ones) is that of predicting whether a given flare will emit an intense flux of radiation and particles.

The second problem is that of predicting whether these bursts will produce magnetic storms, auroras, ionospheric disturbances, and so on. The terrestrial effects vary markedly from flare to flare. High energy protons reach the earth from a few minutes to a few hours after the flare peak. Other protons are strung out in time (and space) and the maximum flux of protons is usually observed several hours after the first measurable terrestrial effect. Low energy particles emitted at the same time travel much slower. Their effects are observed two or three days later in the form of magnetic storms and ionospheric disturbances on a worldwide basis. Low energy electrons modulate the earth's magnetosphere causing magnetic storms. The problem is not only that of predicting whether a solar flare will produce a terrestrial effect, but also the kind of effect, its onset, and its duration.

The first two prediction problems are only concerned with effects, if any, once a flare is observed. The third problem, that of forecasting the occurrence of the flares, can only be solved by monitoring the visible features of the sun and associated magnetic configurations. If flares could be predicted, longer range forecasts would be possible. Not known, except in a general way, are the characteristics on the visible surface that portend a flare. Although clues for predicting that a flare will occur are elusive, scientists can presently predict with great confidence that, given certain conditions, no disruptive event is likely to occur during the next three to five days.

In connection with the Space Forecasting System, AFCRL established this solar radio observatory in Hamilton, Mass., where solar radio emissions over several frequencies are continuously monitored and data routinely submitted to the AWS where forecasts of geomagnetic and other solar influences are made.

THE OBSERVATIONAL NETWORK: The heart of the Solar Forecasting System is the Air Force Global Weather Central Complex of UNIVAC 1108 computers at Offutt AFB in Omaha, Nebraska. Linked to these computers is a world-wide net of optical and radio observatories which provide real-time inputs from the radio and optically observed sun. Every observable feature of the sun is monitored by the system, together with changes in these features and their rate of change. In addition, observations from riometers, neutron monitors, magnetometers, and satellites are fed directly into the network. From these observations, the AWS-AFCRL system designers hope to define conditions that precede a burst of solar energy and the terrestrial effects that follow the burst.

In the future, the system observational net will be expanded to include a more comprehensive array of both solar and terrestrial monitoring stations. In addition to optical observations and centimeter radio observations, millimeter solar radiations could provide a key parameter for prediction. AFCRL operates such a telescope at its site in Waltham, Mass. (see Chapter IX). From millimeter wave emissions, it is possible to map temperature profiles just above the visible surface of the sun in the chromosphere. Activity regions on these radio maps of the sun seem to be highly correlated with bursts of radio, x-ray and particle emissions from the sun.

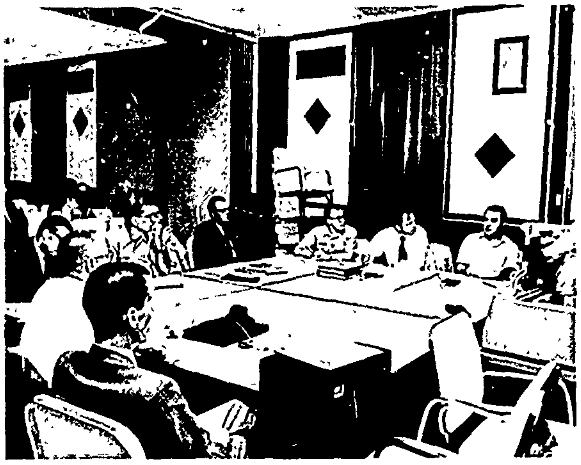
Future plans call for observing the UV and XUV emissions from the sun with satellite sensors. Almost no work has been done to date in correlating UV data with proton events, but such observations may prove most valuable. The ultimate system—but not the initial system that will become operational in 1970—will observe all solar emissions across a broad spectrum of radio and optical wavelengths.

PLANNING AND MANAGEMENT: The nature of the space forecasting enterprise requires close participation by specialists in a diversity of fields—energetic particles, ionospheric variability, solar physics, the earth's magnetosphere, atmospheric density, and so on. Specialists are drawn from several of the AFCRL laboratories.

Technical planning and systems evaluation are done through the Space Forecasting Workshop, which meets every two months to plan, review schedules, assign priorities, and to look into special problems. Established in 1966, the Workshop is composed of about 12 AFCRL and about six AWS representatives, plus interested representatives from other Government organizations, with the composition and number varying from meeting to meeting.

The Workshop has two primary tasks. The first is to review, advise and work out problems associated with the updating of the observational network of stations and the reduction of data. These particular problems have occupied most of the attention of the Workshop to date. The other task is to look at all available scientific knowledge that might be applied to improve the accuracy of predictions and extend the warning time.

Initially, system planning called for the use of existing observatories at various locations all over the world for solar data inputs. It was soon discovered that data from existing observatories are frequently inconsistent. Because the need for a common data base became a prime system requirement, AWS in 1967 decided that the system could not rely on data from existing observatories. Accordingly, plans were concluded by AWS to establish new observatories whose exclusive function would be to provide data for the system. These observatories would be located worldwide so as to give continuous coverage of the sun. Observing sites were selected in Tehran, Puerto Rico, Hawaii, and the Philippines. Others are planned but their exact locations are not yet determined.



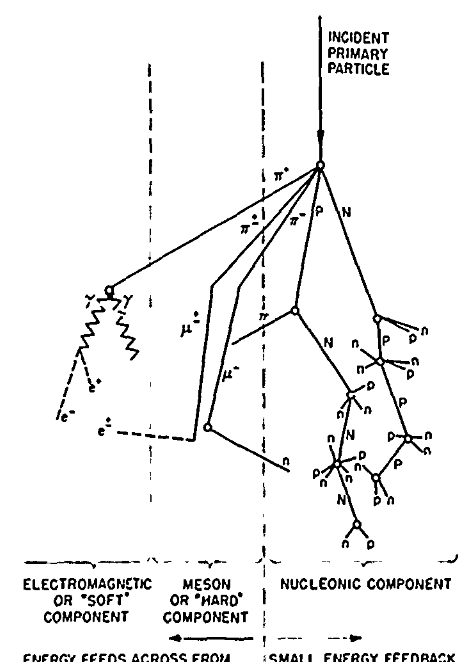
Several times a year the Space Forecasting Workshop, consisting of specialists in the atmospheric sciences from AFCRL and from the Air Weather Service, meet to review progress in the evolution of the Space Forecasting System.

SCIENTIFIC FALLOUT: The Space Forecasting System is evolving from knowledge uncovered by astronomy and the environmental sciences—the normal progression in which science precedes technology. But through the operation of the system, the environmental sciences will realize benefits in return. The standardization of solar and upper atmosphere data, and the techniques for correlating the data on a real-time, long-term, continuous basis, all promise to enhance our understanding of solar processes and the effects of these processes on the terrestrial environment. From the scientific standpoint, the system may prove in the long run to be more valuable than the huge international programs of scientific observations carried out during the International Geophysical Year in the 1950's and the International Quiet Sun Year in the 1960's.

COSMIC RAYS AND ENERGETIC PARTICLES

A charged particle in the upper atmosphere or space having energies in the BeV range can be assumed to be a cosmic ray that has originated from beyond the solar system. All others have their origin in the sun or are created by physical processes in the atmosphere. The energies, distributions, trajectories and effects of these particles are of concern to the Space Physics Laboratory.

Of particular interest to the Laboratory are the charged particles from the sun, particles that make up the benign solar wind through which the earth continuously moves, or that are accelerated to great energies by periodic solar explosions known as flares. The high energy protons emitted by these flares are a radiation hazard to men in space and to electronic systems aboard satellites. Both the less energetic solar wind particles and the high energy protons are captured by the earth's magnetic field to form the earth's radiation belts. But the high energy protons, when they are captured and channeled into the earth's upper atmosphere at the geomagnetic poles, can have profound effects on Air Force communications and surveillance systems. They can cause radio blackout over



High energy charged particles may originate either from deep space or from the sun. The most energetic of these are galactic cosmic rays from deep space. When they collide with an atmospheric molecule they may produce a cosmic ray shower of the type depicted in the lower diagram.

vast areas of the arctic. The development of the Space Forecasting System, discussed earlier, depends upon a thorough knowledge of the origination and effects of these particles.

SATELLITE STUDIES: During the reporting period, the Laboratory instrumented two satellites for energetic particle research. These were the OV1-13, launched from Vandenberg AFB on March 30, 1968, and the OV5-6, launched on May 23, 1969 from Cape Kennedy. The OV1-13 was designed to measure changes in the trapped radiation flux associated with solar flares. The satellite had an apogee of 9486 km and a perigee of 551 km. It carried seven particle detectors for measuring electron energy between one keV and ten MeV and to measure protons between one keV and 100 MeV.

The OV5-6 was a small, 25-pound, octahedron-shaped satellite measuring 11 inches on each side. It was placed in a highly elliptical orbit of about 12,000 by 75,000 km, an orbit that took it into and out of the magnetosphere. Instrumentation was designed to measure electrons, protons, and alpha particles and x-ray and gamma radiation.

One scientifically important result obtained under the satellite program was produced by the OV1-9 which was placed in orbit by the AFCRL cosmic ray group on December 11, 1966, during the previous reporting period. Instruments aboard this satellite measured for the first time evidence of the earth's electric field.

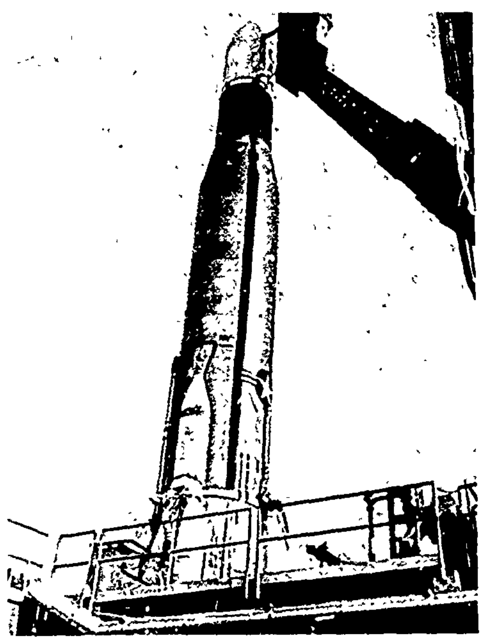
Geophysicists have assumed that the earth has an electric field as well as a magnetic field, but before the OV1-9, no one had ever measured it. Evidence for the electric field was obtained during a period of high solar and magnetic activity in late May 1967. The polar-orbiting satellite, with an apogee of

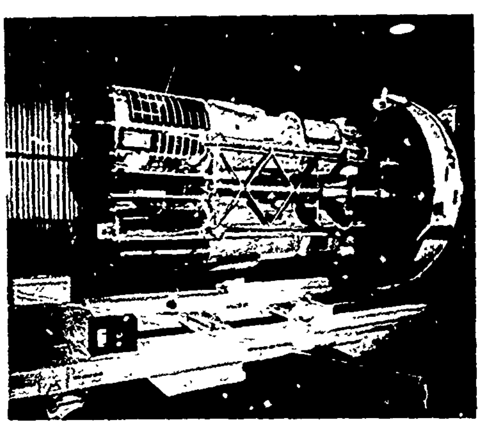
The OV5-6 was launched May 23, 1969 into a 9100 by 60,300 n.m. orbit. The 25-lb satellite was designed to measur X-radiation and particulate radiatio from the sun.

4800 km when it was over the magnetic North Pole, detected a concentrated stream of protons flowing upward from the atmosphere outward into space. The upward-moving protons were traveling at more than 60,000 km per second.

To show that the protons emanated from some point in the earth's atmosphere, AFCRL scientists carefully calculated angular distributions and energies. The average strength of the electric field was calculated to be 0.14 volts per meter.

The modulation of trapped proton fluxes in the outer Van Allen Belt during the same period of high solar activity was also studied by using data from the satellite OV1-9. Four days after the period of maximum solar activity, particle fluxes in the outer belt were ten times greater than the preflare values. This increase decayed slowly during a period of relatively stable magnetic activity so that about ten days later the flux had returned to the pre-





Launched from an Atlas rocket on March 30, 1968, was the OV1-13 and its sister satellite, OV1-14. The OV1-13 carried instruments for measuring protons between .01 and 100 MeV and electrons between .01 and 10 MeV.

flare value for particles with energies between 240 and 290 keV while the fluxes of particles with energies between 320 and 390 keV were still somewhat enhanced.

PROTON EVENT CLASSIFICATION: When researchers at AFCRL began to plan the Space Forecasting System (see above) in 1963, it was assumed that a historical record of solar activity, if properly analyzed and interpreted, could be used to correlate solar features with subsequent solar flares and high energy protons.

The assumption was not well founded. The problem was that observers had not reported solar flare and proton emissions in a disciplined, standardized manner. The absence of an objective method for reporting solar proton events led AFCRL astrophysicists to develop a uniform classification scheme. They presented this scheme to members of the Inter-Union Commission on Solar Terrestrial Physics in London in January of 1969. The favorable reaction by the Commission to the scheme indicates that it may be adopted internationally for uniform reporting.

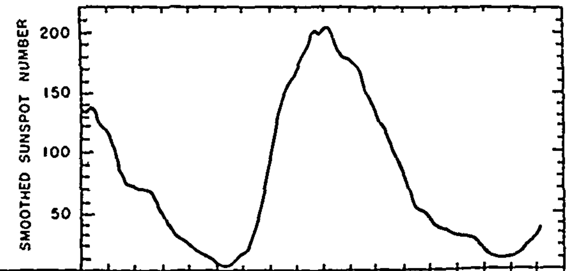
The classification method characterizes proton events by two interrelated parameters—flux and particle energy. Five levels of intensities are established. Each of the five intensity levels is separated from the preceding level by two orders of magnitude in terms of particle flux. For example, a proton event classified as an importance 1 event would have a particle flux exceeding the threshold of 0.3 particles (20 MeV or greater) per square centimeter per second, while a flux exceeding 30 such particles would be rated as an importance 2 event.

STATISTICAL PREDICTION OF FLARES: The larger the sunspot, the more likely it is that the sunspot will produce a solar flare. And if that sunspot produced a flare on one day, it is more likely that it will produce another flare the next day. By analyzing past records of sunspot sizes and their flariness, it is possible to derive a set of probability tables for predicting the likelihood that a particular sunspot will produce a flare of a given magnitude within the next 24-hour period. Using daily records of sunspots and flares during the period 1957 through 1964, the Laboratory has compiled such a set of probability tables.

During the period covered in the study, 13,143 sunspot groups were analyzed. (A particular sunspot group analyzed on seven days would constitute seven observations.) Each sunspot group was placed into one of ten size categories. The largest flare produced by a sunspot group on a particular day was recorded for each of the 13,143 cases.

By way of example of the kinds of data yielded by the tables, an average size sunspot group is observed, one covering an area of about 500 millionths of the visible solar hemisphere. What is the probability that a large flare (class 2 or greater) will occur on the next day? If this sunspot group produced no flares on the day of observation, there is a 10 percent probability that it will produce a flare of class 2 importance or greater on the next day. If the sunspot group produced a class 1 flare on one day, there is a 17 percent probability that it will produce a flare of class 2 or greater magnitude on the next day. Last, if a flare of class 2 magnitude or greater was produced on one day, there is a 24 percent probability that a flare of equal magnitude would occur again on the next day.

At the conclusion of the reporting period, AFCRL investigators were collecting historical statistical data on radio brightness temperature and magnetic classification of sunspot groups. When these two parameters are added to the present parameters of sunspot group size and flariness, the probability that a flare of a given magnitude will occur within 24 hours of a given observation can be stated with even greater assurance.



YEAR 19	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
SEA LEVEL (NEUTRON-MONITOR) EVENTS	1	0	0	0	0	0	0	2	0	0	1	5	2	0	0	0	0	1
PCA EVENTS	6*	4*	4*	0*	2*	0*	1	5	15	12	7	13	7	3	4	1	1	4

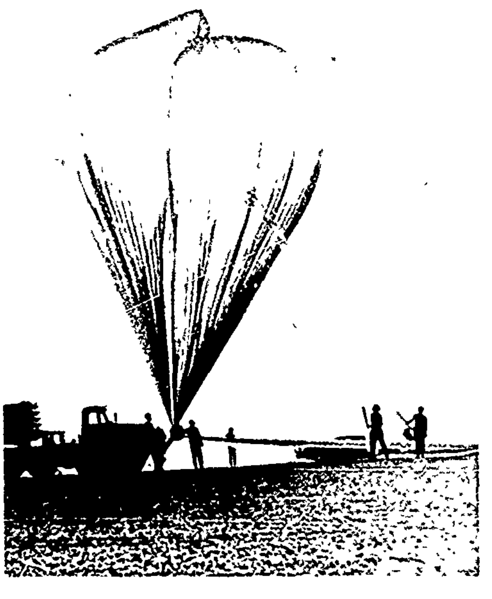
*IONOSONDE DATA, SOME EVENTS MAY HAVE BEEN MISSED

This plot shows the annual frequency of PCA events as a function of the 11-Year Solar Cycle.

COSMIC RAYS AT SST ALTITUDES: Some people feared, when planning for the supersonic transport first got underway, that cosmic rays penetrating the rarefied atmosphere at the 60,000- to 70,000-foot altitude of the SST would provide a radiation hazard to passengers and crews.

Fears subsequently abated, but there was still residual uncertainty. AFCRL has sent three instrumented balloons to supersonic flight levels to obtain quantitative data on the energies and fluxes of heavy cosmic ray nuclei. As a result of these tests, there appears to be negligible cause for concern.

The danger, it was thought, would arise primarily from heavy cosmic ray



This balloon, carrying an experiment to measure cosmic rays at altitudes up to 100,000 feet was launched from Ft. Churchill, Can., on July 2, 1968.

nuclei—atoms completely stripped of electrons and having masses as great as that of iron. When such a nucleus enters the atmosphere, a radiation dosage of several thousand rads is deposited along its entire trajectory. The encounter between the nucleus and a body cell can destroy the cell. Certain body cells are particularly vulnerable. Most sensitive are cells in the lens of the eye, reproductive cells, and hair follicles, the destruction of which results in the graying of the hair.

The three AFCRL balloons were sent to SST altitudes, and higher. The experimental packages consisted of a stack of about 100 emulsion plates, each measuring about 3 inches square. The three balloon flights averaged about 15 hours each. A total of 391 tracks were analyzed in the three emulsion blocks.

The analysis produced some rather smooth plots of atmospheric penetration as a function of atmospheric depth and particle energy. These plots show that from the top of the atmosphere to about 80,000 feet, the absorption of the cosmic ray energy is very rapid. The number of heavy nuclei encountered at the SST flight level of 60,000 to 70,000 feet was calculated to be only a few percent of the number encountered at the top of the atmosphere.

This strong atmospheric shielding, coupled with the additional shielding of the aircraft fuselage metal, serves to protect, almost completely, the passengers and crew from the ionizing radiation of heavy cosmic ray nuclei.

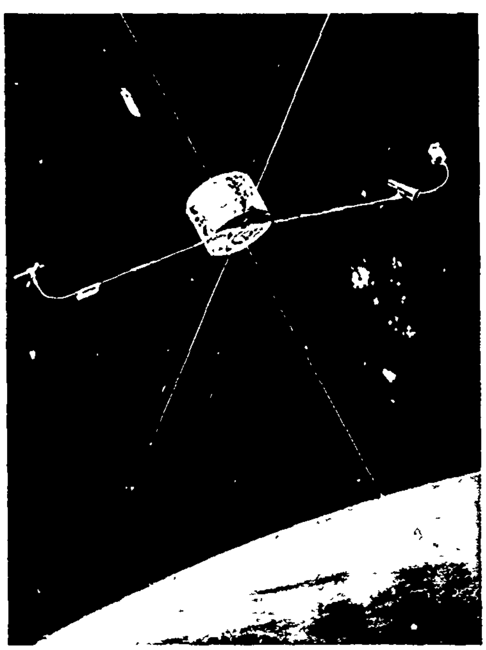
GEOMAGNETISM

The earth's magnetic field has a profound effect on the trajectories of the energetic particles discussed in the foregoing section. These particles in turn distort and alter the character of the magnetic field itself. The charged particles of the solar wind compress the magnetic field on the day side of the earth, while on the night side of the earth the magnetic field lines expand in a long, tail-like configuration extending out to 10 to 30 earth radii. This magnetic envelope surrounding the earth is known as the magnetosphere.

The 24-hour cycle of contraction and expansion of the magnetic field constitutes a huge dynamo that induces detectable currents in the earth's ionosphere and in the near earth movement. The most dramatic terrestrial effect in which the magnetosphere has a role is polar cap absorption. High energy solar protons are channeled by the earth's magnetic field to the geomagnetic poles to produce intense aurora, magnetic storms, and sudden ionospheric disturbances.

From this it can be seen that studies of the earth's magnetic field are an intrinsic part of the Space Forecasting Program (discussed earlier), the goal of which is to forecast all natural phenomena likely to affect Air Force operations.

ROCKET AND SATELLITE MEASUREMENTS: During the reporting period, AFCRL launched eight rockets specifically instrumented for measurements of the earth's magnetic field and magnetic field effects. All were launched from Ft. Churchill Research Range,



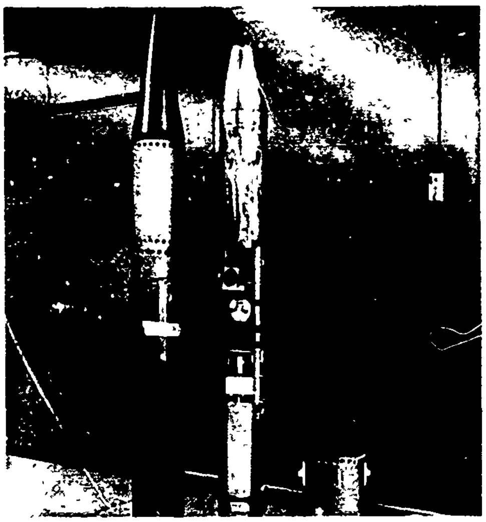
Scheduled for launch — probably in 1972 — is this Magnetic Storm Spacecraft (MSS). The satellite will have two pairs of E-field antennas, 40 ft tip to tip along the spin axis, and 100 ft transverse. A star sensor is used for orientation. Fluxgate and search coil magnetometers are mounted at the ends of the deployable 6-ft beams.

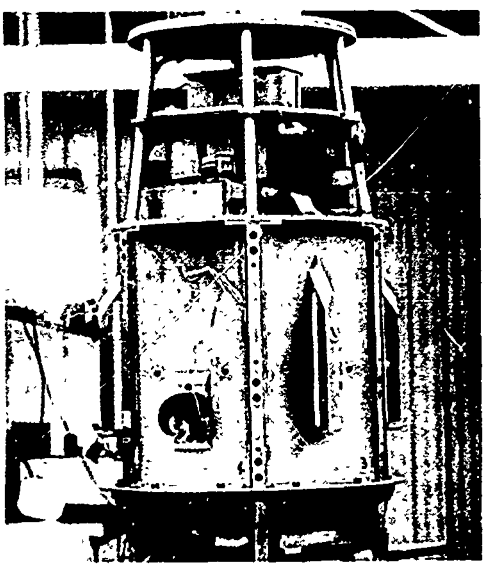
Canada, because magnetic effects are most marked in the polar regions. In addition to the six rockets, a triaxial fluxgate magnetometer was placed aboard the OV2-5 satellite launched on September 26, 1968. This instrument was designed to measure the vector (about 30,000 km) altitudes.

The six rockets launched by the group carried such instruments as cesium vapor magnetometers, three aspect magnetometers and electron-proton detectors. Purpose of the experiments was to measure particle energies, fluxes and pitch angles during magnetic disturbances and associated auroras. The group is particularly interested in the height, extent and intensity of the current system associated with magnetic disturbances.

Four of the eight rockets were launched in pairs on two different dates (November 9, 1968, and April 7, 1969) in order to establish the spatial and temporal characteristics of such disturbances. The rockets in each pair, launched within a space of a few minutes, covered different altitude regimes. Results of these experiments indicate that a magnetic disturbance in the auroral region may be a very localized event.

THEORETICAL MODELING: Rocket and satellite experimentation provide the essential inputs for theoretical studies involving the magnetic field. These studies take the form of models. Theoretical modeling is used to study the interaction of the varying solar wind with the geomagnetic field, to study the acceleration and precipitation of charged particles into the ionosphere at high latitudes, and to study the ionospheric and field-aligned currents. In addition, geomagnetic variations which are measured at the earth's surface are compared with theoretical predictions





The NIRO rocket payload (above) and the Javelin rocket payload (below) carried magnetic field and charged particle experiments. The rockets were launched during a magnetic auroral disturbance.

and are related to geophysical phenomena such as magnetic disturbances, polar cap absorption, sudden ionospheric disturbances, and so forth.

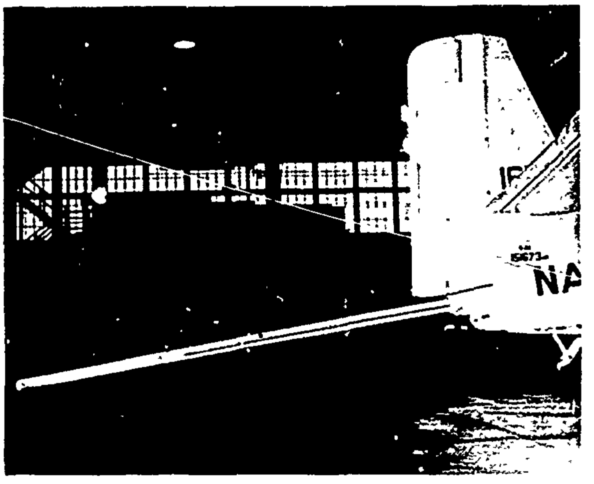
The Laboratory has completed a spherical harmonic analysis of the main geomagnetic field, the results of which have been incorporated in the International Geomagnetic Reference Field. The International Geomagnetic Reference Field is the culmination of several years of work under the guidance of the International Association of Geomagnetism and Aeronomy. Scientists from AFCRL, NASA, the U.S. Coast and Geodetic Survey, the Royal Greenwich Observatory in Great Britain, and IZMIRAN in the Soviet Union participated in this work. This newly established Reference Field now provides a stable base line or standard to which a variety of Air Force research efforts in geomagnetism may be referenced.

One way geomagnetic variations can be investigated is through a study of micropulsations. Micropulsations are short-period fluctuations of the geomagnetic field, observable at the earth's surface, and occurring in the frequency range 0.001 to 50 cycles per second. The most detailed study to date was based on the polarization characteristics of micropulsations and has demonstrated that at middle latitudes most of the energy observed at the earth's surface in the frequency range 0.001 to 0.05 cycles per second represents hydromagnetic wave activity originating in the magnetosphere. Larger samples of the data were reduced to tables of average field strengths in octave frequency bandwidths as a function of time, and the results correlated with geophysical and solar phenomena.

MAGNETIC SENSING OF GROUND TARGETS: The development of ultrasensitive magnetic field detectors for rocket and satellite instrumentation has led to a direct military fallout. These magnetic sensors can be carried aboard aircraft to detect trucks, tanks, guns, and other military hardware. The Laboratory is conducting an experimental program to develop such airborne detectors. The variations of the magnetic signatures among a group of similar trucks were measured, and signatures of vehicles were derived. Next, an airborne reconnaissance magnetometer system was tested to determine system noise, heading error, and general response to the terrain itself. Flight tests were made in areas of the United States having geological similarity to the terrain of Southeast Asia. These tests have been highly encouraging.

Magnetic field studies are being applied to meet another Air Force requirement, a requirement for more precise prediction of the future position and lifetimes of satellites. Variations in aerodynamic drag is the fundamental factor limiting the accuracy of orbit prediction. There is a high correlation between the drag experienced by a satellite and magnetic activity. Drag increases markedly, for example, during magnetic storms. The reason for this drag increase is that the solar particles that produce magnetic storms also heat the upper atmosphere, thus changing its density. If knowledge of magnetic activity on a world-wide basis is available, and if the level of magnetic activity is precisely correlated with densities of the extreme upper atmosphere, appropriate correlation factors can be incorporated into the satellite orbit computations.

This problem, together with the need to monitor magnetic activity for other purposes, led the Laboratory and the Air Weather Service to establish a network of stations all over the world to monitor magnetic activity. Stations in this net are in operation 24 hours a day and report magnetic activity every three hours to the AWS Solar Forecast Facility (now called Aerospace Environmental Support Center) in Colorado. Data obtained from these stations will be used by the Laboratory as a basis for formulating prediction criteria for magnetic activity. The prediction of such activity is one of the projected functions of the Space Forecasting System.



In a joint program with the Navy, Varian cesium magnetometers were carried in the external boom of this aircraft to determine the feasibility of detecting ferromagnetic targets on the ground.

ASTROPHYSICS

The astrophysicist attempts to explain the energies and forces of the sun and stars in terms of physical law. He may be an astronomer, a spectroscopist, a cosmologist, or a plasma physicist. Often he is a combination of all of these.

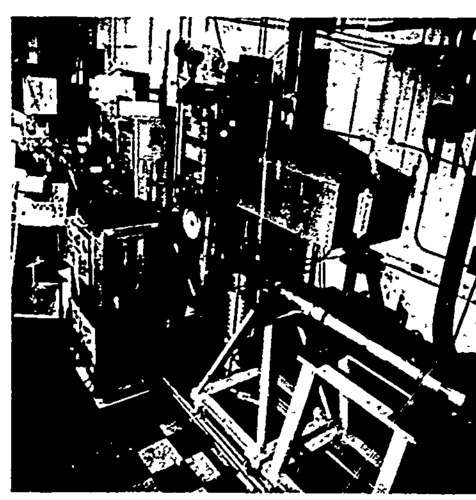
In the Space Physics Laboratory, he is most likely to be concerned with the physics of plasmas and with the interaction of plasmas (again charged particles) with magnetic fields. Most

A key to the interpretation of spectroscopic data is the known radiative lifetimes of various heated gases. Precise measurements of radiative lifetimes are being carried out in the Laboratory.

of the material of the universe is in the form of ionized gases, and the behavior of these gases is modified by magnetic fields. Ionized gases in turn modify the geometry of these fields. The interplay gives rise to electric fields, to electromagnetic energy, to current flow, and to much of the observable phenomena in space.

Ionized gas-magnetic field phenomena are sometimes difficult to observe and measure by ground, rocket, or satellite instrumentation. But the phenomena can often be approximated in laboratory experiments. One instrument for simulating the space environment phenomena is the shock tube. One of the shock tubes at AFCRL is 20 feet long and has a 2-inch square cross section. Temperatures between 3,000 and 15,000 degrees K can be obtained. This tube is used primarily to derive information on the emission spectra of various elements. By placing a known gas in the tube and subjecting this gas to known pressures and temperatures, a spectrogram is obtained which can help the spectroscopist decode the more complex solar spectral record.

In addition to spectral interpretation, other problems of interest to AFCRL astrophysicists are the solar wind and its interaction with the earth's geomagnetic field, stellar radio sources, and the mechanisms of solar flares. Not all of the astrophysics research is conducted with laboratory instrumentation. AFCRL astrophysicists until recently had made observations at the Cerro Tololo Inter-American Observatory in Chile. During the reporting period, laboratory personnel made several trips to the Chilean Observatory to make direct measurements of the composition of nebulae. This observatory is the subject of the following discussion.



To produce the extreme heat needed to measure the radiative properties of various elements, AFCRL produces a shock-heated homogeneous gas that travels down this 20-ft long shock tube.

THE CERRO TOLOLO OBSERVATORY: The Cerro Tololo Inter-American Observatory in Chile was dedicated in November 1967. Very quickly, astronomers realized that this observatory, from the standpoint of seeing, instrumentation, and geographic location, must be ranked as one of the world's most important observatories. Located 300 km north of Santiago at 30 degrees south latitude at an altitude of 2200 meters, the site has the best location of any observatory in the world for astronomical seeing. The clear, convection-free air permits about five hours of steady imaging almost nightly.

Soon after the opening, an AFCRL astronomer was accorded the honor of making the first observations using the largest of the five observing instruments. The reason for this honor is that in 1958, AFCRL and the Yerkes Observatory originated the Cerro Tololo Observatory project, and AFCRL provided the initial funds—the seed money—to get it started. The observatory is now managed by the Association of Universities for Research in Astronomy (AURA) and funded by the National Science Foundation.

With so many outstanding questions regarding so many Southern Hemisphere astronomical bodies, what then did the AFCRL astronomer give priority to for his first observations? He chose to observe the Great 30 Doradus Nebula in the Clouds of Magellan. This nebula, a fairly dense gas cloud, has no known counterpart in our galactic system. Its mass is estimated to be that of five million suns. It seems to have an intricate system of wisps and filaments indicating density fluctuations. The question to be resolved was whether or not the chemical composition of this unique object differed from that of bodies in our galaxy, such as the sun, for example.

For the study, the 36-inch Cerro Tololo telescope was used to obtain emission spectra. Photometrically calibrated spectrograms were interpreted with the aid of spectra of standard stars. Helium, oxygen, neon, and sulphur were studied in various ionic states. It was found that the composition of the Great 30 Doradus Nebula is essentially the same as that of stars belonging to population Type I.

Research at the Cerro Tololo Observatory by AFCRL astronomers was terminated as an active AFCRL program during the reporting period. A review showed it to have only indirect relevance to the Air Force mission.

FLOW OF IONIZED GASES: Two problems relating to the flow of ionized gases encountering obstacles—physical objects and magnetic fields—were investigated during the period.

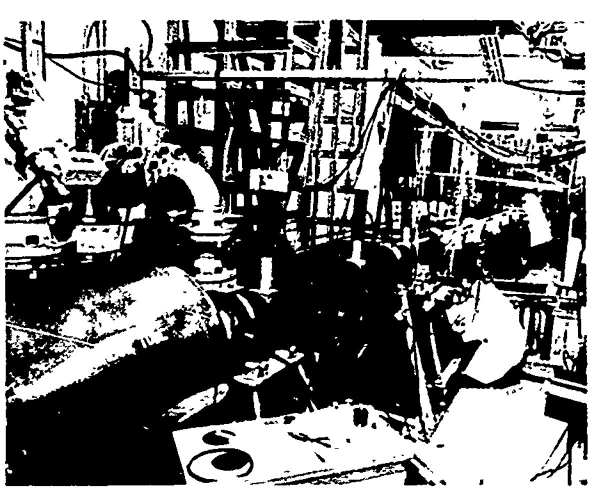
One measurement program was concerned with the boundary layer between a high velocity ionized gas and a smooth surface. A cross section of electron density of the gas can be measured very exactly with lasers. These measurements show under what conditions turbulence exists in the boundary layer.

These experiments have turned up two phenomena for future examination. One relates to the chemistry of a shock wave by a surface, in which case chemical equilibrium in a shocked gas can be reached much earlier along the surface than it can in the main stream of gas flow. The other was the discovery of an instability in the plasma stream that developed at the boundary between the ionizing shock and the driver. Technically, this instability is analogous to the Raleigh-Taylor instability where the role of gravity is substituted by the slowing down of the shock wave during the period of ionization.

Major emphasis has been the astrophysical modeling work. In one experiment a plasma is shot from a plasma gun at a magnetic dipole. This experiment models the flow of the solar wind over the earth's magnetosphere, creating the collisionless shock which occurs at the boundary between the magnetosphere and the solar wind. Scaling parameters are such that one could not hope to replicate the solar wind problem in the laboratory, but it should be possible to perform a very significant experiment in regard to the collisionless shock and the mechanism by which this shock converts its energy into heat.

Using spectroscopic techniques, measurements were made of the magnetic and electric field fluctuations in the bow shock. These data are then related to the theory of drift instabilities and help in understanding the generation and damping of waves in the plasma.

RADIATIVE LIFETIMES: The optical energies emitted by the sun and stars—infrared, visible and UV—derive from atomic and molecular properties known as oscillator strengths or transition probabilities and radiative lifetimes. These atomic properties are directly related to the atom's ability to absorb and to radiate electromagnetic radiation at a specific wavelength. Knowledge of these properties is necessary in determining the composition of radiating or emitting bodies. It is necessary, for example, to know how many atoms of a specific element are radiating at a particular frequency to produce the intensity being observed. Calculations of electron densities and electron temperatures in plasmas also depend on a knowledge of transition probabilities and radiative lifetimes.

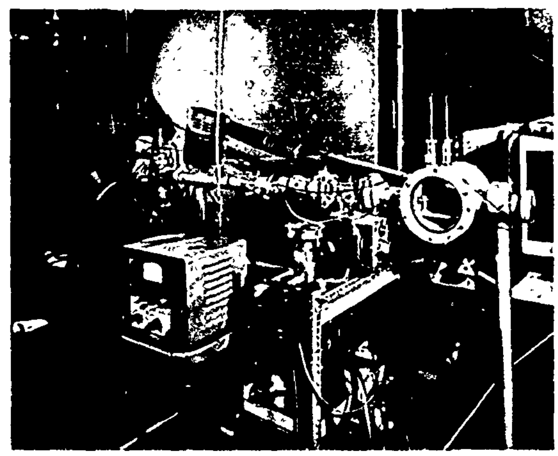


This 30-ft arc driven shock tube with a driver velocity of 60,000 ft per sec is used to study shock in low pressure gases.

For several years, AFCRL has used shock tubes to generate the high temperature, high density plasma for measuring oscillator strengths, and radiative lifetimes. During the reporting period, a new and more powerful technique was introduced. With this technique, a Van de Graaff accelerator is used to produce a beam of ions. By passing the ions through thin foil, they are further stripped and excited. The Van de Graaff accelerator used in the experiments is operated by AFCRL's Solid State Sciences Laboratory (see Chapter III). A special port was constructed for these radiative lifetime measurements.

The beam-foil technique marks a sizable quantum advance in the spectroscopy of ions. The technique can produce extreme degrees of ionization—ionization levels otherwise obtainable only in nuclear fusion reactions or in combinations of temperatures and densities found in stars. Furthermore, these levels can be reached at room temperature and under controlled conditions.

Work with the Van de Graaff beam-foil technique has resulted in the determination of radiative lifetimes for the upper excited states of 31 known and five new lines of singly to quintuply ionized oxygen. For seven of these lines it was possible also to determine their transition probabilities. Radiative lifetimes were determined in the same manner for 21 known and three new lines of singly to quadruply ionized nitrogen. These experimentally determined values have been used by the National Bureau of Standards as an absolute scale for verification of theoretically determined transition probabilities.



From this discharge tube of AFCRL's Van de Graaff generator is emitted a beam of ions. A source of such ions is essential to beam-foil spectroscopy which is a powerful new method for deriving absolute f-values.

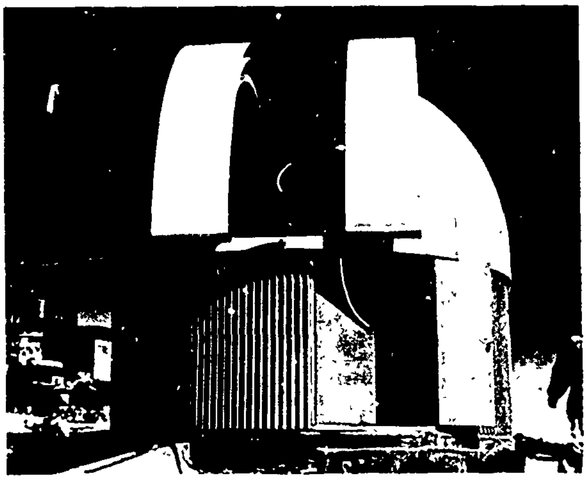
MOON, MARS AND METEORS

The programs discussed in this section were marked for termination as a result of a review of all AFCRL programs against relevance criteria. Lunar and planetary research is scheduled for termination at the end of Fiscal Year 1970. Research in meteor physics also will terminate at the end of Fiscal Year 1970. Both programs have a long history at AFCRL. Man's first knowledge of the concentrations of micrometeorites in space was gained through simple acoustic and wire grid detectors which AFCRL placed aboard the first U.S. satellites.

And long before Surveyor 3 had sent back to earth the first photos of a disturbed lunar soil, or the Apollo 11 and 12 astronauts stepped upon the moon, AFCRL scientists had derived what proved to be a fairly valid model of lunar surface material. They concluded that the surface would be covered by a very fine powder, that it would be relatively firm, and that the lunar powder would tend to adhere to all surfaces with which it came in contact.

During the present reporting period, however, lunar research concentrated on more general geological properties and possible internal thermal activity. Studies of the surface composition and geology of Mars also received increased emphasis. The Laboratory's meteor physics program consisted almost entirely of the collection of meteoric dust by rockets and the analysis of this material. Seven rockets were sent to altitudes above 75 km to collect meteoric dust during the 1967-1970 period—four from Natal, Brazil, two from Ft. Churchill, Canada, and one from the White Sands Missile Range in New Mexico.

For its studies of the moon and planets, AFCRL used two 24-inch telescopes. One was placed in operation in 1968 and is located in Hawaii atop Mauna Kea at an altitude of 13,700 feet. At

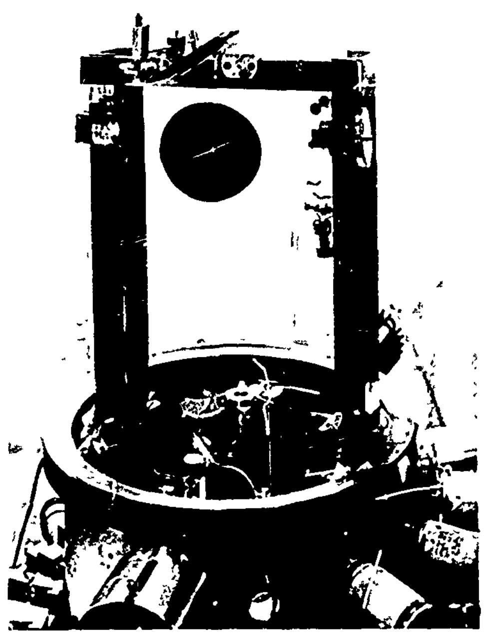


In 1968, AFCRL placed in operation this lunar observatory located in Hawaii atop Mauna Kea at an altitude of 13,700 ft.

about the time that this new telescope went into use, AFCRL's observatory in Concord, Massachusetts, was closed and its 24-inch telescope removed for reinstallation at the main AFCRL laboratory complex at L. G. Hanscom Field. In addition to ground observations, measurements were made with a 24-inch balloon-borne telescope. Eleven balloon flights were made during the period in which the telescope and associated infrared spectroscopic equipments were carried to altitudes of 70,000 feet or so for a clear infrared view of the moon above most of the earth's atmosphere.

NEW INSTRUMENT DEVELOPMENTS: During the course of the lunar observational program over the last three years, an infrared detection and sensing technique was developed by scientists which advanced significantly the state of the art in infrared remote sensing. This thermal enhancement technique has proved so effective that a separate development program was initiated to apply it to Air Force infrared reconnaissance. An airborne version was designed by the University of Michigan under an AFCRL contract. Flight tests of the equipment under a variety of weather conditions in June 1968 showed that it is fully workable. Flight data obtained on a real-time basis over various targets and under different conditions showed that this technique offers significant advantages in discriminating and displaying small thermal anomalies.

Another instrument, which like the infrared sensor was originally developed



A by-product of AFCRL's lunar research was a microbalance operating by light pressure, one of the most sensitive weight-measuring devices ever constructed. Thin horizontal tungsten wires extending from either side of the "W" shaped glass spring (black circle) support the microbalance. From the balance beam across the "W" the weight and counterweight are suspended on thin tungsten wires. When in operation the apparatus is enclosed in a high vacuum.

for lunar research but promises to have much broader application, is one that uses light pressure to measure weight. Laboratory scientists wanted to know how much weight is added to soil by the bombardment of soils by solar protons. Because no instrument was available for measuring such minute weight changes, the scientists developed an extremely delicate microbalance that can sense weight changes as small as 100 millionths of a gram and which can be restored to perfect balance again by the pressure of light. This is the first application of light pressure to weight measurement. The instrument was built for operation in a chamber evacuated to 10^{-11} torr. The microbalance itself rests on a taut tungsten wire with known torque properties. Light pressure is used to restore the balance to equilibrium when weight is added to one side of the balance. By measuring the amount of light pressure required to do this, a measurement of weight can be derived.

INTERNAL HEAT AND LUNAR RIVERS: Observations made during the April 3, 1968 lunar eclipse using the 24-inch telescope in Concord, Mass., strongly suggested to AFCRL scientists that the moon may be thermally active. The evidence supporting this view is a number of infrared images in the 8 to 14 micron range obtained with the infrared sensor noted in the preceding section. The question of whether the moon is a burnt out cinder or is still thermally active is a major question awaiting resolution.

During the brief hour or so of an eclipse when the earth shadows the moon, sensitive infrared instruments can record hundreds of hot spots on the moon. Most of these hot spots are simply reradiated solar heat that has been stored in the lunar surface materials. Examination of these hot spots during the eclipse, however, uncovered an interesting thermal anomaly in Mare Humorum in the southwestern portion of the lunar disk. This anomaly extended along a 100-mile line coinciding with a crustal fracture.

Temperatures along this fracture remained warm long after the other hot spots began to cool. There could be several explanations for this. The soil along the fault could have distinctive heat-absorbing properties, or the existence of a sharp ridge could expose the material longer and more directly to the sun. After analysis of these and other alternate explanations, the conclusion was reached that the thermal anomaly is most likely due to the slow leakage of hot gases to the surface along the fault zone. Confirmation must of course await future measurements.

Another study related to lunar water, the sinuous rills observed on the moon, are so suggestive of meandering river beds that many scientists have speculated that these rills are caused by surface erosion of water. The water, according to this hypothesis, would have its source in the lunar interior and could be released by a meteoritic impact. Once it reached the surface, evaporative cooling would cause a protective ice layer to form, protecting the water from further evaporation. In this way, an ice-covered river could be formed.

AFCRL scientists, after studying the behavior of water in a vacuum, considered this concept to be unlikely. They found that when water is introduced into a vacuum, there is an almost instantaneous explosion of boiling water. Although ice quickly forms after the boiling period, the initial explosion of the water when exposed to the lunar vacuum is so violent as to make im-

In AFCRL's Class 100 Laminar Flow Clean Room, samples of noctilucent cloud particles and other small aerosols collected in the upper atmosphere by rockets are brought for examination.

probable the formation of a long ice-covered river.

METEOR RESEARCH: The AFCRL meteor research program has been concerned almost exclusively with meteoric dust—particles of only a few microns—in the upper atmosphere. The research was conducted by rockets. These rockets, when they reached altitude, exposed a collecting surface. On descent, the surface was again sealed to prevent contamination by particles in the lower atmosphere.

Historically, contamination has been the primary problem in these rocket experiments. But during the past three years, techniques have been developed for overcoming background contamination. The AFCRL anti-contamination technique is one in which, after the rocket reaches altitude, a thin gold wire is melted and diffused over the collecting surface. In this way, those contaminants already on the surface are sealed off. Once the collection of particles has been made and while the rocket is still in flight, another thin gold film is diffused over the surface but from a different direction, which causes collected particles to show a shadow effect on the initial coating laid down earlier.

When the collection plate reaches the Laboratory for analysis, additional care

One of several electron microscopes at AFCRL is used to examine noctilucent cloud particles and micrometeorites. Below is an electron micrograph of noctilucent cloud particles.

must be taken. To guard against contamination during analysis, a special clean room was installed at AFCRL. In addition to other analytical instruments, the clean room contains two electron microscopes.

These techniques were used for four rockets launched from Natal, Brazil, in August 1968 to study meteoroids present in the Perseid meteor shower. One objective of these flights was to explore the latitude variation in meteor flux. These were the first rockets ever launched in the equatorial region. Another objective was to measure any increase in particle flux due to the meteor showers. Two rockets, one launched before the shower and one launched into the peak of the shower, were successful. The collection device opened on ascent at about 75 km and remained open for approximately two minutes. Curiously, the results indicated that the Perseid meteor shower contributed only minutely to the amount of micron-size particles in the upper atmosphere.

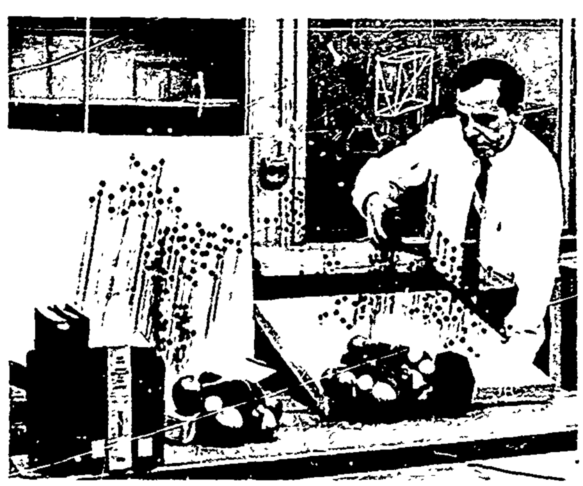
AFCRL supplied collection devices for three European Scientific Research Organization rockets flown into the Arietids and Zeta Perseids meteor showers in June 1968. The rockets were launched near Kiruna, Sweden. The results indicated a particle concentration of 10 to 15 particles per square centimeter, which is only slightly greater than concentrations normally present. This value corresponds to those obtained by the Laboratory's observations in Brazil.

ENERGETICS RESEARCH

Energetics research is the study of the phenomena which control energy conversion processes. Included in the scope of energetics research are studies on the various sources of energy as well as the techniques by which this energy is converted from one form to another. The main thrust of this program is the development of novel methods of electrical power generation and the improvement of known energy conversion processes.

The research is divided into four tasks. These tasks concentrate on the utilization of solar, chemical and thermal energy sources which are of major importance to electrical power generation. The tasks are: 1) *Quantum Processes:* The study of photoconducting and semiconducting materials for converting solar energy to electrical energy; 2) *Thermal Processes:* Analysis of techniques such as thermionic energy conversion for obtaining electrical power from sources of heat; 3) *Photochemistry:* Studies of the photosynthetic types of fuel cells, and 4) *Electrochemistry:* A study of electrodes and electrolytes for use in new batteries of high energy density.

QUANTUM PROCESSES: The silicon n-on-p solar cell used in operational



Energy conversion is essentially a problem in physical chemistry.

spacecraft is the most widely known example of a quantum process device. The active electronic component in these devices is doped silicon semiconducting material. AFCRL is searching for alternatives to the silicon cell which can be fabricated more economically and which have improved power-to-weight ratios.

Organic and metal-organic materials are promising alternatives for reducing the weight and cost of current silicon-cell hardware. The feasibility of the use of organic photoconductors and semiconductors as photovoltaic generators has been demonstrated, and prototype solar cells have been fabricated reproducibly in the laboratory. Presently, the efficiency of these cells is lower than that of the silicon cell by approximately two orders of magnitude, but amelioration of these performance levels is possible by several routes. Organic compounds can be altered by laboratory synthesis techniques, and the electronic behavior of a typical material can be changed by rearranging the molecular geometry or components. In addition, the bandwidth of optical response can be shifted by careful selection of substituent groups, and response of the device to a broader segment of the solar spectrum can be optimized. Low cost and light weight are possible because the desirable electrical properties can be incorporated into polymer films.

The research program has focused on several classes of organic compounds as the most promising candidates for components of solar cells or other electronic devices. Among these are substituted dibenzothiophenes, pyrazines, naphthaquinones and dicyanomethylene derivatives. Crystallographic work on several dicyanomethylene derivatives has shed some light on the mechanisms of the conduction process in molecular crystals and has provided insight on the nature of the correlation between the structure of organic crystals and their function as components of electronic devices.

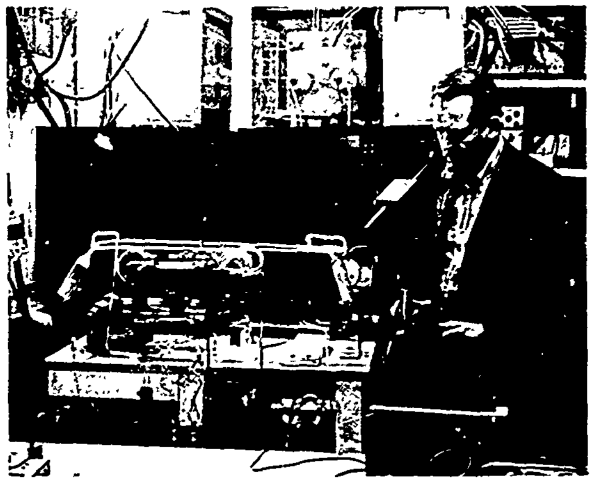
THERMAL PROCESSES: AFCRL research in thermal processes emphasizes two related areas. The first area deals with the thermionic energy converter in which a heat source provides the energy which is used to "boil off" electrons from a metal emitter. These electrons flow under vacuum to a metal collector electrode possessing a lower work function than the emitter. This electron flow creates a potential which can be tapped for useful work through an outside load. The second research area in the thermal processes task is a study of electrophoretic effects and their application for new sources of useful electrical power from any type of high-temperature gas flow. Measurements of this effort have been performed on a "racetrack" discharge tube and have been carried out for the electrophoretically induced gas flows in helium discharges. A theory is being developed to account for these results.

PHOTOCHEMISTRY: The high efficiency of the natural photosynthetic process has continually drawn the interest of research workers in this field of energy conversion. Chlorophyll, a major constituent of the chloroplast, the green matter in plants, has been shown to produce a photovoltaic effect in the presence of certain chemical compounds such as the quinones. The efficiency and magnitude of such an effect is subject to the influence of chemical species such as dimethylformamide and triethylamine. An analysis of the reactions between chlorophyll and electron donors or acceptors has shown that photopotentials and photocurrents are generated in these electron transfer systems and that these reactions are accompanied by an increase in acidity. A photoelectrochemical fuel cell based on these principles has been designed and is now undergoing engineering development.

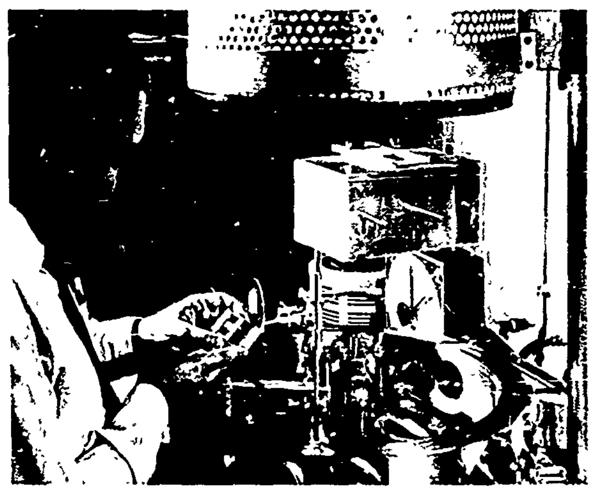
ELECTROCHEMISTRY: The AFCRL electrochemistry program is concerned with the problems of developing new battery types of improved specific capacity. Many organic solvents, for example, dimethylsulfoxide and dimenthylformamide, dissolve a wide range of electrolytes to give conducting solutions. Furthermore, they contain no replaceable hydrogen ions and, hence, are relatively inert to alkali metals which react strongly with solvents such as water and methanol. This stability makes possible the use of the alkali metals as high energetic electrodes in new batteries with energy densities possibly more than ten times that of the best batteries currently available. The research approach is to establish, by accurate physico-chemical measurements, the solvents which are most suitable for this type of battery. Among the parameters evaluated are the dielectric constant, dipolar relaxation times, and the viscosity. These parameters establish, to a good extent, the maximum conductance of the solvent and hence the maximum useful power density of a working battery incorporating that solvent.

In addition, two major areas of electrode processes are being studied: electrode reaction kinetics and equilibrium properties. The kinetics studies indicate the general potential usefulness of an electrode material in a working battery and the equilibrium studies are closely related to the interface between an electrode and the solution which surrounds it—the "electrical double layer."

The direct conversion of solar energy



Plasma electrophoresis is a possible energy conversion mechanism. As a part of such studies in thermionic energy conversion, the scientist here is measuring cathode temperature in a high-voltage DC discharge.



Organic photocells, such as the one being examined here, potentially offer much greater efficiency than the conventional silicon solar cells presently used for energy conversion. The thin-film organic photovoltaic cell was prepared by vacuum-sublimation techniq .es.

in a photo-electrochemical cell has been explored using thin film silver halide electrodes. A device incorporating this principle has been designed and tested and is now being examined for possible advanced development.

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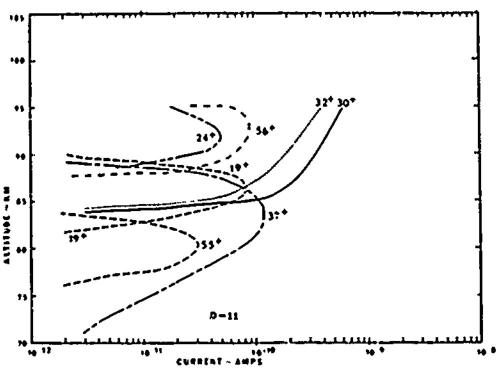
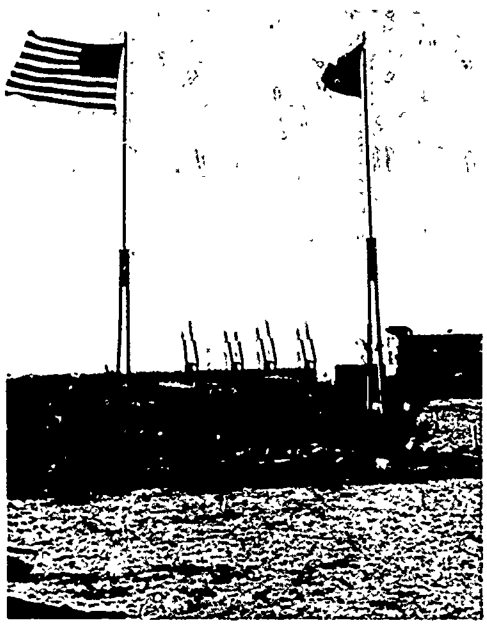
The rocket range at Natal, Brazil, is located on the geomagnetic equator, and for this reason is ideally situated for many upper atmospheric studies. The accompanying data, acquired over Natal by a rocket-borne mass spectrometer, shows positive ions as a function of altitude.





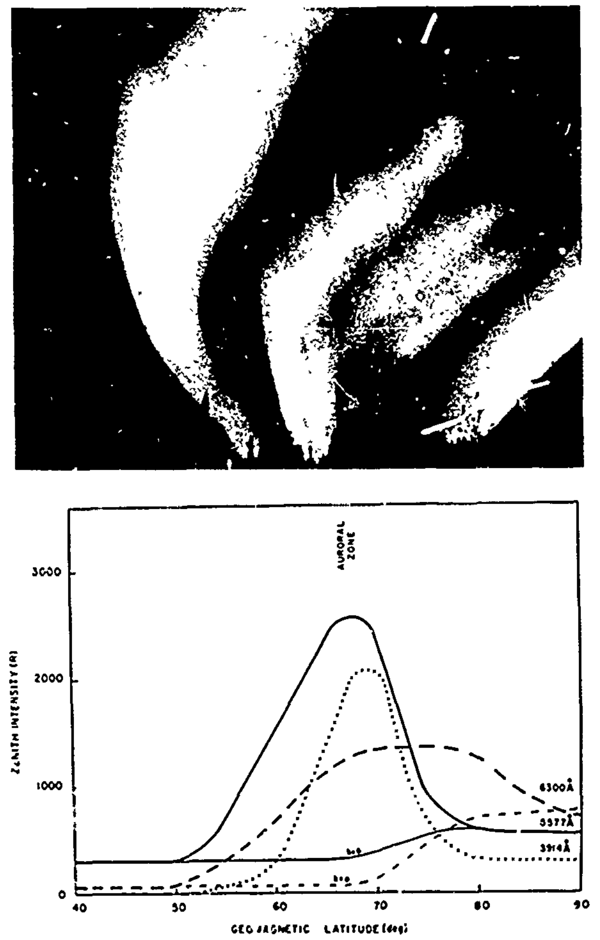
VIII Aeronomy Laboratory

Aeronomy is the study of the physical and chemical properties of the earth's upper atmosphere, a region that extends from the top of the stratosphere at about 50 km to interplanetary space at several thousand km. Although this region comprises only about a tenth of 1 percent of the earth's atmosphere, dramatic physical and chemical processes take place there that profoundly affect the earth's environment. Some of these processes are readily visible to the eye such as the brilliant auroral displays that predominate at the higher latitudes. Other processes are invisible but no less dramatic, such as the vast and dynamic processes of chemical and physical change set in motion and sustained by solar ultraviolet energy.

Much of the research conducted by the Aeronomy Laboratory is related to Air Force missions in surveillance, missile targeting accuracy, and long-range environmental prediction. In some cases the relevance is direct and readily apparent. For example, atmospheric nuclear tests prior to 1962 provide the basis for present operational planning and associated technologies. Although the nuclear test ban precludes further tests of nuclear effects, such effects are simulated in high energy proton bursts from the sun. The giant solar proton burst on November 2, 1969 was in effect such a nuclear burst, and this explains the Laboratory's large participation in the large Polar Cap Absorption (PCA) experiment in the Arctic.

Project Secede, a multi-agency program that began in 1968, is even more directly relevant. Project Secede involves the release of barium by rocket into the upper atmosphere, a technique pioneered by the Laboratory. Barium forms dense electron clouds creating strong electromagnetic interference, and as such has clear operational potential.

The general properties of the upper atmosphere of interest to the Laboratory are density, composition and physical and chemical processes. None of these properties can be considered in true isolation. Together they form a single vast interrelating system in the sense that an understanding of any one of the properties depends on an understanding of the other two. Density variation, for example, has its causal explanation in composition and in physical and chemical processes. The rate of these processes is in turn governed in part by density and composition in a kind of stabilizing feedback arrangement. Composition, which is essential to understanding physical and chemical processes, consists of many things—the number of atoms and molecules present at various altitude regimes, whether they are electrically charged or neutral, whether they are in the ground state or excited states and what the transition probabilities are in going from one state to another.

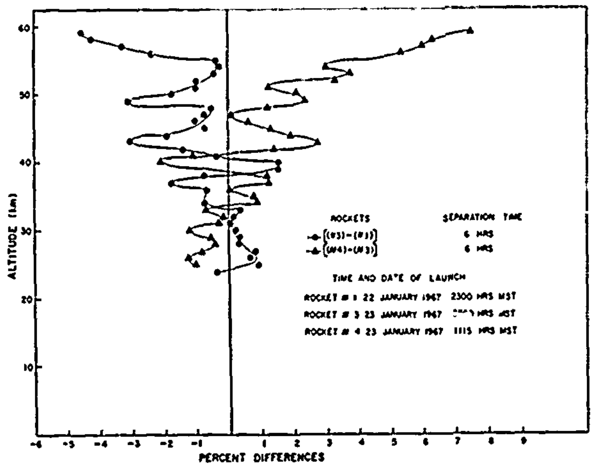


Auroral displays introduce noise in optical surveillance systems, masking targets of interest. The lower plot shows the relative intensities of auroral emissions at several wavelengths.

The primary source of energy for the dynamic interplay of these properties is solar ultraviolet. A large Laboratory program centers around the rocket and satellite measurement of solar UV. This program is supplemented by ultraviolet spectroscopic studies in the Laboratory. These spectroscopic measurements are designed to explain theoretically the physical mechanisms involved in UV emission and absorption.

The Aeronomy Laboratory is AFCRL's largest user of satellites and rockets. During the three years of this report, the Laboratory launched 106 rockets, placed instruments aboard three NASA satellites, and completely instrumented and launched three additional AFCRL satellites. Seldom does a rocket or satellite carry a single experiment. Thus, a particular vehicle may have instruments for measuring density, temperature, charged particles, composition, and so on. Space on a particular vehicle is often shared by AFCRL's Ionospheric Physics Laboratory (Chapter VI). The Aeronomy Laboratory receives much instrumentation and engineering help from the Aerospace Instrumentation Laboratory (Chapter XII) in the design and launch of its rocket experiments.

On June 13, 1970, the Climatology Branch of the Aerospace Instrumentation Laboratory was transferred without change in function to the Aeronomy Laboratory. This Branch is concerned with the analysis of meteorological extremes as these extremes might affect the design of military equipment and military operations.



Under disturbed conditions atmospheric density may vary in a wavelike pattern with altitude. The sine wave nature of these density variations is shown in these rocket measurements made at six-hour intervals.

DENSITY AND WINDS

Phenomena in the earth's atmosphere above the stratopause are perhaps the least amenable of all natural phenomena to quantitative prediction. The upper atmospheric physicist deals with a complex multi-dimensional matrix of closely interrelated and dynamically varying factors.

Through hydrostatic control considerations, atmospheric temperatures are derived through density measurements, with density itself being largely governed by temperature. Upper atmospheric winds are the product of diverse factors, of which density variation is but one. Winds are also the product of the interaction of neutral particles with charged particles whose movements come under the laws of hydromagnetics. And the rate of diffusion of atmospheric particles in time and space are derived from formulas that take into account the foregoing properties and others. All this is by way of emphasizing the essential unity of the problems in aeronomy.

Atmospheric density above 100 km or so is acutely sensitive to solar ultraviolet emissions and may expand outward by hundreds of km with increased solar activity. This outward swelling can set off a chain of causally related events. As the density increases at higher altitudes, particles in the radiation belts that dip down into the atmosphere near the geomagnetic poles collide more frequently with atmospheric particles. Radiation belt particles are lost, causing a decrease in the flux of particles in the radiation belts. At the same time, collisions with atmospheric particles induce increased auroral activity.

Increased auroral activity in turn interferes with the performance of optical sensors. And when the atmosphere expands outward by increased solar activity, sensor data are increasingly obscured in cases where satellite sensors must scan horizontally through a cross section of the atmosphere. One would like to know the range of the

The 23-inch diameter Cannonball satellite weighed 600 pounds and carried a tri-axial accelerometer to measure atmospheric densities.

variations of upper atmospheric density in order to define the limit of sensor performance. One would like to know the latitude and diurnal dependence of the variations. And one would like to know the causal factors which may lead to prediction. Quite apart from sensor and surveillance problems, density variations would play a more direct role in the operation of shuttle spacecraft that reenter on skip-glide paths into the atmosphere. And atmospheric drag is also a factor in the targeting of missiles.

The ability to take instruments directly into the environment with rockets and satellites has brought a revolutionary change in the picture of the upper atmosphere from that of 15 or 20 years ago. The picture is continuously being refined, and a major part of these refinements derived from AFCRL-acquired data.

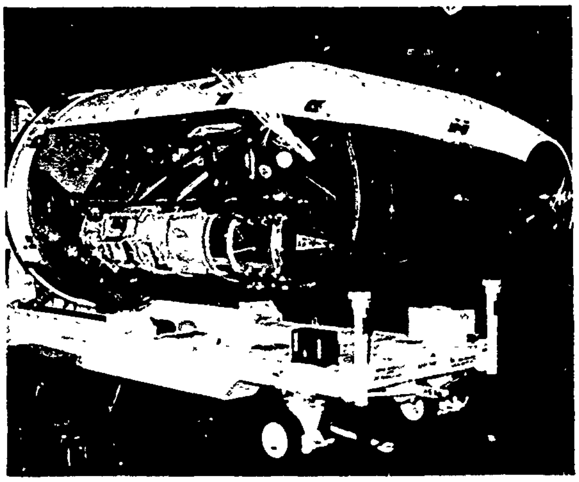
Values for atmospheric densities and other parameters are periodically compiled in "standard atmosphere models" which are essentially a set of values formally agreed upon by a committee of experts and based on the best available data at the time of compilation. The current compilation is the *U.S. Standard Atmosphere Supplements, 1966.* Scientists from this Laboratory serve as chairmen of the basic committees that analyze and update the standard models. AFCRL has contributed a large proportion of the data on which this standard atmosphere is based.

DENSITY MEASUREMENT BY SATELLITE: On July 11, 1968, AFCRL launched from a common booster two satellites instrumented for measuring upper atmosphere density. Both had unusually low perigees of about 120 km, taking them deep into the atmosphere. These two satellites were the SPADES satellite (OV1-15) and the Cannonball satellite (OV1-16).

The SPADES satellite was a more or less conventional vehicle. With this vehicle, atmospheric density was measured by ionization gauges, a triaxial accelerometer and by orbital decay measurement. The Cannonball satellite was unique. Never before had a satellite been constructed to obtain the heaviest possible vehicle in the smallest possible volume. The satellite weighed 600 pounds and was 23 inches in diameter. The weight-to-size ratio enabled it to remain in orbit for an extended period at unusually low altitudes. It had a planned lifetime of 30 days; its actual lifetime was 39 days.

The Cannonball satellite carried a triaxial accelerometer to measure atmospheric drag. And as with the SPADES satellite, orbital decay data were obtained by radar tracking. The radar data then served as inputs to a very accurate double precision numerical integration program. The large amount of data and the use of sliding fit-spans made it possible to obtain density values for successive perigee passes.

The atmospheric density data obtained from the Cannonball and SPADES satellites in some cases is in agreement with standard atmosphere model values, but in some cases were 10-20 percent below model values. Then density profiles obtained by SPADES at high latitudes showed a longitudinal variation and an unsuspected wave structure. For both satellites, the accelerometer drag values were in excellent agreement with the radar-detected orbital decay.

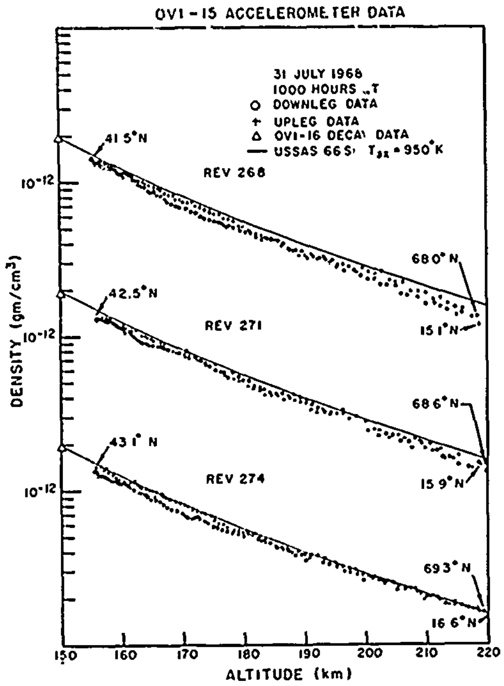


The Cannonball satellite, OV1-16, and the SPADES satellite, OV1-15, were packaged in the same nose cone and simultaneously placed in orbit July 11, 1968.

DENSITY MEASUREMENT BY ROCKETS: Atmospheric density up to 200 km can be measured by rockets. Many measurement techniques are used. Most frequently used is the falling sphere method in which small, heavy spheres of either 7 or 10 inches in diameter are ejected at altitude from the rocket. Accelerometers in the free-falling spheres measure drag from which density is deduced. Falling spheres are most effective at altitudes below 100 km.

For measuring densities at altitudes as high as 200 km, AFCRL has used a technique based on the Bremsstrahlung effect. An electron gun in the rocket sends out an electron beam. The electrons, interacting with atmospheric atoms, produce X-radiation that is detected by sensors in the rocket.

Another density measuring method, one used by AFCRL for many years, is that of releasing chemicals at high altitude. By simultaneously measuring the temperature and diffusion rate of persistence of the resultant luminous clouds, density can be determined. Rocket flights made on a summer night over Ft. Churchill, Canada, using this technique showed that at altitudes of 110, 130, 150 and 170 km, the density values



This chart, covering three different revolutions of the OV1-15, on July 31, 1968, shows close agreement between data and the *U.S. Standard Atmosphere Supplement* model indicated by the straight line. Agreement on other days and at other geographic regions was not so close.

are 1×10^{-10}, 1×10^{-11}, 2×10^{-12}, and 9×10^{-13} gm cm^{-3}, respectively. These values are all within 20 percent of those listed for the *U.S. Standard Atmosphere.*

Two density measurement techniques are sometimes employed simultaneously. The PCA expedition to Ft. Churchill in 1969, one of the largest scientific expeditions of its kind since the last nuclear test series in the Pacific in 1962, is described in Chapter VI. Many of the rocket measurements for this expedition were made by the Aeronomy Laboratory. Five Aeronomy Laboratory rockets were launched to obtain density data prior to and during the PCA event. These rockets carried 7-inch falling spheres and barium chemicals. Four of the five rockets were launched on November 2 during the event itself. Density and temperature profiles during the event showed large perturbations from normal conditions. Decreases in density of 40 to 50 percent from the *U.S. Standard Atmosphere* at 40 km were observed.

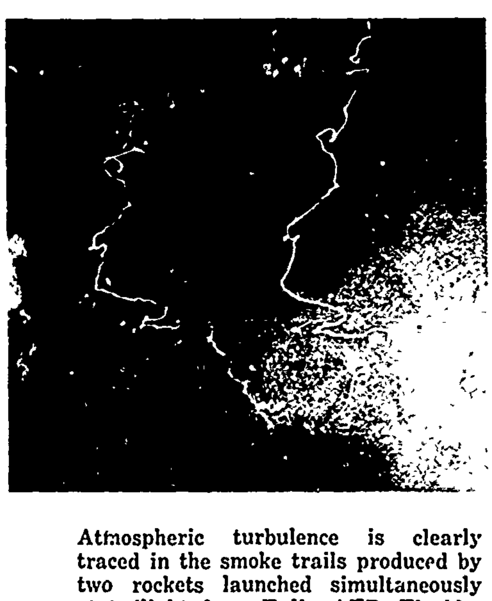
Combined falling sphere and chemical release (this time the chemical was NaLi) density measurements were made also at the Eglin Gulf Test Range in Florida during the March 7, 1970 solar eclipse. The purpose was to measure changes in atmospheric density when solar radiation is suddenly blocked. Data were obtained over an altitude range of 30 to 150 km, with a new 10-inch falling sphere (a 7-inch sphere has been routinely used in the past) providing exceptional results. The data showed a greater increase in density and decrease in temperature than had been anticipated for the short-term transient conditions of a total eclipse.

One of the more interesting results during the period was contained in the data from four flights from the White Sands Missile Range. The flights were made during a period when the region of the upper stratosphere and the lower mesosphere (40 to 50 km) was quite disturbed. At that time, White Sands was near the boundary of a low pressure system and a weak high pressure system. This, according to the AFCRL analysis, triggered the propagation of gravity waves. (Gravity waves can be considered to be wavelike variations in atmospheric density.) The wave structure showed a vertical wavelength of 60 km and an amplitude increasing with altitude. In other words, density gradients were shown to oscillate over a vertical span of 60 km.

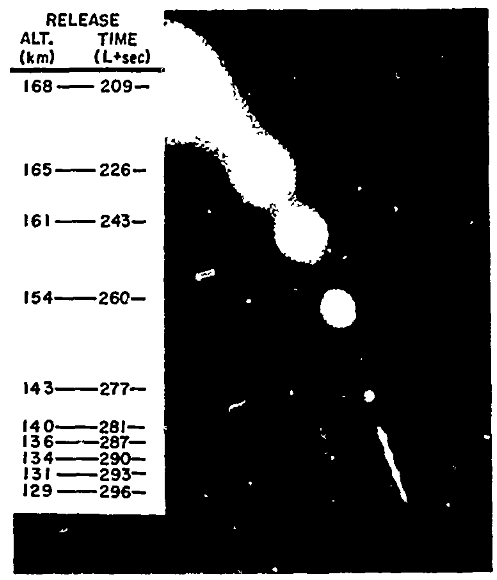
WINDS AND TURBULENCE: By injecting visible chemicals into the upper atmosphere, winds and turbulences can be observed directly. Chemicals can be released in long vertical trails of 100 km or so, or they can be released in intermittent puffs along the rocket trajectory. Chemical release techniques that AFCRL originated have now been widely adopted by researchers all over the world.

The technique has been most effectively employed in the measurement of the neutral wind field in the ionosphere and the interaction of the neutral wind field and the ionized particle motions. Charged particles are influenced both by magnetic fields and by the neutral particles with which they are associated.

From these chemical release measurements, AFCRL has defined the vertical wind profile of the ionospheric region. The profile shows a velocity wavelike structure with a wavelength of 9 km and an amplitude of 11 meters per second. Small-scale turbulence is almost completely absent.



Atmospheric turbulence is clearly traced in the smoke trails produced by two rockets launched simultaneously at twilight from Eglin AFB, Florida. The photograph was taken 2 minutes after rocket launch.



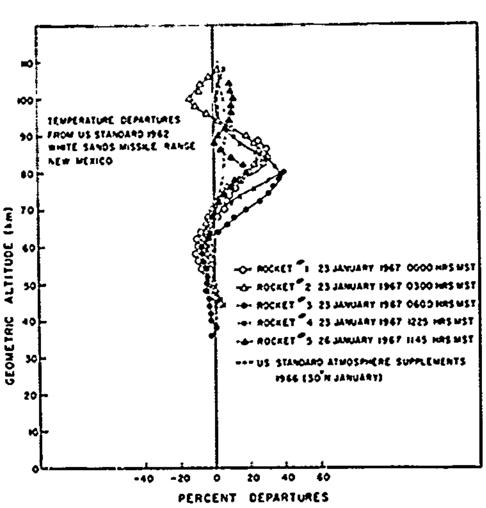
A technique for deriving three-dimensional motions in the upper atmosphere is by releasing chemicals in small puffs. The positions of these puffs are then determined from the ground by triangulation.

The study of the interaction of the neutral and ionized constituents has been extended to include space and the time variations of number density in a simplified ionospheric model. Transport effects due to a neutral wind which varies in altitude but is constant in time were shown to produce large perturbations of the evening E-region ionization profile, implying that a detailed understanding of ionospheric ionization profiles is impossible without taking transport effects into account.

An improved technique was developed for tracing three-dimensional motions in the upper atmosphere at twilight using the puffed release of diborane. Accurate triangulation on one of the small puffs revealed wave motions of ten meters per second amplitude and period 300 seconds at 112 km superposed on a long period background wind of 57 meters per second.

When a long chemical trail is released by a rocket, the trail soon forms itself into a helix. This means that the upper atmosphere winds at altitude intervals of 20 km or so reverse direction in a systematic clockwise direction with altitude. The Laboratory has constructed theoretical models to explain the helical pattern assumed by the trails.

Theoretical work was completed on new mathematical procedures to give helicity representations for the coordinate, momentum and angular momentum operators. Although motivated by considerations rooted in quantum mechanics, the main function of this work was to provide a new way of treating vector fields such as the velocity in fluid dynamics. Sharpened forms of the Helmholtz theorem have been obtained which can be used for the fluid dynamical problems of the upper atmosphere. New solutions of the fluid dynamical equations have been obtained which are expected to have applications. It has also been possible to set up the solution for the propagation of weak heated spherical pulses in gases to the point where only comparatively simple numerical work is needed to complete the work.



The *U.S. Standard Atmosphere* consists of formally agreed-upon values for atmospheric properties. Any particular observation of a property — in this case, temperatures as a function of altitude — will depart from these average values. The 1962 *U.S. Standard Atmosphere* for temperature is represented by the vertical center line. The 1966 *U.S. Standard Atmosphere Supplement* added additional models for different latitudes and seasons and one new model is represented by the broken line. Superimposed on these models are actual temperatures measured by five rockets over a three-day interval.

DIFFUSION AND TEMPERATURE MEASUREMENTS: Several chemical release experiments were conducted in 1968 and in 1969 at Ft. Churchill to measure atmospheric diffusion coefficients, density and temperature in the 120-180 km altitude region. Pairs of rockets, one in the morning, the other in the evening, were launched for comparison purposes. Diffusion coefficients were measured from the rate of growth of glow clouds. The coefficients cluster along a mean curve and have values of 4×10^7, 1.5×10^8, 3.5×10^8 and 6×10^8 $cm^2\ sec^{-1}$ at 120, 140, 160 and 180 km, respectively. However, deviations from the mean by as much as plus or minus 50 percent have been observed in morning-evening pairs, both in summer and winter. No great differences have been obtained in corresponding summer-winter and latitude pairs. Wavelike structures that appeared in some of the diffusion curves are unexplained and are being further investigated.

Aluminum oxide releases provide a means of measuring temperature. Temperatures were measured from the vibrational-rotational spectra of sunlit fluorescent aluminum oxide at twilight. The mean of the temperature measurements at Ft. Churchill in January and August 1968 can be represented by a linear increase in temperature from 400 degrees K at 130 km to 850 degrees K at 180 km. Summer and winter temperatures are quite similar. However, morning temperatures are roughly 100 degrees K higher than corresponding evening temperatures.

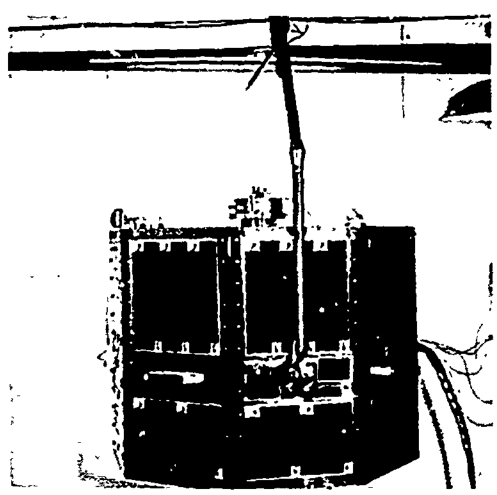
Total atmospheric densities have been obtained from the initial radius of luminous jets released during rocket flights and from the simultaneous measurement of temperature and diffusion rate of persistent luminous clouds. On a summer night over Ft. Churchill, the densities are 1×10^{-10}, 1×10^{-11}, 2×10^{-12}, and 9×10^{-13} gm cm^{-3} at 110, 130, 150 and 170 km, respectively. These values are all within 20 percent of those listed for the *U.S. Standard Atmosphere.*

ATMOSPHERIC COMPOSITION

The composition of the atmosphere, as would be expected, changes with altitude. A molecular or atomic species found in abundance at one altitude regime may exist only in trace amounts, if at all, at another.

The interactions between solar radiation and the atmosphere can only be defined if the composition is known. The formation of the lower part of the ionosphere is dependent almost entirely on the interaction of solar radiation with the neutral constituents. In this region, the minor neutral constituents play the major role of forming the stable ions and controlling the ion concentrations and distributions. At higher altitudes, above 100 km, gravitational separation of the atmospheric gases, photodissociation of molecular gases and solar heating of the atmosphere control the neutral distribution and thus also strongly influence the distribution of ion species.

The mass spectrometer is the primary instrument for measuring atmospheric composition. Small sophisticated mass spectrometers, designed by AFCRL, are carried aloft on rockets and satellites. During the three-year period covered by this report, 33 mass spectrometer experiments have been flown on three satellites and 27 rockets. Data have been gathered from 60 to 3500 km. The Laboratory's basic instrument is the rf quadrupole mass spectrometer. The research efforts have included positive and negative ion studies of the D and E regions of the ionosphere with cryopumped quadrupole mass spectrometers. These studies have included an investigation of the sunrise and sunset effects, daytime aurora, intense sporadic E layering, a mid-latitude winter anomaly, the PCA event of November 2, 1969, and a total solar eclipse. The satellite program has included study of the neutral and ion composition with experiments on two satellites (OV3-6 and OV1-15) and a study of the posi-



The OV3-6 satellite carried two mass spectrometers and three density gauges. The magnetometer boom and impedance probe antennas were deployed perpendicular to the sides of the satellite after launch.

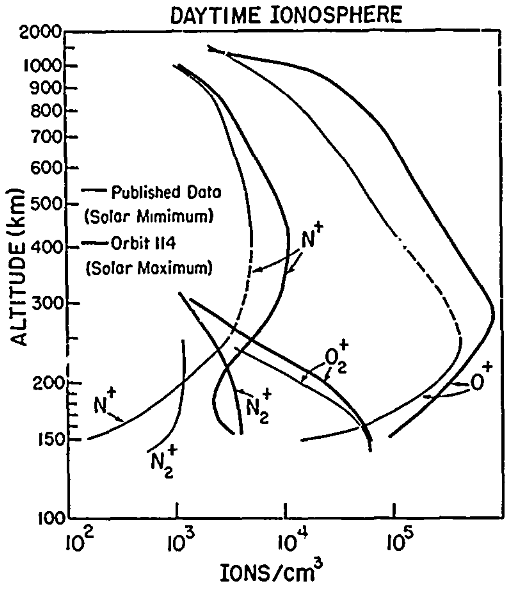
tive ion composition with a pair of instruments on the ISIS-I satellite.

Composition can also be measured by the chemical release technique. With this technique, the reaction of the chemical with an atmospheric molecular species produces a luminosity, and the intensity of the light is a product of the abundance of the species being measured.

SATELLITE MEASUREMENTS OF ATMOSPHERIC COMPOSITION: The OV3-6 satellite was built, instrumented, and launched by AFCRL. On December 4, 1967, it was placed into a circular polar orbit at 440 km. Instruments consisted of two mass spectrometers, three density gauges, and an impedance probe. The purpose of the satellite was to study the latitude and diurnal variations of the atmosphere and investigate the effects of solar disturbances on the neutral and ion composition and densities. Good experimental data were obtained from the satellite over the satellite's 15-month lifetime. The neutral composition studies of the O, N_2, and O_2 show much larger latitude variations than current atmospheric models predict. A bulge in the neutral density in the summer hemisphere was clearly evident. The ion species measured included O^+, N^+, NO^+, O_2^+, O^{++}, He^+, H^+, and Ne^+.

The OV1-15 (SPADES) satellite, noted earlier under the discussion of densities, was launched July 11, 1968 into a polar orbit with a perigee of 160 km and an apogee of 1820 km. The satellite was in orbit for 114 days. It was designed to measure the altitude, latitude, and diurnal variations of composition and density with special emphasis on the effects produced by solar and geomagnetic disturbances.

The apsidal precession of the orbit caused the perigee to move from the injection point through slightly more than 360 degrees; thus data were obtained at all latitudes and in both polar regions. The two mass spectrometer experiments were similar to the instruments aboard the OV3-6 satellite. They were designed to sit on a mass peak for a spin cycle (initially 10 rpm) and periodically scan the mass range from 1 to 46 amu to obtain the data on the minor constituents and background constituents. The masses studied in detail in the sit mode include O, N_2, O_2, A, and He, and in the ion mode N^+, O^+, N_2^+, and O_2^+. Other ion species measured in the scan mode include NO^+, O^{++}, He^+, and H^+. The data which have been obtained will be used to construct more accurate atmospheric models, and to correlate physical chemistry reactions to disturbances originating from the sun.



This plot compares oxygen and nitrogen ion concentrations during periods of minimum and maximum solar activity.

The ISIS-I satellite was launched January 29, 1969, into an elliptical orbit 580 by 3520 km. The satellite was designed to study the upper part of the ionosphere with various probes which can measure electron and ion temperatures and densities. A positive ion mass spectrometer experiment with two sensors was included on the satellite. Some ion composition results were obtained early in the lifetime of the satellite before a high voltage power supply failure occurred.

POSITIVE ION PROFILE: A typical profile based on many rocket observations of the positive ion composition between 60 and 130 km could be described as follows: From 60 km to the mesopause at about 85 km, the water cluster ions H_3O^+ and $H_5O_2^+$ are the principle ion species. Above 85 km, NO^+ becomes dominant with O_2^+ second in concentration.

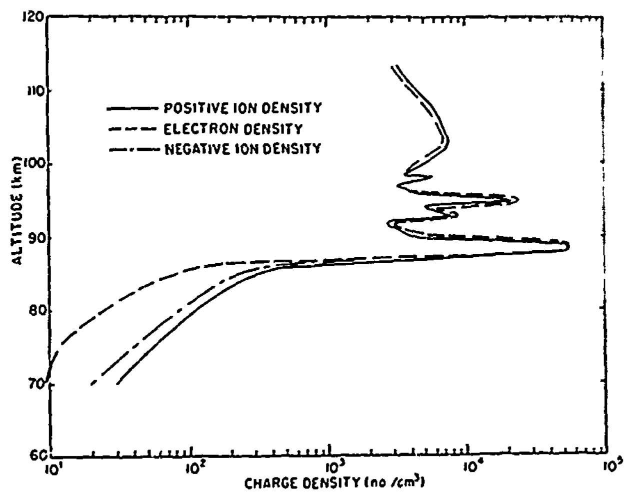
On all rocket flights to date, a metal ion layer has been found in the vicinity of 95 km with a width of about 10 km. This metal ion layer includes Fe, Mg, Ca, Al, Ni, Na, and Cr—the metals found in meteorites which vaporize at altitudes between 80 and 120 km. Normally, this metal ion layer makes up about 10 to 50 percent of the ionized constituents around 95 km. But during a meteor shower the percentage increases. In addition to the large and relatively stable layer of metal ions at 95 km, often narrow layers of Mg, Fe, and Si occur in the 100 to 140 km region.

In looking at the distributions and concentrations of the metallic ions, two questions arise: First, by what process is the metal element transformed from a neutral state to an ionized state? Second, what is the mechanism that causes the metal ions to concentrate in layers?

A theoretical model developed by the Laboratory indicates that the metal ions are created and maintained by a simple charge transfer process in which a neutral metal specie gives up an electron to either ionized nitric oxide or molecular oxygen (NO^+ or O_2^+). The nitric oxide and oxygen then become neutralized. A rocket flight during the annual Leonid meteor shower, when there is a great increase in metal species in the upper atmosphere, supports this thesis. During the shower there was a marked decrease in NO^+ and O_2^+ as their charges were transferred to the high influx of metal species.

The separation of metal ions of different types into different altitude strata depends on atmospheric transport processes, the ion chemistry, and the type of meteoroid. A stony type, for example, would vaporize at a higher altitude than an iron-type meteoroid.

The layering may be explained as an effect of ion motions produced by the ionospheric neutral wind field. The neutral wind induces a motion in the ions which, being constrained by the geomagnetic field, are forced to move vertically with a velocity component



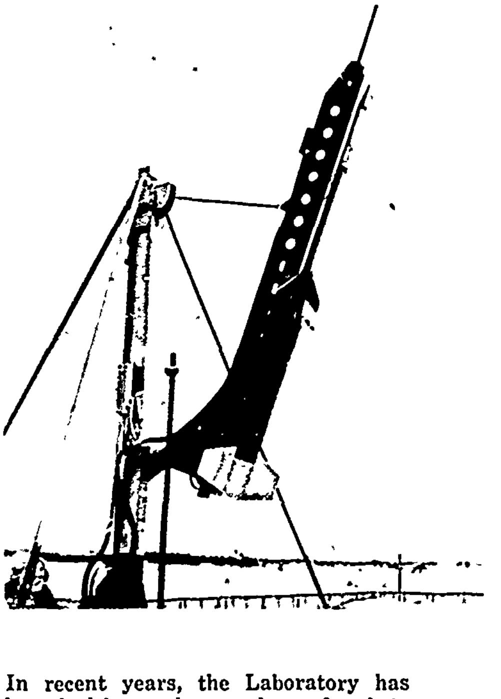
Above 80 km at midnight, positive ions and electrons — the charged particles that form the ionosphere — have approximately the same concentrations as a function of altitude.

perpendicular to the wind and the geomagnetic field. Since the neutral wind changes direction at altitude intervals of 10 to 15 km, alternate increases and decreases of the ion densities result and lead to thin layers. This may also be the mechanism which creates the dense ionized layers known as Sporadic E and suggests that intense Sporadic E is composed almost entirely of metallic ions.

NEGATIVE ION COMPOSITION: For many years, the negative ion composition of the D region was, in the absence of a measurement technique, speculated upon in the scientific literature. During 1967, AFCRL developed the first rocket-borne negative ion mass spectrometer. This instrument was flown in December 1967. The first experiment suffered from a low instrument sensitivity, but negative ion species were observed in the E region with masses 46 (NO_2^-), 16 (O^-), 32 (O_2^-), and 35 and 37 (chlorine isotopes, which may be simply contaminates).

Following similar inconclusive flights in 1968, the very first clear-cut measurements of D region negative ions were made on two rocket flights during August and October 1969. These measurements indicated that the negative ions were predominately located below 90 km where large cluster ions, tentatively identified as $NO_3^-\,(H_2O)_n$ with $n = 0$ to 5, were the major negative ions. Like the positive water cluster ions, the negative ion clusters also disappear above 90 km.

Two negative ion spectrometers were launched during the PCA event of November 2, 1969. Both were launched simultaneously with positive ion spectrometers. A positive ion and negative ion pair was launched near midnight on November 3 when the riometer absorption was 2.5 db. A similar pair was launched near midday on November 3 during a 6 db absorption, and finally a positive ion payload was fired near sunset on November 4 during a 1 db absorption. These measurements showed drastic changes in D region ion composition. Positive water cluster ions during the day, night and sunset, instead of being predominant up to 86 km, become the major ions only at lower altitudes below about 70 km. The major positive ions above 75 km were NO^+ and O_2^+. The negative ion composition results showed O^- as a major ion at night between 75 and 94 km while O_2^- and also CO_4^- became predominant during the daytime. These results have already given considerable insight into disturbed ionospheric chemistry and electromagnetic absorption



In recent years, the Laboratory has launched increasing numbers of rockets from Ft. Churchill, Canada. Payload aboard this rocket was designed to measure nitric oxide and atomic oxygen reactions.

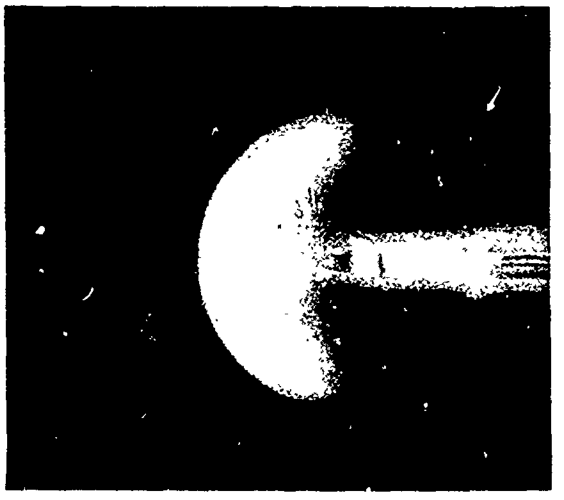
effects. The results are being used to derive a disturbed ionospheric model of the D and E regions.

OZONE AND ATOMIC OXYGEN: Two constitutents of the upper atmosphere of particular interest are oxygen and ozone. Oxygen most readily enters into interactions with solar energy and with other atmospheric constituents and much of the chemistry of the upper atmosphere involves oxygen in one way or another. Ozone is important because of its interaction with solar ultraviolet radiation and its role in maintaining the earth's heat balance.

Oxygen atom number density can be derived by the chemical release technique in which the chemical—nitric oxide—interacts with atmospheric oxygen to generate visible light. Oxygen atom number densities were measured in the 90 to 160 km altitude region in the predawn hours of August 20, 1968 over Ft. Churchill using the nitric oxide headglow. The observed density profile has a peak at 150 km. This profile is quite different from those determined by other techniques. In spite of the lack of agreement, the technique appears to be quite promising.

Prior to the August 20 flight, when AFCRL scientists first released nitric oxide from a rocket into the upper atmosphere, they were surprised to find that the resultant chemiluminescent glow was much brighter than expected. When nitric oxide reacts with atomic oxygen in the atmosphere, the photoemission rate exceeded by four to five orders of magnitude the expected rate of NO-O reactions.

A hypothesis for the brightness was suggested by two scientists outside AFCRL, and AFCRL undertook to test the hypothesis by simulation in the Arnold Engineering and Development Center's low density wind tunnel. These



To study nitric oxide and atomic oxygen reactions, tests were carried out at the Arnold Engineering and Development Center's Low Density Wind Tunnel. When supersonic air containing atomic oxygen collides with nitric oxide molecules, the reaction produces a glow.

tests supported the hypothesis which is this: During the adiabatic expansion of the nitric oxide, the nitric oxide temperature drops rapidly and the condensation point of the gas is passed. Therefore, part of the gas may form molecular clusters, and possibly, condensed particles. When a molecular cluster collides with an oxygen atom, an excited NO_2 is formed. The excited molecule subsequently radiates light. The formation of excited NO_2 is greatly facilitated in a cluster-atom encounter as compared to the molecule-atom encounter, because momentum is conserved, and the excited NO_2 does not fall apart during the collision. Hence, the higher probability of light emission in the cluster reaction.

During the March 7, 1970 solar eclipse, two rockets were launched from Eglin AFB, Florida, instrumented with ultraviolet and x-ray photometers to measure molecular oxygen and ozone distributions during and after the solar eclipse. As the solar radiation is obscured, high altitude ozone (50-80 km) increases. The magnitude of this increase as the result of the brief stoppage of solar energy provided valuable inputs to photochemical models of the mesosphere and may help to explain certain features of the ionosphere.

PHYSICAL AND CHEMICAL PROCESSES

Gross properties such as density and composition discussed in previous sections can be fully understood only when the physical and chemical processes that take place at the microscopic level are also understood. These processes modulate both density variations and composition.

Airglow, aurora and the atmospheric emissions and absorptions that affect the operation of Air Force optical sensors are produced directly by these chemical and physical processes. The ionosphere is another direct product. One research goal is to mitigate (by predicting intensity levels) the effects of these reaction products on Air Force operations. In the course of these studies, unsuspected effects may be uncovered that could lead to an operational advantage. Three other AFCRL Laboratories (Optical Physics, Ionospheric Physics, and Space Physics) also conduct research in upper atmosphere chemistry, but on a more limited and specialized basis.

Essentially, research on the physical and chemical processes in the upper atmosphere is concerned with the rate of chemical reactions and with the mechanisms whereby an atom or a molecule absorbs and emits radiation. A given reaction product (for instance, the process whereby a single nitrogen atom is set free) can be achieved by several pathways. One thing that the researcher wants to know is the relative efficiency of the many possible processes. And this in turn takes him into considerations of the energy states of various atoms and molecules, their relative concentrations, transition probabilities, cross sections, and so on.

The primary instrument for these studies is the spectrograph, of which the Laboratory has many. Most of AFCRL's spectrographic studies are confined to the vacuum ultraviolet region, and this research has yielded new knowledge of physical processes that has, over the years, become an enduring part of the literature on the subject.

In the discussion immediately below, the emphasis is on certain gross effects of Air Force interest that are the products of physical and chemical processes. Later, physical and chemical processes as such are discussed.

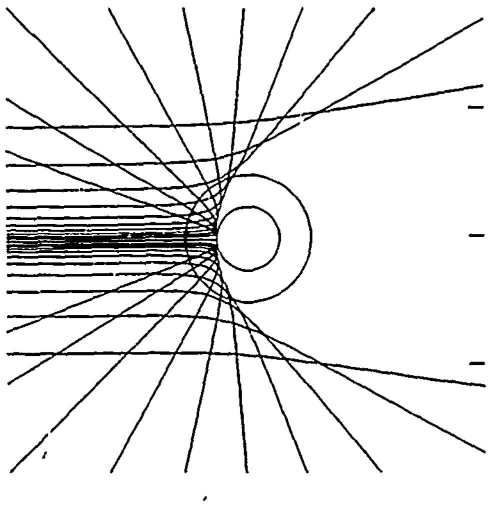
ARTIFICIAL IONOSPHERES: Many reactions produce free electrons and positive ions and in this way the ionosphere is produced. By releasing certain chemicals in the upper atmosphere, dense artificial ionospheres can be produced in localized regions. Project Secede, noted in the introductory section, is based on this technique. Because dense electron clouds interfere with radar detection and surveillance, the technique has an important Air Force operational application.

The research involves barium vapor releases by rocket at altitudes of 100 to 250 km. At these heights barium rapidly ionizes, and at twilight, the resonance light scatter of both the neutral and ion clouds is clearly visible. At the same time, radio frequency scatter of the ion cloud can be observed by radar. AFCRL has defined payload composition and altitude regions for achieving maximum electron densities by means of barium release techniques.

Barium vapor is generated by a thermite reaction between copper oxide and barium metal ignited in a rocket-borne canister. At the instant of release, a mixture of ground-state neutral barium vapor, hot liquid droplets and particulate by-products is ejected. A small fraction of thermally produced ions is also present but becomes invisible during initial expansion of the vapor. The droplets rapidly evaporate as they travel radially from the release point, and within one second of release, emission lines appear which indicate the production of metastable levels of neutral barium and of barium ions. It is believed that the fast production of ions is due to photoionization out of the metastable levels, for which light of wavelength 3260 angstroms is needed, which is some 50 times more intense in the solar spectrum than the light required for photoionization out of the ground state.

Ion clouds are detected at radio frequencies. Four clouds released at 106, 108, 110 and 120 km were detected by ionosonde and coherent radar. Radio frequency dropout times for the 106 km release of about 10 kilograms of barium were one minute after release at 15 MHz and five minutes at 9 MHz. For the 108 km release, dropout times were 90 seconds for 20 MHz, 120 seconds for 15 MHz, and seven minutes for 9 MHz. It has been found that the altitude dependence of the ionization time constant is due to the competing process of oxidation of the metastable barium atoms by atmospheric molecular oxygen.

After the barium vapor has been converted into ion and oxide clouds, the two species drift separately under the influences of neutral winds and electric and magnetic fields. A faint "bridge" is observed to form between the ion and neutral clouds. It is believed that this bridge is formed by late-time ionization in the barium oxide cloud in a three-step process where the BaO must first be dissociated by sunlight of wavelength 2640 angstroms. Spectra show that the oxide cloud always contains a small amount of neutral barium, both excited and ground state.



Radio frequency waves impinging on a barium cloud are scattered in the manner depicted in this computer-generated ray tracing.

AIRGLOW: Airglow is one of several sources of natural background "noise" that must be taken into account by the designers of optical sensors. Other sources are the aurora, zodiacal light, stellar emissions and reflected light from the moon and planets. Airglow is readily visible on dark, moonless nights, sharply silhouetting trees and hills against the background of the faintly luminous sky.

The most pronounced airglow emissions occur at 5577 angstroms and most of the airglow research of the Laboratory during the three years of this report was concentrated on this green line. Two of several airglow studies will be reported here.

One of these concerns measurements made from a rocket launched at Natal, Brazil, on November 15, 1968 to obtain a profile of daytime emissions—dayglow—over an altitude range extending from 70 to 220 km. The Natal rocket experiments produced the first sharp profile of equatorial dayglow that has been obtained to date. The most pronounced airglow emissions—both dayglow and nightglow—occur at an altitude centered at about 95 km. Such emissions result from collisional mechanisms involving atomic oxygen. Dayglow emissions were also observed in the 110-150 km range and are due to the photo-dissociation of O_2. At altitudes of 170 and 200 km, where two additional peaks were observed, airglow is produced by the process of dissociative recombination of O_2^+ and excitation by photoelectrons.

The other study was a statistical correlation analysis to determine to what extent solar phenomena affect 5577 angstrom emissions. The data of 1129 nights over a period of 80 months from 1956 to 1963 obtained at AFCRL's Sacramento Peak Observatory in New Mexico were used to determine whether a correlation existed between the daily and monthly 5577 angstrom intensities and both the Zurich relative sunspot number and the 10.7 cm solar radio flux. It was found that 1) a statistically significant positive correlation exists between monthly and nightly averages of green line activity and both indices of solar activity, 2) the 10.7 cm flux shows a somewhat higher correlation with green line activity than is shown by the Zurich relative sunspot number, and 3) the degree of correlation is dependent on the phase of the solar cycle.

This photo taken by the light of airglow at Thule, Greenland, required a four-minute exposure at f3.5.

REACTIONS AND THEIR PRODUCTS: Nitrogen and oxygen in their many forms and combinations enter into most upper atmosphere reactions. The measurement problem is one of defining reaction mechanisms and the internal energy content of the products of such reactions. Here is a description of one fairly typical study:

The oxygen ion, O^+, is one of the most common of the charged particles that make up the ionosphere. Now if it were possible to isolate just one of these oxygen ions, it would be seen that it undergoes a kaleidoscopic pattern of transfigurations. It may collide with another atom or molecule to become a part of a molecular system, or it may simply pick up a random free electron to become a neutral oxygen atom, or it may collide with a neutral molecule, pick up an electron, and from this encounter emerge as a neutral atom.

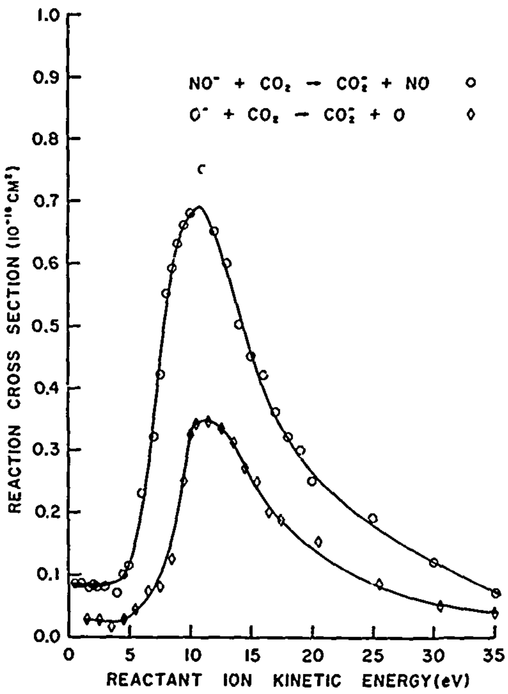
Two reactions, both involving O^+, have been widely studied by the Laboratory. These are $O^+ + O_2 \rightarrow O_2^+ + O$ and $O^+ + NO \rightarrow NO^+ + O$. Both reactions, in principle, may proceed through electron transfer (in which the original ion simply picks up an electron from the molecule), or by a more complex mechanism in which the neutral atom that emerges free from molecular constraint could be any one of the oxygen atoms in either of the reacting groups. Until recently, no one had any quantitative data on which of the two processes occurred more often.

By using isotopically labeled oxygen ions, AFCRL has shown that in both the oxygen molecule or the nitric oxide molecule cases, the reactions occur largely by simple electron transfer rather than by the more complex ion-molecule reaction.

In the simple electron transfer process, it was found that the probability of reaction (the cross section) is independent of the O^+ kinetic energy in the range from 0.7 to 20 eV. When the more complex ion-molecule reaction takes place, it occurs at the low end of this energy range. At energies of about 1.0 eV, the probability that the neutral oxygen atom is produced by the ion-molecule mechanism is about 20 percent of the probability of its production by the electron transfer process. Last, it was found that the ion-molecule reaction cross section decreases with increasing O^+ kinetic energy.

Among other processes for which the Laboratory has obtained rate coefficients are the following:

$O^+ + N_2 \rightarrow NO^+ + N$
$O^+ + CO_2 \rightarrow O_2^+ + CO$
$N^+ + O_2 \rightarrow NO^+ + O$
$N^+ + CO_2 \rightarrow CO_2^+ + N$
$N^+ + NO \rightarrow NO^+ + N$
$O^- + O_2 \rightarrow O_2^- + O$
$O^- + N_2O \rightarrow NO^- + NO$
$NO^- + O_2 \rightarrow O_2^- + NO$
$NO^- + N_2O \rightarrow N_2O^- + NO$
$O_2^- + CO_2 \rightarrow CO_3^- + O$
$H^- + O_2 \rightarrow O_2^- + H$

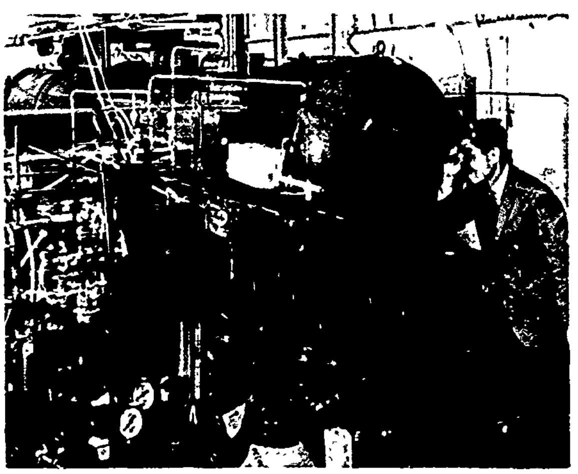


Considerable Laboratory effort is concentrated on the study of reactions taking place among the various atmospheric constituents. Typical reaction cross section for CO_2 with NO^- and O^- is shown.

VACUUM ULTRAVIOLET SPECTROSCOPY: The ultraviolet spectroscopist seeks insight into the fundamental energy mechanisms of particular molecules. These are the mechanisms that produce the emission and absorption lines that the spectroscopist uses to identify a particular gas species. The high resolution spectrographs used by the Aeronomy Laboratory bring into focus many new spectral lines. The spectroscopist then attempts to explain the energy mechanism that produces each of these lines.

The energy mechanisms that produce the full spectrum of a particular gas are so many and complex as to elude full comprehension. For absorption lines, the mechanism is one in which the atom or molecule is raised from a lower energy state to one of several possible higher energy states. For the emission lines, the mechanism is reversed. The molecule falls to a lower energy level and in doing so emits radiation. The particular specie under study will generate a great number of lines which the spectroscopist groups together into band systems.

During the reporting period, Laboratory spectroscopists produced the definitive study to date of the argon absorption spectra. The study covers the UV region of 780 to 1080 angstroms. Within this region, the AFCRL spectroscopists observed nine discrete band systems for the argon molecule, some of these encompassing 30 or more individual lines. They analyzed the particular electronic transitions from the ground state that resulted in each of these band systems, and suggested the energy mechanisms for each. This energy is not completely the result of electronic excitation. For example, six vibration levels for argon molecules in the ground state were identified, as well as lines produced by the splitting of the diatomic argon molecule into separate atoms. (Molecular vibrations are ordinarily associated with infrared spectroscopy, but can have a role in UV absorption and emission as well.)



This is one of several large vacuum ultraviolet spectrographs operated by the Laboratory in studies of the fundamental energy mechanisms of molecules.

Measurements of the argon molecule were made at the partial pressure of less than 0.01 torr with the absorption cell cooled with liquid nitrogen. For analytical purposes, however, measurements were also made over a range of temperatures and pressures. The equipment used for the measurements was a 6.65 meter normal-incidence vacuum spectrograph.

A detailed analysis of the rotational structure for 29 bands of N_2 in the vacuum UV region was completed during the reporting period. Improved absorption and photo-ionization cross sections for N_2 also have been obtained. These data are a needed improvement over former values both in accuracy and resolution. Additional information has been obtained on thermal and recombination emissions at visible wavelengths for nitrogen dioxide (NO_2).

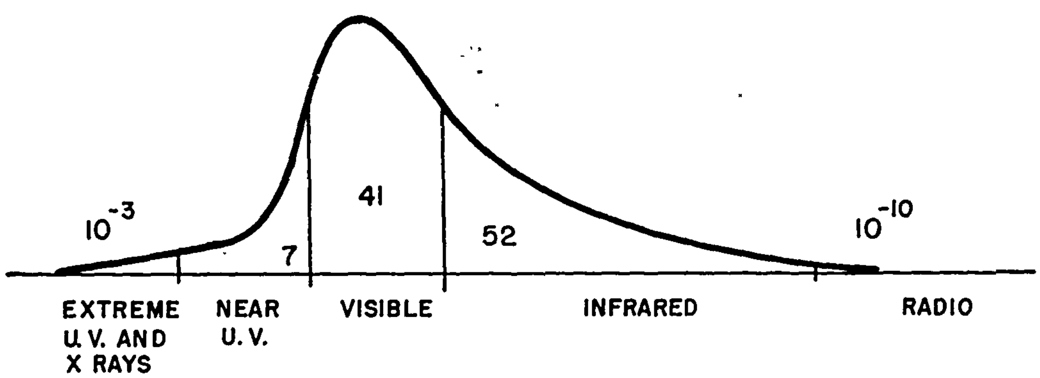
New measurements of the absorption series for atomic oxygen (O) were also completed using the 6.65 meter vacuum spectrograph. Not only was the accuracy improved, but some new lines were observed. This work on O and atomic nitrogen (N) served as the basis for several critical reviews of solar absorption in the upper atmosphere. Metastable O_2, $a^1\Delta$—and $b^1\Sigma$—states, are two more examples of important atmospheric constituents which have been studied. Production of these metastable states was realized by microwave discharge and by photolysis of ozone (O_3) with the result that previously undetected bands were observed. Cross sections obtained for absorption by O_2 and the effects of absorption by CO_2 have been used in the assessment of photoionization rates of O_2 ($^1\Delta g$) in the ionosphere. Calculations based on these AFCRL data reveal that this source of O_2^+ ions for certain upper atmospheric reactions is less important than previously believed.

Cross sections for absorption of O_3 (the atmospheric ultraviolet shield) have been obtained using new procedures to handle this reactive gas. Data have been reduced to obtain absorption cross sections for H_2O and D_2O. Ion cell calibrations were made to support measurements of solar flux and atmospheric composition during the solar eclipse of March 1970.

In the theoretical field the method of quasi-spin has been used to develop and simplify some of the formulas of atomic spectroscopy. Studies have been made with the goal of improving the accuracy of calculated atomic energies, and a number of associated spectroscopic coefficients have been deduced for the light atoms including nitrogen (N) and oxygen (O). Improvements in techniques for the determination of vibrational force constants have been effected for upper atmospheric polyatomic molecules such H_2O, NO_2 and O_3, and the characteristic properties of their vibrations have been related to certain vibration-rotation interactions.

SOLAR ULTRAVIOLET RADIATION

This section is concerned with X-radiation and the extreme ultraviolet (to be referred to as XUV) radiation from the sun and its variability. Relative to the intensity of visible sunlight, the intensity of solar XUV is small—a hundred thousand times smaller. Yet solar XUV



In terms of watts per square meter, most of the energy from the sun is in the form of visible and infrared radiation. Only a small fraction is in the extreme ultraviolet. But this UV energy sustains most of the chemical processes of the upper atmosphere.

radiation contributes a million times more energy to the earth's upper atmosphere than does visible radiation. The reason is that XUV is absorbed almost completely by atoms and molecules in the upper atmosphere while longer wavelength radiation passes through the upper atmosphere with almost no absorption.

The absorbed XUV sustains the chemical reactions discussed in previous sections, helps form the earth's ionosphere and modulates upper atmospheric densities by its control over atmospheric temperatures. During periods of high solar activity when solar XUV emission increases in intensity, the daytime temperature in the upper atmosphere may rise to 1700 degrees K. During quiescent solar periods, the temperature may fall to 900 degrees K.

For many years, AFCRL has been a major center of solar XUV studies. Because each specie of atoms, ions and molecules (as well as the different energy states of each) absorbs ultraviolet radiation with characteristic differences for different wavelengths, atmospheric attenuation measurements of solar XUV radiation provide a valuable means of deriving information on the vertical structure of atmospheric densities and composition.

During the past three years, AFCRL placed XUV spectrometers aboard 14 rockets and two satellites, principally to study temporal variations in solar intensities and atmospheric structure. The wavelength range of radiation intensities measurable from a rocket experiment was greatly extended during the reporting period, and the accuracy of absolute photometry at widely differing wavelengths was improved significantly.

ROCKET OBSERVATIONS OF XUV: Each of the 14 rocket payloads carried a grazing-incidence grating monochromator (spectrophotometer) as the primary experiment to measure solar radiation in selected regions within a total range of 30 to 1260 angstroms. The region observed on a particular flight depended on the choice of diffraction grating and detector. The monochromators were designed either as scanners, in which successive scans of the entire spectrum are made only a few times during flight, or as fixed-wavelength, in which certain strong intensity lines were observed repeatedly, thus providing greater resolution for radiation of special interest.

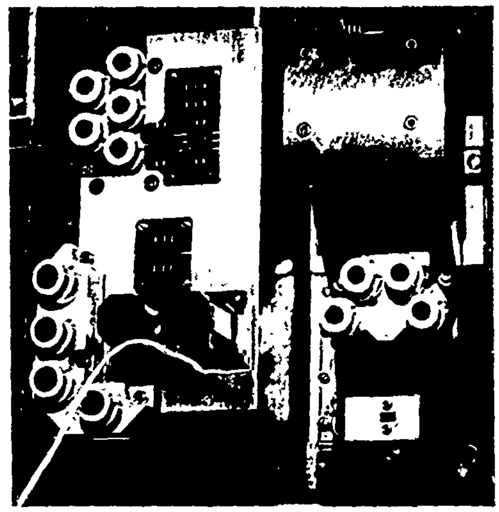
Retarding potential analyzers, to measure ion and electron densities, were usually flown as auxiliary experiments. The rocket flights—12 from White Sands Missile Range, New Mexico, one

AFCRL's extreme ultraviolet monochromator is mounted on a biaxial solar pointing control and is being prepared for flight as a nose cone payload of an Aerobee rocket.

from Wallops Island, Virginia, and one from Eglin, Florida—made observations over an altitude range of from 100 to 250 km. Data acquisition during the entire flight trajectory was made possible by the use of a biaxial solar pointing control, a servomechanism which points the sensor in the nose of the rocket accurately toward the sun.

The 14 rocket flights, in general, were spaced in time to obtain a picture of long-term variations in solar XUV radiation. One flight—from Wallops Island on September 30, 1967—was made in conjunction with an overflight of the AFCRL EUV monochromator onboard the OSO-III satellite to calibrate the satellite experiment.

The first flight of a new rocket monochromator was performed successfully on an Aerobee 150 from White Sands Missile Range on April 4, 1969. The instrument incorporated such previously untried features as channel electron multipliers, and was developed to combine good resolution with capabilities of making better use of the short time of exposure and the recording of two wavelengths spaced too widely apart for any single-grating instrument. Good spectral resolution was achieved over the wide range of wavelengths from 50 to 1260 angstroms, using two focusing gratings of different ruling, each being associated with four exit slits at different wavelengths. The instrument provided simultaneous recording of the radiation from all eight exits for any given position in the wavelength scan.



The OSO-III carried this grazing incidence grating monochromator for measuring solar radiation at wavelengths between 250 and 1300 angstroms.

SATELLITE OBSERVATIONS OF XUV: Two XUV experiments were carried aboard satellites during the reporting period. These satellites were NASA's OGO-IV launched in July 1967 and OGO-VI launched in June 1969. In addition, data from an AFCRL experiment aboard the OSO-III launched in March 1967 were analyzed during the period.

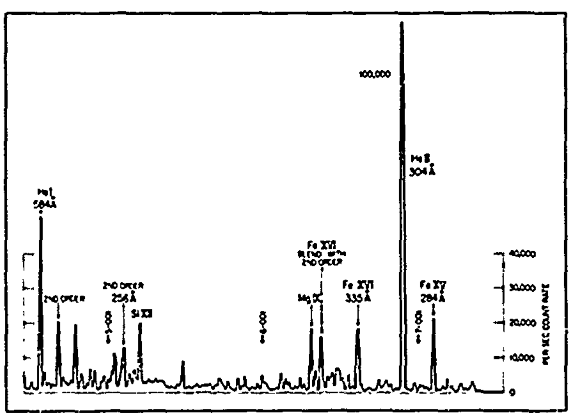
The OSO-III instrument, a grazing-incidence grating monochromator, monitored solar radiation fluxes at wavelengths ranging from 250 to 1300 angstroms, being commanded either to scan the entire range or to observe certain wavelengths continuously. In addition to observing time variations of solar EUV radiation (see next subheading), the experiment yielded extremely valuable determinations of absorption characteristics of the upper atmosphere.

The two OGO satellites carried spectrophotometers utilizing collimator-planar grating optical systems. These spectrophotometers monitored the levels of incident solar radiation in the wavelength range between 170 and 1700 angstroms with a complete spectral scan occurring every seven minutes (or by choice with ground command, a limited scan every minute). The total wavelength coverage of the instruments is achieved by combining the outputs of six independent spectrophotometers, each contributing a portion of the total spectral scan. Adjacent sub-ranges were designed with considerable spectral overlap, allowing redundant measurements of many of the more intense solar lines, and providing useful information relative to internal instrument stability.

XUV TEMPORAL VARIATIONS: AFCRL's solar XUV measurement program has extended over a complete 11-year solar cycle. Based on rocket and satellite data acquired during this span, AFCRL has put together a picture of solar XUV variations over both the solar cycle and the 27-day solar rotation period.

AFCRL has found that solar XUV can vary markedly—by as much as 40 percent—over the period of one solar revolution. Variations during the 27-day rotation period compare with those observed over the 11-year solar cycle when wide variations would be expected.

The 27-day variation in solar XUV was not the product of large energetic flares, although such flares do bring sharp increases in solar UV emissions.



Here is a typical emission spectrum obtained by the AFCRL EUV spectrophotometer placed aboard the OSO-III.

The measured variations had no single cause, but emerged from the continuous shifting convections, the roiling energies, the innumerable minor flares and explosions in random patterns, and small crescendos of solar activity. Such activities, at any given time, may be more pronounced on one side of the sun than the other, and thus 27-day solar XUV variations are observed.

The spectral character of emissions is of particular interest. Increases or decreases in solar XUV emissions are really the average of many emissions at discrete wavelengths from many ionized species. AFCRL considered some 20 emission lines between 270 and 1310 angstroms. The intensities of these lines do not increase or decrease in unison. Increases or decreases depend on ionization potential of an ion species and this depends on the thermal environment at some particular location on the sun.

During one ten-day measurement period, it was found that the ions that produced the largest flux increases were those with the highest ionization potentials. However, during large energetic flares, the largest flux increases come from those ions in the middle range of ionization potential.

How do general increases in solar XUV measured by OSO-III correlate with flux increases at much longer wavelengths—say radio wavelengths at 10.7 cm? It was found that while solar XUV flux increased by 40 percent, the 10.7 cm flux (measured by ground-based radio monitors) increased by almost 100 percent—from 111 to 201.

DESIGN CLIMATOLOGY

Design climatology deals with atmospheric and meteorological factors likely to affect Air Force operations and the performance of equipment. A basic customer for climatology studies is the equipment designer who must know the environmental limits within which the equipment will operate.

Often, the basic data for these studies are historical meteorological records. In this connection, the Laboratory carried out several studies during the reporting period for a revision of Military Standard 210A, "Climatic Extremes for Military Equipment," a basic reference for establishing specifications for military equipment. One of these studies examined the extremes of hot weather all over the world. The study in essence gives the probabilities at several percentage levels that given temperatures during a particular month will be reached or exceeded at any geographical location. As a matter of interest, this particular study on extremes of hot weather showed that El-Azizia, Libya, has the distinction of being the location of the highest temperature ever recorded by standard meteorological instruments—136 degrees F. A similar study on the extremes of cold over the North American continent showed that the lowest temperature ever recorded in North America was −81 degrees F at Snag, Yukon Territory.

Often, data on atmospheric parameters of interest are lacking. This then requires that the Laboratory undertake observational programs. Absence of data on stratospheric humidity, winds and temperatures in connection with the operation of supersonic military aircraft (and the SST) required that the Laboratory undertake several such observational programs.

But a more typical problem is one in which the Air Force might wish to know the percent of the time that a given radar, operating at a specific location in Viet Nam, might be inoperative because of excessive clutter caused by severe tropical rains. The typical answer might be that the radar would be unable to penetrate the rain clutter 1 percent of the time during the monsoon season.

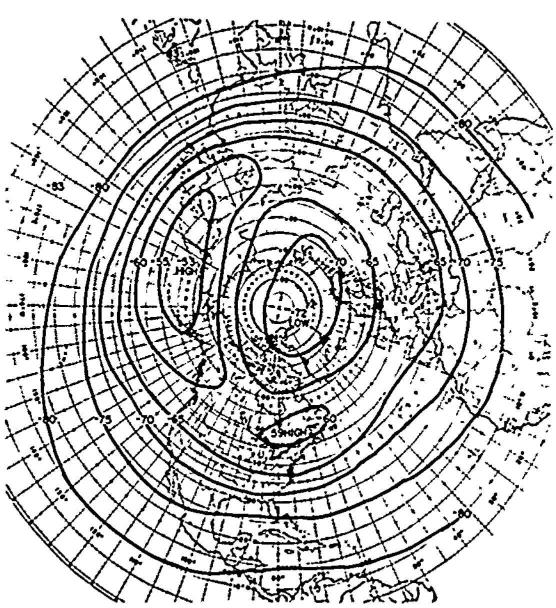
Design climatology is statistical in nature with a strong focus being on climatic extremes likely to be encountered at particular geographical locations.

STRATOSPHERIC WINDS AND TEMPERATURES: An SST flying between London and New York will use 400 to 600 pounds of additional fuel for an increase of just 1 degree C over the mean route temperature. For an SST flying at roughly 20 km altitude over the same route, 100 pounds of additional fuel are needed for each knot above the mean headwind.

While these figures will vary with engine and aircraft design, they won't vary all that much. Both the commercial SST and operational military aircraft will use polar routes and it is in the polar stratosphere that extreme variability in temperatures and winds take place.

Atmospheric scientists have been especially concerned with a feature of polar meteorology known as "explosive warmings." These warmings, which seem to precede the breakdown of the strong polar cyclone in winter, sometimes increase temperatures sharply. Through studies at AFCRL and elsewhere it was found that although winter stratospheric warming occasionally has been spectacular, 24-hour increases are rarely greater than 10 degrees C within a 500 nautical mile radius.

The AFCRL study concluded that the severity of stratospheric winds may not be as great as previously reported. Stratospheric winds of 200 to 300 knots have been measured by Canadian meteorologists and were not uncommon in reports of measurements made before 1966. Since that time, there have been few reports of winds of this magnitude. The reason, AFCRL suggests, may be in the measuring instrumentation and procedures previously used.



This is one of a hundred or so isotherm plots taken from the AFCRL study, "Point and Route Temperatures for Supersonic Aircraft." It indicates that in the winter months at an altitude of 100 mb, roughly 53,000 ft, there is a 10 percent chance that the temperatures shown will be exceeded.

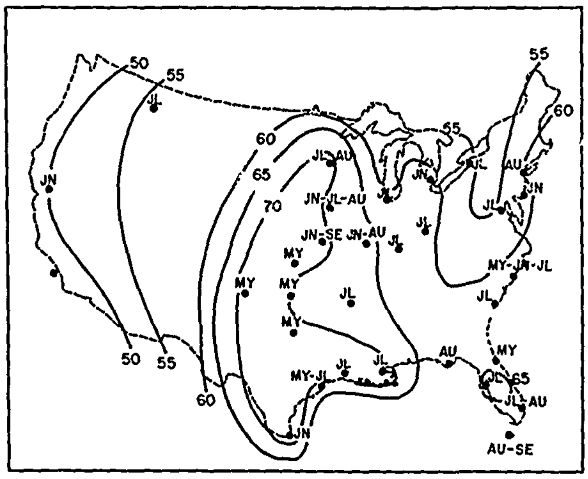
From one study, a new method for calculating route temperatures for supersonic aircraft flying between 60,000 and 80,000 feet over the North American continent was evolved. With this model, the average temperature for any randomly selected route over the North American continent can be calculated in a relatively simple manner. The model is purely statistical. The calculations do not require a knowledge of observed upper air temperatures at any specified time. For the study, daily observations from 66 North American stations for a five-year period were used.

The model is one that uses temperature checkpoints along the route and knowing not only the individual mean temperature and standard deviations of each checkpoint, but also the correlation coefficients between pairs of checkpoints.

Several interesting phenomena have appeared on charts developed for the model. In winter, a belt of warm air circles the globe around latitude 55 degrees N, with the most persistently warm air centering over the Aleutian Basin. In summer, when there is no such belt, the air temperatures are coldest over the Equator and warmest over the North Pole. On the New York-San Francisco route, the temperatures proved to be lower in summer than in winter, although only slightly.

Still another problem investigated related to stratospheric flights of supersonic aircraft is one that relates back to conventional barometric altimeters aboard the aircraft. Such altimeters do not measure absolute altitude, but merely the atmospheric pressure which is closely correlated with absolute altitude—sufficiently close so as not to be a problem in subsonic flight. Because atmospheric pressures vary along an absolute altitude plane, the pilot actually ascends or descends in altitude while his altimeter reading remains constant. So gradual are these changes in altitude that the passengers and the pilot in subsonic aircraft are seldom aware of them.

But an SST at speeds approaching Mach 3 flying at a constant pressure altitude might, over a given distance, ascend or descend sharply. Assuming an absolute altitude change of 272 feet within a four-mile distance, the four-mile stretch would be covered in about eight seconds. This change could produce a g-force of 0.25 (an acceleration of 8 feet/sec^2). As a general rule, passenger discomfort sets in when a g-force of 0.2 is exceeded.



During May over most of the central U.S., extending from Texas to Minnesota, cloud tops may sometimes reach as high as 70,000 ft. The chart shows the month and altitude of maximum vertical extent of radar echoes from clouds.

TURBULENCE AT EXTREME ALTITUDES: During the period, the Laboratory completed a study of turbulences at altitudes up to 70 km. Such turbulences could cause structural failures in lifting boost-glide or reentry vehicles. The study involved a field experiment in which rockets released four simultaneous and spatially separated smoke trails between 30 and 70 km altitude. The trails presented a three-dimensional picture of spatial and temporal variations.

This experiment dispelled the concept held by many scientists that the thermally stable stratosphere is quiescent. Smoke trails were found to be good sensors of atmospheric motions and indicate that vertical motions are present at all levels between 30 and 70 km. Vertical motions greater than 5 mps and probably as great as 15 mps were found to be present below the stratopause.

In a somewhat related study, a series of ARCAS-ROBIN rockets were launched simultaneously from San Nicolas Island, Point Mugu and Vandenberg AFB to investigate the spatial variations of wind over distances of 100 to 200 km at levels between 20 and 70 km. The information was needed to determine an optimum distribution of sites from which meteorological rocket observations should be taken to support tests conducted at the missile ranges. Twelve sets of simultaneous wind measurements were obtained. Small-scale oscillations in the observed wind profiles were traced over horizontal distances of 200 km and horizontal and vertical wave parameters were determined. Oscillation with vertical wavelengths of 3 to 4 km and amplitudes of 4 to 12 mps were highly correlated over horizontal distances of 200 km and have an estimated wavelength of 1200 to 1600 km. Oscillations with vertical wavelengths of less than 3 km usually had amplitudes of 1 to 2 mps. The spatial correlation of these smaller oscillations decreases rapidly with horizontal separation.

CLEAR LINES OF SIGHT FROM AIRCRAFT: What appears to be a clear day to the ground observer looking up may not be a clear day to the observer in an aircraft looking down. This is the basic conclusion reached in an 18-month study by AFCRL on clear lines of sight from aircraft. The study which is continuing has involved more than 100,000 observations covering much of the Northern Hemisphere.

Making these observations for AFCRL were pilots and aircrew members of the Strategic Air Command, weather reconnaissance squadrons, the U.S. Navy, and Pan American World Airways. The last of these, Pan American, participated on a no-cost basis. Special AFCRL forms were supplied to each of these organizations and monthly submissions of these completed forms were made to AFCRL. Also supplied was a simple clinometer for making the observations.

Motivating this study was the need for precise statistical data on the impact of cloudiness on optical and infrared airborne detection and tracking systems.

Pilots and aircrew members were asked to make observations at five different angles—minus 90 degrees (directly below the aircraft), minus 30 degrees, 0 degrees (the horizon), plus 30 degrees, and plus 90 degrees (directly overhead). Observations were made at altitudes ranging from 1,000 feet to above 45,000 feet.

The study contains many surprises. One of these is the large differences between estimated probability of clear lines of sight derived from a modeling technique and those obtained from the observational data. For example, data from 300 observations over the Washington, D.C., area were compared with the line of sight predicted by the model and based on climatological records from the area. The estimates indicated a 75 percent likelihood of seeing the ground at a minus 30 degree angle from 30,000 feet during the winter months. The actual data accumulated by AFCRL indicate the likelihood to be only about 20 percent. Discrepancies equally as great occurred in the Seattle area.

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This model of a C-121 was placed at the highest point atop AFCRL's main laboratory complex for tests of the SAD-FRAD radar antenna (wavelengths were scaled correspondingly) prior to the design of the antenna system.

IX Microwave Physics Laboratory

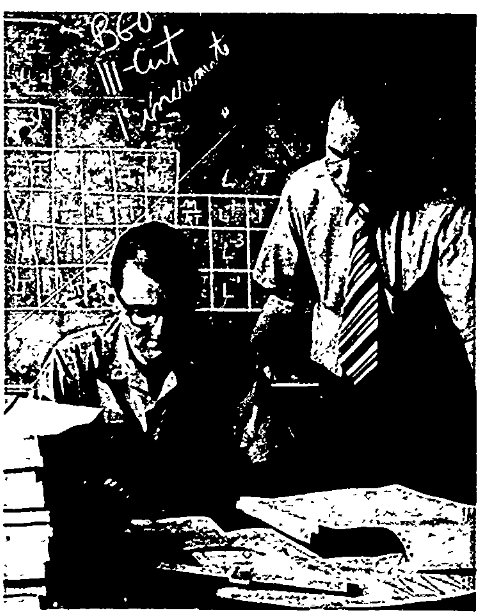
The Microwave Physics Laboratory performs research in electromagnetics. Within this research category is encompassed all of the Laboratory's program areas—antenna theory, electromagnetic field theory, microwave scattering and diffraction, radar sensor design, millimeter wave probing and mapping of the terrestrial and solar atmospheres, plasma physics and microwave acoustics. Each of these research areas is linked to well-identified Air Force technological objectives in surveillance, reconnaissance, communications and navigation.

Many Laboratory programs that were still in preliminary exploratory stages at the time of the previous report are now approaching technical feasibility. For this reason the Laboratory program has a more applied development complexion than was the case three years ago at the time of the previous report.

For example, in the plasma physics area, emphasis is more on the curative than on the diagnostic phase of the reentry communications blackout. The Laboratory is now confident that it will find solutions for penetrating the dense plasma shroud and for the severe antenna voltage breakdown problems on re-entering vehicles.

The ability to map and interpret the sun's surface and turbulences in the atmosphere by millimeter wave flux has been vastly improved. This new ability has bearing on the Air Weather Service Space Forecasting Program, on tropospheric scatter communication nets and on ground-based systems for detecting clear air turbulence.

Resolving targets buried deep in clutter taxes the limits of technology. Because the problem can be shown to be theoretically amenable to solution, several possible approaches exist. Some of the approaches that were in the conceptual stage just three years ago have now emerged at AFCRL as hardware ready for testing. What has emerged are basically new radar concepts. Of these, dual harmonic phase signature radars that exploit resonant region electromagnetic scattering phenomena are the most promising. One airborne version, known as SADFRAD, is scheduled for its first flight test from Hanscom Field in July 1970. SADFRAD is designed to locate stationary military ordnance in a foliage background.



Microwave acoustics witnessed a renewed growth during the period as emphasis shifted to surface wave propagation rather than propagation through the bulk material. One study undertaken by Laboratory scientists was an analysis of the propagation and attenuation properties of all known acoustic materials.

The Laboratory program in microwave acoustics was reinvigorated as emphasis shifted from bulk propagation studies to surface propagation. Also in the microwave device area, the Laboratory has discovered some fundamentally new and exploitable properties of magnetic surface waves and nuclear spin resonance. The Laboratory is now investigating millimeter devices using antiferrimagnetic materials.

Tested during the period was a new 2 mm antenna array, an antenna at the very frontiers of antenna technology. Interferometric and data restoration techniques incorporated into this antenna system may well represent the first application of techniques that will be widely adopted in the future. For the foregoing research, the Laboratory operates a 350-acre range in Ipswich, Mass., the largest single AFCRL off-base site in terms of acreage.

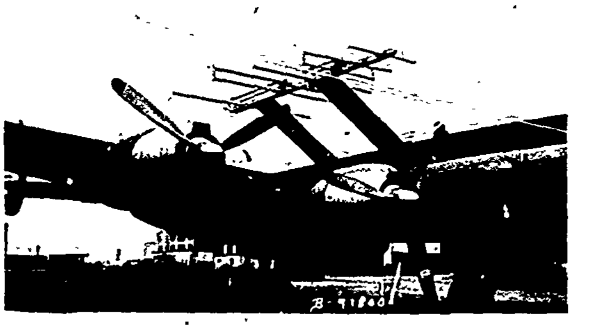
During the period, two rockets were launched, one a Nike Cajun launched in October 1967 to measure antenna voltage breakdown; the second, launched in June 1969, was a Trailblazer rocket to measure attenuation of high power signals passing through a plasma sheath. The data obtained from this latter flight supplement low power signal measurements made in the previous reported Trailblazer flight test of June 1967.

RADAR TECHNIQUES

A sizable portion of this section on radar techniques will be devoted to the SADFRAD radar system. Such prominence is warranted. This radar promises to give the Air Force a capability that the state-of-the-art has long denied —the capability of detecting targets through foliage and against cluttered terrain. If tests are favorable, SADFRAD will come to be recognized as a benchmark in the evolution of radar technology.

Its evolution can be cited as a classic example of the progression from theoretical research in microwave coherence and electromagnetic scattering to a fully developed test system. The Microwave Physics Laboratory has been a national center for such theoretical studies for well over a decade.

Phase comparison radar systems offer the best known approach to the detection of targets in clutter. Three distinct phase comparison systems under study by the Laboratory are reviewed preparatory to a discussion of the SADFRAD system which is a member of the same radar family. In addition to radars of this type, AFCRL's Spectrum Analysis Radar—a radar based on an entirely new radar principle and having potential application in range measurement of targets—is discussed. Last, this section will cover AFCRL studies of a more general nature on scattering properties of targets. Such general studies are the essential foundation for new radar concepts further on the horizon.



Phase comparison radars were tested using this large VHF antenna aboard a test aircraft. Several phase comparison radar schemes were evaluated during the period.

PHASE COMPARISON RADAR SYSTEMS: Phase comparison radars have in common the use of two or more transmitted frequencies. The three separate systems designed by AFCRL all operate at HF and VHF. Phase comparison radars offer the possibility of revealing targets obscured in clutter. The three AFCRL-developed systems each employs different receiver-processing techniques.

The first of these systems is the Resonant Region Radar and is an HF monopulse phase comparison radar that yields target azimuth versus range information as a display output. The second system, the Dual Harmonic Frequency Radar, is an HF-VHF harmonically related phase comparison radar with a receiver-processing scheme providing target signature, azimuth, and range presented on a color display. The third system is comprised of two logarithmic clutter receivers operating at two different frequencies with the clutter data presented on a normal "A-scope" display. The antenna for this multipurpose radar system is made up of two interlaced YAGI-UDA antennas, each designed to radiate at two frequencies of interest.

Initial ground tests of the Resonant Region Radar were conducted at the AFCRL Ipswich field test site. These tests verified the theoretical design studies. The encouraging test results showed that the design was capable of enhancing the detection of low flying airborne targets in a clutter environment. The entire radar system and associated recording equipment was then installed on a structurally modified C-121 Super-Constellation aircraft for airborne experiments.

Initial tests of the SADFRAD antenna system were made using this model of a C-121 aircraft. Modeling experiments were necessary to determine optimum antenna pattern shape and location on the aircraft.

The flight test program was accomplished in four phases and consisted of 100 hours of airborne time. The first phase, conducted during the mechanical air-worthiness trials of the modified aircraft, took advantage of targets of opportunity such as ships at sea, large metallic structures and vehicles on the ground. The second phase involved flights over controlled radar targets, such as vehicles and dipole arrays placed in various terrain environments, to provide a variety of clutter-target returns. The third phase was conducted at the RADC UNDERBRUSH range at Eglin AFB, Florida, using a combination of controlled and tactical targets immersed in a pseudo-tropical terrain. The tactical targets included a convoy of military vehicles, single vehicles, and a simulated SAM missile site. The fourth phase centered on the detection of airborne aircraft at various altitudes.

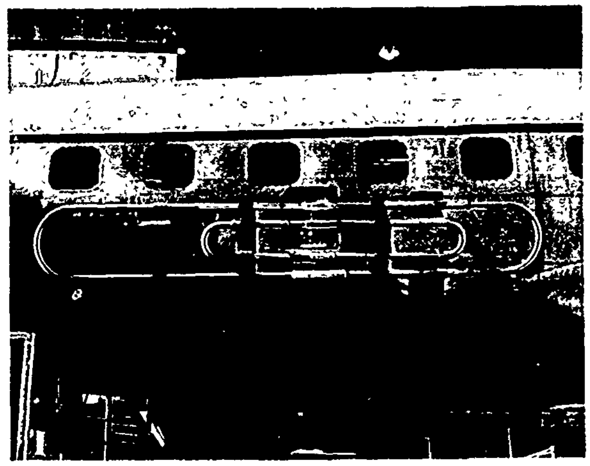
Many aspects of this radar system, such as the use of differential phase signature, were new and previously untried. Targets with appropriate signal-to-clutter ratios displayed a unique phase signature, proving this to be a good parameter for target detection. The backscatter from various terrain types was collected, analyzed, and catalogued for use in future radar designs. The system turned out to be quite efficient in detecting airborne aircraft and the phase signature of such targets.

The Phase Comparison Radar, then, proved the feasibility of the new approach to radar detection. The encouraging tests led to the second generation, higher performance radar system that is described below.

SADFRAD—GENERAL DESCRIPTION: The experimental airborne Synthetic Aperture Dual Frequency Radar (SADFRAD) may come to be cited as one of AFCRL's most significant Air Force contributions during the three years of this report. The radar was designed to detect, locate, and identify stationary tactical military targets in a high clutter environment. The basic technique making this performance possible is a new signal processing technique developed at AFCRL.

The SADFRAD system, in contrast to the first generation Phase Comparison Radars reviewed above, uses a focused synthetic aperture to achieve high azimuthal resolution. The signal processing technique not only uses target amplitude data (as do most radars) but also dual harmonic differential phase signature data at HF and VHF frequencies with real-time on-board synthetic aperture processing. A differential phase signature characteristic of each target type is generated. Real-time target information from the synthetic aperture processor is used to provide both target amplitude and phase signature strip imagery displayed on black and white and color TV monitors.

The SADFRAD system offers several advantages over existing airborne sensor systems and techniques. These are: clutter or foliage penetration, resonant region target detection, and real-time radar strip imagery. In the first part of 1970, the system was installed on an AFSC Avionics Laboratory C-121 flight test aircraft. Initial tests from Hanscom Field will begin in July or August of 1970. These tests are designed to (1) determine the operational effectiveness of the system, (2) acquire resonant region dual harmonic phase signature data, and (3) collect radar clutter data at frequencies previously not investigated.



Tests of the SADFRAD radar began in the summer of 1970. These two antennas, mounted on a C-121, were found to be of optimum design.

SADFRAD—DEVELOPMENT AND DETAIL: SADFRAD's large dual frequency antennas were designed and fabricated by AFCRL and consist of two closely interlaced, asymmetrical, folded dipoles. Extensive experimentation was conducted on the AFCRL antenna test range using a 1/10th scale C-121 aircraft model to determine the antenna configuration which would yield the required radiation patterns, sidelobe levels, complementary front-to-back ratios and impedance (bandwidth).

The dual channel receiver system consists of both a phase stable limiting channel to generate bipolar video data for the synthetic aperture processor and a linear channel which generates stretched bipolar video. These two separate receiver systems are necessary because the radar system provides both instantaneous target data and background clutter data which is recorded on magnetic tape for later computer analysis. This latter necessitated the design and construction of a data stretcher which effectively slows down the incoming target data rate by a factor of 128:1. At this rate, target data can be recorded on tape running at 120 inches per second. These records provide radar clutter data at frequencies heretofore little explored in radar detection systems.

The heart of the system is the radar processor which is a digital, focused, synthetic aperture subsystem with pulse compression. Unlike most synthetic aperture devices which are non real-time and require elaborate ground optical processing to generate radar strip imagery, the SADFRAD processor operates real-time on-board the aircraft. This is achieved by a sophisticated parallel subarray data flow scheme. It provides simultaneous digital signals proportional to the amplitude of the target at the two frequencies, and in addition, the dual harmonic target differential phase signature data. These outputs provide (azimuth versus range) radar strip imagery to drive the display. The processor also controls the PRF of the radar and is proportional to aircraft velocity. Consequently, the individual elements of the synthetic aperture are equally spaced similar to a linear array and the returns can be added and phase compensated without regard to nonconstant aircraft velocity along the flight path. Motion compensation signals from a modified AN/ASN-63 Inertial Navigation System are also provided to the processor to correct for flight path deviations.

SADFRAD—DISPLAY: A unique feature of SADFRAD is the display. Display of the data in a form meaningful to the operator required a new approach to radar imagery display design. The display console provides the operator with three TV monitors presenting radar strip imagery. The real-time target amplitude data at the two frequencies are displayed on black and white monitors, while the target differential phase signature data are presented as one of the 16 possible colors on the color monitor.

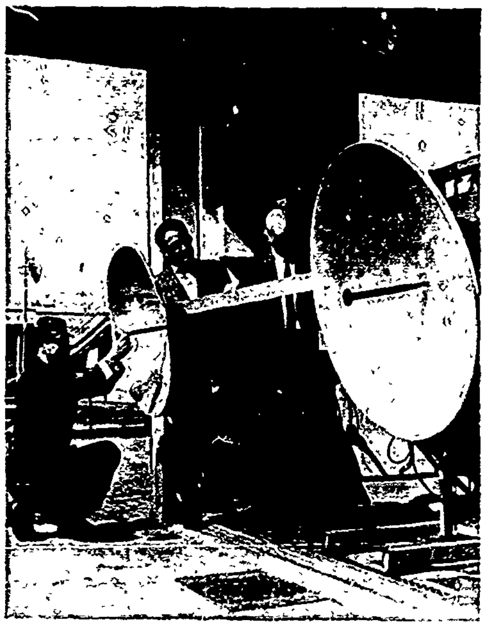
The SADFRAD display system consists of three scopes. The two upper scopes display target amplitude at two separate frequencies. The large third scope presents differential phase data in color. The operator uses all three to locate targets obscured by foliage and clutter.

The console equipment accumulates the processed radar data and continuously reads through all this stored data at the standard television rate of 30 frames a second. The data are stored in a digital core memory which is large enough so that 12,000 range/azimuth cells can be displayed at one time. Newly processed data from the synthetic aperture radar enters the display at the top of the screen. Previously stored data are shifted downward, line by line. The oldest stored data drop off the lower edge of the picture and are discarded. In this way, a continuously moving view of the terrain below is obtained.

If the airborne tests that will be conducted in 1970 and 1971 are successful, a new detection and display philosophy will have been proved feasible and the Air Force given a new capability.

SPECTRUM ANALYSIS RADAR: The spectrum analysis radar seemed to promise too much from such simple componentry. What was promised was a radar that was difficult to jam, having almost no mutual interference between nearby radars of the same type, high range resolution of closely spaced multiple targets, high accuracy, and the capability of measuring range down to zero to within accuracy of a foot or so. Test results matched optimistic expectations.

The spectrum analysis radar is based on a new radar principle. Its key component is a spectrum analyzer. AFCRL's test model, in fact, used a standard spectrum analyzer of the type found in all well-equipped microwave laboratories. The signal source used in the test model was a gaseous discharge noise tube producing a Gaussian noise signal. Basically, the radar is a cw noise radar.



The spectrum analysis radar uses a dual antenna system. Wide band noise is transmitted, and the reflected signals are processed by spectrum analyzers.

But it must not be confused with other cw noise radars or frequency agile radars such as CHIRP or DITHER. Such radars usually require complex delaying and cross-correlation techniques. The spectrum analysis radar requires neither.

The radar had its origin in partial coherence theory, a theory that describes the behavior of broadband noise signals as they propagate. The theory predicts that even after all traces of amplitude interaction due to phasing between two signals have vanished, it is still possible for their power spectra to interact.

The spectrum analysis radar is the direct result of the discovery that when a noise signal illuminates a target or any discontinuity, the power spectrum of the reflected signal, and not its intensity, contains the target information. The spectrum of random noise by itself gives no meaningful information. A reference signal is needed. For the reference signal, a small part of the transmitted signal is extracted and delayed. This reference signal is then added to the received signal and their sum observed on a spectrum analyzer. Although these two signals are uncorrelated, the power spectrum of their sum is modulated. The modulation frequency depends only on the range of the target.

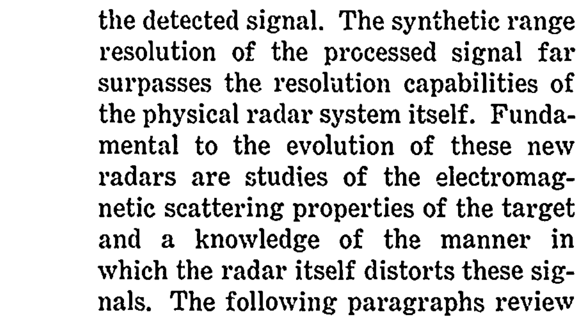
If the signal is put through a peak detector and a filter and displayed on a second spectrum analyzer, an A-scope display would result. Pips along the horizontal line of the scope indicate the presence of targets. The location of these pips is linearly proportional to the range of the target. It would, if desirable, be fairly easy to convert the A-scope display to a standard radial or PPI display.

Angular location of a target can be determined by using two systems (or one, time-shared between two antennas) separated by a small distance. The small difference in range to the target as seen by each of the antennas will cause the location of the nulls observed in the spectrum of one system to shift relative to the other. If the spacing between antennas is known, this shift can be converted into angular position.

The radar could be used for a wide variety of short range applications—up to about 20 miles or so. Because of its basic simplicity and relative immunity to mutual interference, a foremost application could be as a collision avoidance radar for military and commercial aircraft.

TARGET SCATTERING PROPERTIES: Future radars will take advantage of the scattering properties of the target with a view toward extracting detail from the scattered waveform. This implies that the signal will be processed as in the case of the SADFRAD radar discussed earlier. Usually a broadband signal rather than the conventional discrete frequency will be transmitted because more information is contained in the detected signal. The synthetic range resolution of the processed signal far surpasses the resolution capabilities of the physical radar system itself. Fundamental to the evolution of these new radars are studies of the electromagnetic scattering properties of the target and a knowledge of the manner in which the radar itself distorts these signals. The following paragraphs review some of the work at AFCRL.

The Laboratory has found that the range imaging properties of targets can be completely characterized by two quantities: the radar system wideband ambiguity function and the target's electromagnetic impulse response. Conceptually, the range image is generated by passing the electromagnetic temporal impulse response of the target through a conventional linear system. The temporal output of the system is



Among the many radar schemes developed by the Laboratory is this configuration of a random signal radar system. A broad bandwidth random signal is scattered by discrete targets, and detection depends on the analysis of the power spectrum density of the far-zone scattered field.

the observable image of the target. The image distortion introduced by the linear system is precisely that due to the radar itself and is characterized by the appropriate doppler cut of the system's ambiguity function.

The temporal impulse response is a function of the target's shape, size, material composition and spatial orientation with respect to the radar. It is theoretically calculable for a large class of shapes. Computer verification of these principles has provided the range and azimuth images of a flat, metal plate illuminated by a standard rectangular pulse of energy.

A closely related topic is the control of the electromagnetic reflecting properties of targets. Detailed knowledge of the electromagnetic field structure in the vicinity of the radar target is essential for the design of effective scatter control techniques. For this, new test facilities not presently available are needed. Such a test range will permit precise measurements of the farfield radar cross section, and at the same time, allow for an investigation of the properties of the near-in scattered field. Such complex shapes as cone-spheres and maneuverable re-entry type vehicle models form an important class of targets for these measurements. Impedance loading, as a means of radar cross section control, has been extended to various object shapes and over wider frequency bands in careful experimental work on the Ipswich scattering range facilities.

AFCRL has also developed a new method for describing the reflection of broadband or partially coherent signals from arrays of randomly spaced scatterers. This situation is often encountered in the radar signal reflection from rough surfaces or in scatter communication links. The technique is based on the statistics of random variables and yields results in the form of probability density functions for the intensity of the reflected signal.

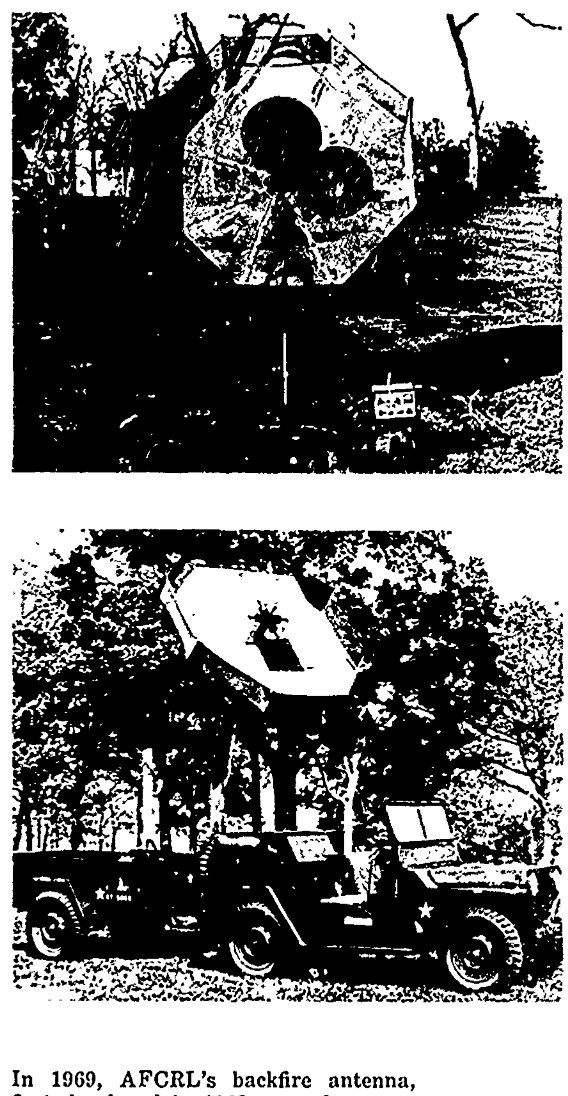
One of the more important consequences of this technique is that it shows the heretofore unknown interconnection between broadband signals that have a discrete spectrum, and those that have a continuous spectrum. For the first time, a continuous noise spectrum can be replaced by a set of suitably spaced monochromatic signals. With this representation one can determine the physical extent of the scattering volume by studying the measured characteristics of the scattered signal. These studies are directly applicable to many scattering problems and in fact are being presently applied in-house to the analysis of a millimeter tropospheric scatter communications link.

ANTENNA DEVELOPMENT AND THEORY

All antennas distort the information they receive. Because antenna performance sets fundamental limits to overall system performance, an antenna research objective is to reduce this distortion. In a practical sense, the designer can reduce it just so far because he must always trade optimum performance for realizable designs in terms of size, weight and cost.

One novel approach to antenna design at AFCRL is one in which the number of radiating elements in an array can be greatly reduced yet giving the same performance as antennas with many more elements. The trade-off in this case is the sacrifice of technical simplicity. Data processors must be incorporated into the antenna design to correlate the signals detected by each of the antenna elements. AFCRL believes this sacrifice is well worth the benefits and that the technique will come to be widely used by antenna designers. During the reporting period, AFCRL placed in operation two experimental antennas based on this principle.

Not all antenna research in the Laboratory takes the designer into complicated processing schemes. The short backfire antenna discused below is a case in point.



In 1969, AFCRL's backfire antenna, first developed in 1962, was chosen as the basic ground terminal antenna of the TACSATCOM System. The antenna opens and closes like an umbrella. Two designs of the antenna are presented.

SHORT BACKFIRE ANTENNA: The performance of the short backfire antenna was first demonstrated by AFCRL in 1962. In 1969 it was placed in production as the primary transmitting and receiving antenna for the new Tactical Satellite Communications System (TACSATCOM). From the accompanying photograph, it can be seen that the highly portable antenna looks somewhat like a pie plate with a flat rim. A small reflecting plate is placed at a given wavelength distance from the larger reflecting surface of the antenna.

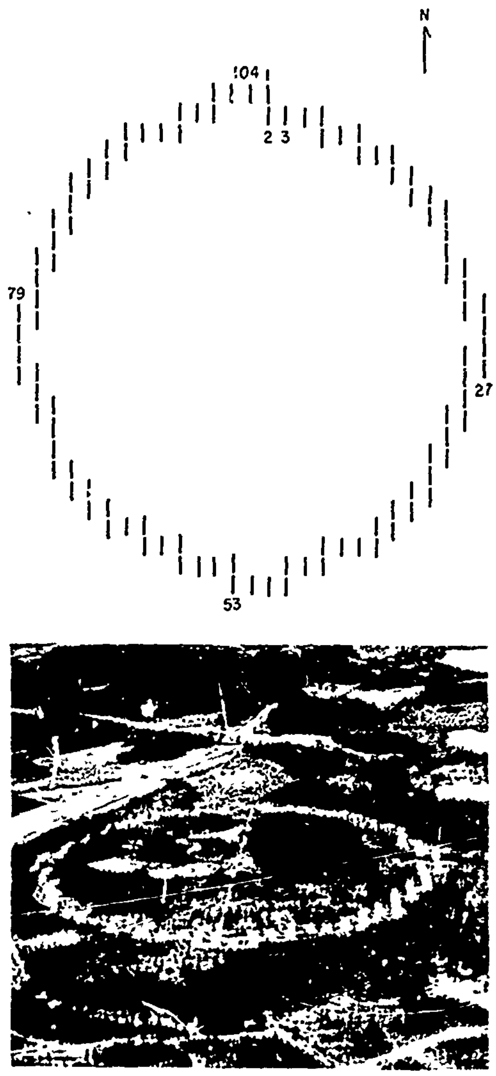
In a joint effort of the Army, Navy, Marine Corps and Air Force the system was tested in a net of 13 stations located on jeeps, ships, and submarines in the area between Bermuda and Hawaii. During the first test of the TACSATCOM Feasibility Program, all 13 stations could be contacted from a control station at Fort Monmouth, N.J., via the 22,000 mile high TACSAT I satellite with voice quality equal to a next door telephone call. Although the backfire antenna provides excellent electrical performance, physically, it is light and simple. One of the three types of backfire antennas currently being manufactured can be opened and closed like an umbrella and even packed in a rucksack for easy transport.

The continuation of in-house research on these backfire antennas has resulted in another new type of high gain endfire antenna, called the cavity endfire antenna. The typical gain of conventional optimized endfire antennas like Yagis, helical or disk antennas, is no more than about 15 dB and is approximately proportional to their structural lengths. For higher gains (in the 20 dB range), however, such antennas become impractically long because their gain increases only slowly with length. Gain limitations of such conventional endfire antennas can be overcome by replacing their feed system by AFCRL's short backfire antenna. A gain of 20 dB can be obtained with an antenna ten wavelengths long. A conventional endfire antenna with the same gain and the same pattern quality but without the backfire feed, would have to be about three times as long.

6.75 MHz ARRAY: This huge antenna consists of 103 dipoles arranged in a circle having a radius of approximately 1000 feet. By processing and correlating the data from the 103 dipoles, resolution comparable to that obtained from a filled array of more than 600 dipoles is possible. The antenna is located in Sudbury, Mass., and operates at a frequency of 6.75 MHz. During this reporting period, various data processing methods for the image reconstruction of incoherent source distributions, such as the radio sky, were tested. The intent of such processing schemes is to account for all known sources of error in a modified antenna transfer function, which is then used to produce a more accurate map of the source. All processing is done in a central computing van.

Interference, both man-made and natural, is a large source of error at this frequency. One method of interference reduction makes use of the fact that the source distribution moves in position while (on the average) the interference is stationary. This allows the signal and the interference to be separated and the interference received by the whole array can be compared to that received by a single dipole element. Methods and equipment have been developed which partially cancel out this type of interference.

The ionosphere introduces a large amount of error at 6.75 MHz. Representing as it does a time and spatially varying medium between the source and



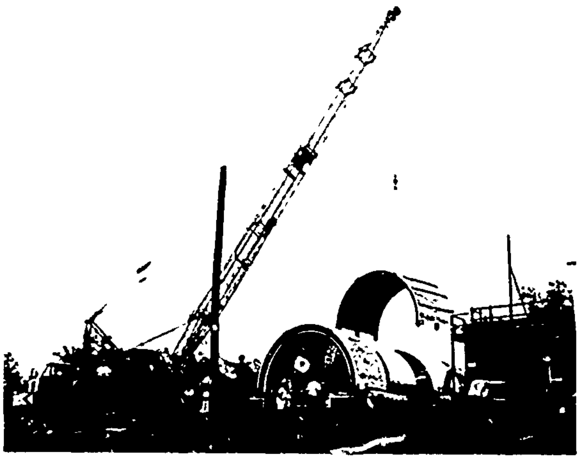
AFCRL's 6.75 MHz array consists of 103 dipoles arranged in a 2000-ft diameter circle. It is located at Sudbury, Mass. By processing signals detected by each of the dipoles, resolution is equivalent to that of an array of 600 dipoles.

the antenna, its effect on the antenna output or image is partly predictable and partly unknown. The known or predictable effects can be included in the modified antenna transfer function and the corresponding image distortions can be minimized in the data processing or image restoration procedures. The random effects of the ionosphere pose more of a problem. With a partial knowledge of some of these random properties, processing schemes to at least minimize such errors have been instrumented and tested.

This array was designed to verify optimum design principles (for a planar aperture) that require the antenna transfer function (or spatial frequency response function) to be flat over a large part of its passband. The antenna's beam can be scanned and mutual coupling effects between antenna elements accounted for in the restoration process. The operating frequencies were chosen because no high resolution radio telescopes exist in this frequency range even though there are many radio stellar sources which are strong emitters in the 5 to 7.5 MHz band. The interference rejecting mechanisms inherent in the data processing may have wide applicability in long range detection radars.

THE MILLIMETER WAVE ARRAY: At the other end of the spectrum—in the mm wavelength range—the Laboratory is constructing a 28-foot linear array of four parabolic reflector antennas operating at a wavelength of 2 mm (140 GHz). Spacing between dishes is such that the array functions as a seven element interferometer. To achieve this, data from the four elements are signal processed by a computer which restores the image and enhances it.

A new temperature controlled structure to house the device has been built and the array components have been installed. Such a building poses construction problems not only because heat and cold distort the precision alignment of the array but because minor vibrations can also upset operations. This



Placed in operation during the period was AFCRL's 2 mm array shown in the construction phase in the photo above. Inside this temperature-controlled building are four high precision dishes. Optical theory rather than antenna theory dictated the design of this system.

latter necessitates a huge antenna base with deep foundations.

This antenna incorporates new concepts for feeding the parabolic dishes. Lenses and mirrors are used for the transmission of this extremely high frequency; it is in fact treated in much the same way as visible light. The finished instrument will be used for experiments at 2 mm, a region of the spectrum relatively unexplored.

DATA PROCESSING FOR INCREASED RESOLUTION: The Laboratory has demonstrated that the resolving power of an antenna can be improved by 50 to 100 percent by signal processing. Directly applicable to situations like those around crowded airports where today's broad-beamed FAA radars are pushed to their limits, the technique can also be adapted to airborne radars forced to use small diameter antennas to fit in the aircraft nose.

The AFCRL spatial frequency processing scheme was tested with the Laboratory's 29-foot antenna in Waltham, Mass. The processing has two major phases: first, the spectral components of the source (like the sun) or target (in radar applications) must be restored. The antenna, because its pattern isn't a single perfect beam but rather is divided into lobes and nulls, always gives an incomplete picture of what it views; so by melding the incoming data together with the known antenna pattern it is possible to reconstruct the image. The second step is to retrieve and sharpen detail through iterative solution of a complex integral equation.

The accuracy of the technique is only as good as the accuracy of the antenna pattern, a quantity usually difficult to obtain with large antennas. But for small dishes whose patterns are easy to gauge, or for larger existing dishes whose characteristics can be measured very accurately—like antennas at major air traffic control centers—the technique can be made to work well.

PRESCRIBED NULLS IN RADIATION PATTERNS: Two distinct problem areas in antenna array design are maximization of directive gain and radiation pattern beam shaping. In the former, generally little consideration is given to the radiation pattern structure that results from the maximization procedure. A high gain antenna may well have a pattern unacceptable from other standpoints. In beam shaping operations on the other hand, control over the pattern structure is the prime requirement and one usually obtains good pattern control only with a significant sacrifice in gain.

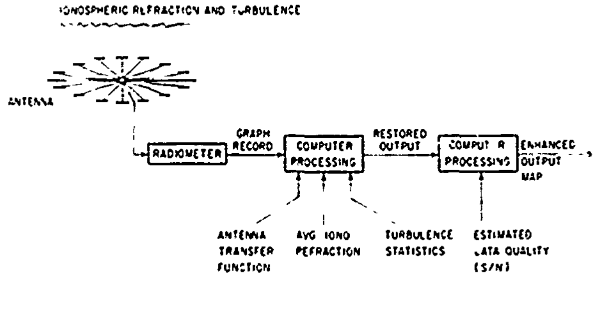
There is, however, a class of very practical problems, intermediate between these two traditional extremes, in which one simultaneously seeks maximum gain in a prescribed direction and some degree of pattern control in one or several other prespecified directions. For example, in a radio communication link or in a missile detection radar, the design goals are maximum gain in the direction of some distant transmitter or receiver and the reduction or elimination of interference or jamming from other directions. In such cases, one would like to restructure the radiation pattern—placing nulls or reducing the radiation level—subject to the constraint that the resultant gain be the largest possible under the conditions imposed.

A technique has been developed that maximizes directive gain subject to certain pattern constraints. The method is applicable to any number of array elements, uniformly or non-uniformly spaced in any geometric configuration, and allows the designer to specify arbitrary directions for pattern nulls and/or sidelobes, while guaranteeing maximum gain in some prespecified direction. All mutual coupling effects are accounted for. Only the element currents need be varied (in amplitude and phase), making the method useful for adaptive operations in which the pattern must be rapidly reconfigured, often without the possibility of a change in element locations. This constraint technique is an attractive way of mak-

Historically, the program of the Microwave Physics Laboratory has been marked by strong emphasis on theory. Theoretical concepts are then translated into test equipments.

ing corrective alterations to the radiation pattern structure in a manner which, at the same time, assures maximum gain.

ANTENNA DESIGN FOR TURBULENT MEDIA: Quite often, the medium through which an electromagnetic wave must pass on its way from transmitter to receiver is a turbulent one. The ionosphere is one example of such a randomly varying medium. Such media tend to decorrelate signals which pass through them, and since correlation represents, in a crude way, the information content of a signal, there is a loss of information in a turbulent medium. The Laboratory has developed antenna design techniques which optimize the amplitude and phase taper of a receiving array which may be part of a communications link operating in a turbulent medium. Maximum information transfer is the objective, and this is accomplished by the maximization of the transcorrelation function (a space-time average of the correlation between the input and output signals of the communications system). The relation between the transcorrelation function and the statistical properties of the parameters of the random medium have been established. Coupled to a previously developed relationship between the transcorrelation function and the antenna parameters, a complete solution linking signal, antenna and turbulent medium has been derived.



Shown here is a block diagram of the HF ionospheric mapping array. Computer processing restores and enhances the image.

MM WAVE PROPAGATION

The Laboratory's millimeter wave research program has two principal objectives. The first is to investigate the limitations imposed by the atmosphere on propagation of electromagnetic energy at millimeter wavelengths. The second is to use the propagated wave as a diagnostic tool to obtain information on lower atmospheric structure and to investigate the gross surface properties of the sun, moon and near planets. Several radiometric systems are used for these studies but the primary instrument is the Laboratory's 29 ft mm radar in Waltham, Mass.

Strongly motivating this research is a requirement for high data rate and broadband earth-to-space communication channels. Small wavelengths mean high gain, high resolution, compact antennas, all of which are obviously desirable in space vehicle instrumentation. As smaller wavelengths are used, however, certain antenna problems arise. One of these is that the ultimate size of the antenna aperture is limited by mechanical tolerance. Contouring of the collecting surface must approach optical tolerances to overcome aberrations. The system is also "atmosphere" limited, in the sense that there is a strong interaction between the lower atmosphere and millimeter waves that degrades antenna performance. It may be possible however to use this effect to obtain information on clear air turbulence, atmospheric temperature, pressure, water vapor profiles and cloud composition by using a short wavelength radar and radiometric sensors.

ATMOSPHERIC ATTENUATION: Use of millimeter waves in earth-to-space communication systems has many attractions but one big disadvantage—atmospheric attenuation. How severe this disadvantage would be must await the accumulation of statistical data on attenuation at various mm wavelengths. Two methods have been used by the Laboratory for obtaining such data: 1) Using the sun as a source and observing the change in the received signal as a function of atmospheric conditions and 2) by assuming the atmosphere is in thermodynamic equilibrium and treating it as a black body, the attenuation is determined from a measurement of atmospheric emission.

Previous measurements at 15 and 35 GHz using both methods have shown that clear sky attenuations are well correlated with absolute humidity and increase proportionally with the secant of the zenith angle. This agrees very well with theory. Although the attenuation is low for clear sky and increases slightly for unsettled conditions, it becomes quite large for heavy rainfall. To gather rainfall statistics, a radiometric system operating at frequencies of 15 GHz and 35 GHz was installed in Hilo, Hawaii, a region that has rain about 300 days per year with a mean annual rainfall of approximately 140 inches.

From the data obtained so far, it is evident that in selected portions of the millimeter band the attenuation is sufficiently low to permit wideband earth-to-satellite communications with moderate reliability. For very high reliability, the earth terminal should be located at a high elevation in a dry climate since atmospheric attenuation decreases with both increasing altitude and decreasing humidity. Because heavy rainfall is usually quite localized, there is also the possibility of using two or more terminals spaced sufficiently far apart with the reasoning that heavy rain occurring at all terminals simultaneously is quite unlikely.

This high precision 29-ft millimeter wave antenna located in Waltham, Mass., has been used for many years for atmospheric and solar research.

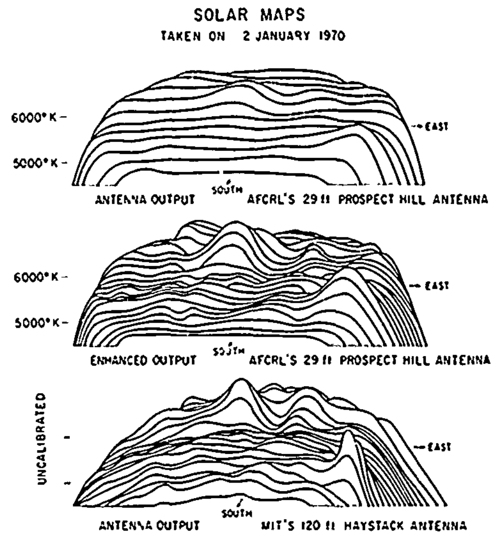
SOLAR OBSERVATIONS: Observations of the sun have been conducted for many years to derive criteria for predicting solar events that are translated into terrestrial effects. (For an expanded discussion of this forecasting problem, see Chapter VII.) Among these terrestrial effects are aurora, hf communication blackouts, and magnetic storms. The most disruptive solar event triggering these effects are proton flares.

The sun can be considered as a

plasma with a plasma cutoff wavelength which is a function of solar altitude. This means that the depth from which electromagnetic radiation is received from the sun is a function of wavelength. Radiation at optical wavelengths originates from the photosphere (the apparent solar surface) ; that at centimeter wavelengths, from the high chromosphere (8-10,000 km above the photosphere) and that at the longer wavelengths from the corona (the outermost section of the sun). Radiation at millimeter wavelengths originates from a region above the photosphere about half way into the chromosphere, the region in which flares are believed to have their origin.

To obtain much needed data for solar flare forecasting, the Laboratory observed the sun over a long period at 8.6 mm, a wavelength at which radiation primarily from the upper and middle chromospheric regions originates. Daily mappings of the blackbody temperature distribution over the solar disk are conducted with the 29 ft mm antenna. Active centers appear as local enhancements in the observed intensity distributions; the sizes and degrees of enhancement depend markedly on wavelength.

The general features of millimeter wavelength observations show that active regions exhibit blackbody temperatures as high as 25 percent above the quiescent background levels. Of particular interest at 8.6 mm are the temporal variations of the active regions as they pass across the solar disk. They exhibit two distinct time scales. The first type, or slow variation, occurs over periods ranging from several hours to a few days. The second type, or burst variations, have time durations of the order of a few minutes. Bursts have been seen only in those regions exhibiting at least a 6 percent level of enhancement and for which there has been an optical event taking place simultaneously. These burst variations have usually produced an order of magnitude increase in the intensity levels, but because of the small size of the brightened region, such bursts have increased the total solar flux by only a few percent. Exceptions to this situation have been found to occur during proton producing burst events where increases comparable to the total flux from the sun have been observed to originate from regions with an area less than 1 percent of the total solar disk. In one case, the intensity of a burst produced an 82 percent increase in the solar flux at a wavelength of 8.6 mm.



The three plots of solar temperatures show that by processing signals from a small dish (center plot), resolution comparable to that obtained with a much larger dish (lower plot) is possible.

The solar mapping program is being

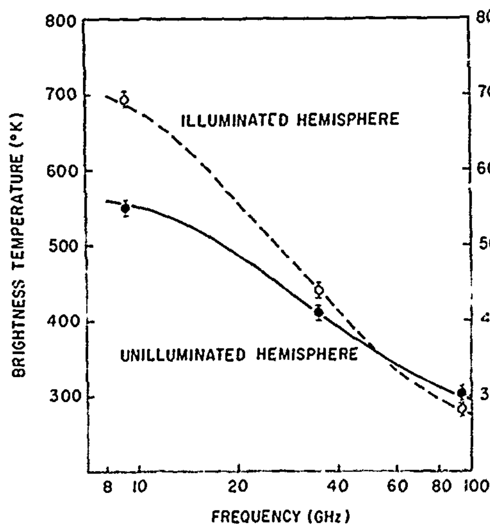
extended to provide observations at three frequencies—15, 35, and 95 GHz—simultaneously. Spectral as well as temporal variations will be studied for use in improving solar forecasting techniques.

THE VENUS ATMOSPHERE: To point up the wealth of information that can be derived from radiometric millimeter measurements, the results of a study of the Venus atmosphere should be noted in passing. The results of these earth-based measurements were in good agreement with those obtained by the Mariner 5 in its Venus flight.

Measurements of the spectral characteristics of the Venus radio brightness temperature were used to construct the following model of the Venus atmosphere: on the Venus surface, one would find an intense and perpetual dust storm, with the wind sweeping across the arid surface picking up dust particles eroded to fine aerosols. The particles are carried to heights of 60 km or so by strong convection currents created by the 820 degree K daytime temperature. The night-time temperature (Venus has a rotation period of 243 days) is about 620 degrees K. During the night when the convection currents cease, dust concentrations at high altitudes greatly decrease although concentrations in the lower Venus atmosphere remain heavy.

LOWER ATMOSPHERIC STRUCTURE: The fine structure and turbulent dynamics of the earth's troposphere—the region from the surface up to heights of 10-18 km—often go unrecorded by sensors carried aloft in balloons, rockets and aircraft since these sensors provide only a fleeting picture of the situation at one instant of time. Tropospheric structure, however, is closely represented by its refractive index which is a function of temperature, humidity and pressure. Inhomogeneities in the refractive index cause scattering of electromagnetic waves. Information about composition, organized motion, and turbulence within the troposphere may be obtained from the magnitude, the doppler shift and the doppler spread of the scattered signals. Using a monostatic or bistatic radar of sufficient spatial resolution, the scattering characteristics of a small portion of the troposphere can be monitored along with the range of doppler shifts occurring in this region.

Forward scatter from relatively weak tropospheric inhomogeneities exceeds backscatter by orders of magnitude. The Laboratory and the Canadian Communications Research Centre in Ottawa have established a high resolution, forward scatter path length of approximately 500 km. Two kilowatts of highly



From this plot of the temperature variations of Planet Venus a model of the Venus atmosphere was postulated. It is interesting to note that the dark side of the planet at a frequency of about 88 GHz appears warmer than the sunlit side. Dust in the Venus atmosphere can produce this effect.

stable cw power are transmitted from the AFCRL 29 ft antenna and received by the Canadian station which has an equivalent antenna. The frequency of 15.73 GHz is the highest ever used for a long-range troposcatter experiment. Both terminals are equipped with synchronous computer-controlled beam-swinging so that the volume common to both antenna beams (beamwidth 0.16°) can be rapidly scanned along arbitrary tropospheric paths.

Data being examined are signals scattered from the troposphere over a five-hour interval. The data show many small-scale changes in the scattering layers during this interval.

A large number of tests have been performed to analyze tropospheric composition, generally in the form of two-dimensional cuts through a volume centered at midpath. These cuts are 200 km long, 100 km wide, and range from 5-15 km in height. Crosspath wind measurements in the upper troposphere have been routinely made by recording the average doppler frequency offset and have been successfully correlated with radiosonde data.

Along with this meteorologically oriented work, the beyond-the-horizon communication characteristics of the medium are investigated. Because tropospheric scattering is a random, fluctuating phenomenon, at least from a microscale point of view, careful consideration is being given to bandwidth limitation and correlation between signals received on discrete frequencies.

PLASMA ELECTROMAGNETICS

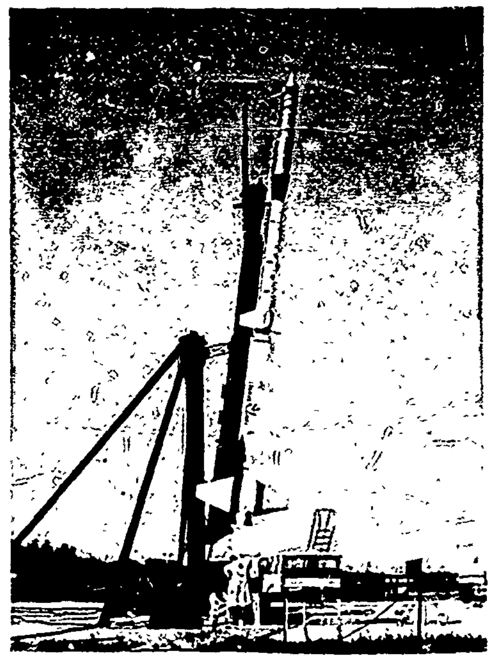
The plasma sheath surrounding a re-entering aerospace vehicle disrupts electromagnetic radiation to and from the spacecraft or missile. The problem, insofar as the ballistic re-entry of manned space vehicles is concerned, presents inconveniences but can be lived with. But in terms of projected Air Force capabilities, solution to the plasma sheath problem is a goal of considerable priority. Disruptive effects include signal attenuation and distortion, antenna voltage breakdown, radio noise generation, and channel cross modulation. Separate from but related to these problems are those caused by vehicle wakes during re-entry and by rocket exhausts during the launch phase.

Research efforts, which range from rocket flight tests to laboratory studies in simulated plasma media, provide both the necessary practical solutions to these problems and a better understanding of the physical nature of the plasma sheath. Plasma alleviation techniques (principally the use of chemical additives and magnetic fields) and diagnostic instruments to measure the in-flight characteristics of the plasma sheath have received major emphasis.

For its simulation experiments, the Laboratory installed two new plasma generators during the reporting period —added to a DC arc-jet facility in operation for many years. One of these is a "button-type" discharge (developed by the Aerospace Corporation) by which means a uniform stable plasma is produced. Another new equipment is a high temperature, high velocity airflow system designed to produce a continuous supersonic airflow in the 2000 degrees K region.

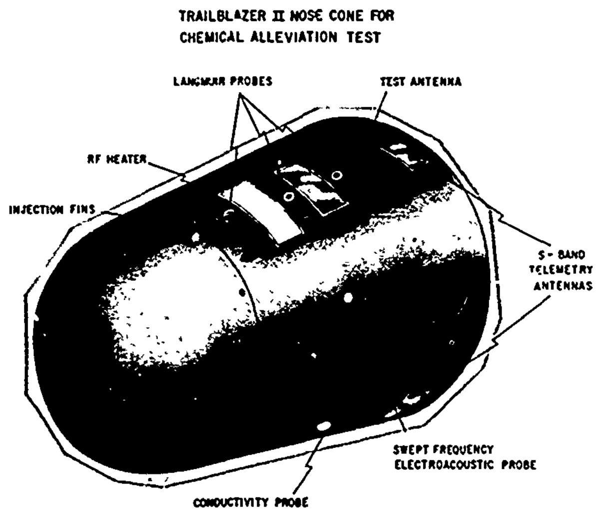
Microwave tests on chemical additives, using the DC arc-jet facility, have shown that liquid droplets of electrophilic compounds, such as the fluorocarbons, are very effective in reducing electron density in a high-temperature plasma. The measurements indicate that the plasma is converted, through the action of additives, into a nonattenuative type of medium, consisting primarily of positive and negative ions rather than electrons. These studies and related work show that chemical additives are very effective in improving radio transmission through the re-entry plasma sheath. The arc-jet facility is, therefore, being upgraded to permit additional tests on the effects of heat shield ablatives, contaminants, and high microwave power levels on the performance of chemical additive systems. Several theoretical studies have also been pursued with the goal of selecting optimum chemical additives (based on their chemical and physical properties) for specific flight parameters and operational requirements.

ROCKET PROGRAM: Two rockets were launched from Wallops Island, Virginia, during the period, one in October 1967 and one in June 1969. The June 1969 flight of a Trailblazer II was similar to an earlier June 1967 flight. Data from these two rockets produced some interesting conclusions. Test results indicate that the radio blackout effects of the plasma sheath occurred at an altitude about 10,000 feet lower than the predicted blackout altitude. This discrepancy remains unexplained even though relatively sophisticated flow field calculations (using a merged plasma flow rather than separate boundary and shock layers) were made.



In June 1969, this Trailblazer II was launched from Wallops Island to measure radio transmission through the plasma sheath. After reaching apogee, the final stage of the rocket was fired downward to achieve reentry velocities.

Measurements of the in-flight radiation patterns of an S-band slot antenna, mounted at the stagnation point of the nose cone, show that the shape of the antenna pattern is unchanged by the thin plasma sheath. But the signal is strongly attenuated. Both effects had been predicted. The theoretical variation of the antenna admittance with the



This nose cone contains chemicals which will be released during re-entry to alleviate plasma sheath effects.

plasma sheath profile displays a strong dependence on only one parameter: the distance from the missile skin to the region where the plasma becomes overdense. This distance is defined as the electromagnetic boundary layer thickness at the operating frequency. The S-band signal was strongly attenuated as altitude decreased, with an almost total radio frequency blackout below 230,000 feet. Measurements of the coupling between the transmitting antenna at the stagnation point and a similar receiving antenna at the shoulder of the nose cone show a slight initial rise in coupling at very high altitudes (which may be indicative of trapped surface waves in the plasma layers) followed by a very sharp decrease. This decoupling at the lower altitudes is almost entirely caused by power reflection losses in the transmitting antenna, rather than by external coupling losses.

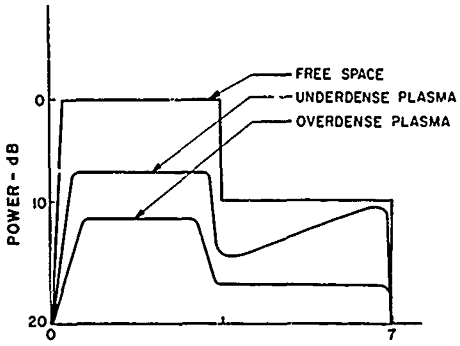
In the Trailblazer II rocket flight of June 1969 the pulsed microwave power to the S-band antenna was varied in discrete steps of 60, 100 and 300 watts. At those altitudes for which the electron density in the plasma sheath was almost critical but still underdense, nonlinear effects of pulse distortion and excess signal attenuation were clearly evident at the high and medium but not the low, power levels. The altitude at which the reflection coefficient of the antenna increased sharply due to plasma sheath effects was about 10,000 feet greater for the high power signals than for low power. Calculations of the nonlinear interactions of S-band microwave signals with ionized flow fields have been initiated to corroborate these results. These flight data, taken under relatively ideal flow conditions, will serve as a benchmark for both linear and nonlinear plasma effects against which theoretical speculation and other field tests may be compared. Two more Trailblazer flights are scheduled. One in October 1970 will carry a plasma diagnostics payload; the other in 1971, a chemical additive experiment.

A Nike-Cajun rocket was launched in October 1967 to measure antenna voltage breakdown effects. The flight showed a strong correlation between the ease of antenna breakdown and the solar illumination of the antenna, confirming a theory proposed earlier. The postulated mechanism for this effect is the photoemission of electrons from the rocket skin, caused by the ultraviolet radiation of the sun. A theoretical and experimental analysis of the antenna breakdown problem is reviewed in the following paragraphs.

ANTENNA BREAKDOWN IN THE PLASMA SHEATH: The prediction of the power level at which a plasma-covered antenna will break down is of crucial importance for ECM vehicles which must operate at high power levels for jamming purposes. Many factors must be considered; the structure of the inhomogeneous near fields of the antenna, the electron density profile, the plasma temperature distribution and, finally, the electron production and loss rate coefficients.

The computations are complex because one must solve the Boltzmann equation for the electron distribution function which is then used in Maxwell's equations to determine the electric and magnetic fields. Since most of the information needed is either unknown or known only to order of magnitude accuracy, an alternate theory has been developed. This approach uses the continuity equation together with electron production and loss terms. In this theoretical model the effect of the plasma upon the radiation pattern of the antenna is neglected.

This continuity equation approach, although simpler than the Boltzmann-Maxwell equation system, is still difficult to solve when inhomogeneous electric fields, like those in the near fields of a re-entry antenna, are present. Recent studies by AFCRL contractors have developed a variational method, suitable for use with the continuity equation, that results in great simplification. In this method, one first selects an electron density trial function which is constructed to provide computational convenience in matching boundary conditions. The trial function contains arbitrary parameters which are used to prod... an approximate expression for the breakdown electric field strength. This method has the drawback that the resulting value for the breakdown field strength is merely an upper bound for the actual value. For field strengths greater than this calculated value, breakdown will definitely result. Unfortunately, there is no guarantee that breakdown will be avoided if the antenna is operated at lower power levels.



HIGH POWER PULSE SHAPE DISTORTION FROM S-BAND ANTENNA

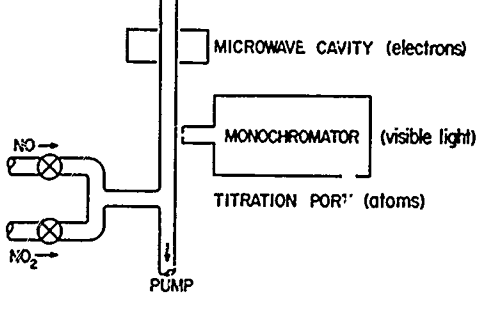
High power microwave pulses transmitted through an S-band antenna on the Trailblazer II nose cone are distorted by passage through the plasma sheath. The idealized, undistorted pulse has a two-level rectangular shape.

For this reason, the variational formulation has been extended to provide a lower bound for the breakdown field strength. This extension of the theory has been applied to several problems such as the gas breakdown in the uniform field between infinite parallel plates and the breakdown over both an infinite slot and a rectangular aperture in an infinite ground plane. These calculations demonstrate that the theoretical extension is mathematically tractable and also provide a comparison with previous calculations.

PLASMA DIAGNOSTICS: Studies of plasma from the standpoint of alleviating transmission effects center around the electron. Electrons, rather than heavier ions, interact with the EM radiation passing through the plasma. Thus if the electron concentrations can be reduced, effects can be alleviated. Tests at AFCRL have shown that chemical aerosols such as the fluorocarbons injected into the plasma can be extremely effective in reducing electron density.

Another electron-depleting technique under study is that of actually elevating the plasma temperature by rf heating.

Of the chemistry which occurs about a re-entry vehicle, the reaction $N + O +$ energy $\rightarrow NO^+ + e^-$ plays the most important role in determining the electronic properties of the plasma. The atomic nitrogen and atomic oxygen, produced by the high temperature dissociation of the ambient molecular species, combine to produce a nitric oxide positive ion and an electron. Although there are other electron producing reactions in the nitrogen-oxygen system, the above reaction requires the lowest energy and is most prevalent. This reaction has been measured in shock tube experiments by earlier investigators. It is being redetermined at AFCRL by a different experimental technique. Briefly, the required atomic species, N and O, are produced by using microwave cavities to dissociate flowing molecular streams which, when combined, give positive ions and electrons. Electron densities are determined by use of a resonant microwave cavity and positive ion densities by means of electrostatic probes, while chemical titration is used to determine atomic concentrations. Optical spectra are also monitored during the reaction.



CHEMICAL REACTIONS IN ATMOSPHERIC GASES

Shown here is a diagram of the apparatus for the measurement of the N + O reaction rate. Atomic nitrogen and oxygen are formed by microwave dissociators in the flowing gas system.

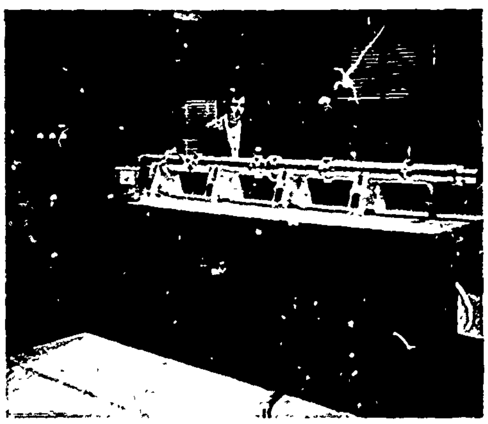
One of the proposals for alleviating the re-entry blackout problem is to induce the attachment of electrons to molecules, thereby forming negative molecular ions. Considerable interest thus exists in determining the rates of formation and subsequent disappearance of negative ions. Mass spectrometry is one method of detection and analysis of negative ions. However, the probing of negative ions is usually done outside of the main plasma region due to practical limitations on mass spectrometers.

When an electrical discharge is produced in certain gases, such as CO_2 and SO_2, extremely intense electromagnetic emission is produced over certain frequency bands in the microwave region. This emission would correspond to temperatures of over 106 degrees K, but it is evident that the noise output is not thermal. Its source is unknown.

Experiments are being performed to determine the basic characteristics of this unexplained emission. A spectrum analyzer is used in these experiments to scan the noise output of various gases at different pressures and discharge conditions. In this way, a catalog of the basic properties can be built up and eventually used to explain this noise phenomenon.

WAVE PROPAGATION IN HOT MAGNETOPLASMAS: Another aspect of plasma work is concerned with deriving dispersion relations for electromagnetic waves propagating in plasmas immersed in a magnetic field. These dispersion properties as functions of frequency can be used to predict the distortion and attenuation of waves propagating in a plasma as a function of the parameters characterizing the medium. The results of such investigations are required in the design of any radio communications system in which waves must propagate through an intervening plasma medium, such as in re-entry communications systems and in ionospheric propagation work.

Conventional dispersion relations, such as the Appleton-Hartree equation, neglect a number of important properties of plasmas affecting wave propagation. The Laboratory effort is concerned with deriving dispersion relations that are much more accurate and that are valid over a much wider range of plasma parameters than previous theoretical formulas.



This 10-ft coaxial transmission line is used to make measurements of plasma attenuation of EM energy. A moving ionized front is propagated within the test chamber.

One effect that is included in the study is termed "transconductance," a nonlocal effect due to the fact that the electrons, because of their thermal motion, can move during one period of oscillation of a wave. Another important effect involves collisionless wave damping which occurs because of phase mixing and is manifested by the transfer of energy from the wave to a resonant group of particles. Also, energy dependent electron-neutral collisions can alter the wave attenuation characteristics. In addition, the Coulomb forces between the charged particles has an effect on the dielectric properties of the plasma. The theoretical dispersion relations predict pass bands, or resonances, at harmonics of the electron cyclotron frequency for waves propagating across the magnetic field lines. The dispersion relations are obtained by solving the Boltzmann kinetic equation using a variety of Fourier transform techniques and perturbation methods. Graphs have been prepared of the propagation constants plotted over a wide range of normalized plasma parameters.

MICROWAVE ACOUSTICS

A renaissance in microwave acoustics, relatively quiescent for several years, has occurred with the shift in emphasis from transmission through bulk material to surface transmission. Many believe that microwave acoustics will be a major growth technology over the next decade, leading to the replacement of a sizable percentage of electronic circuitry by electroacoustic components.

Microwave acoustics involve the manipulation of slowly propagating elastic waves in a material. The waves, which may be acoustic or magnetic, can

Microwave acoustics research at AFCRL involves studies of optimum acoustic materials, wave propagation characteristics of materials and transducers for converting EM energy to acoustical energy.

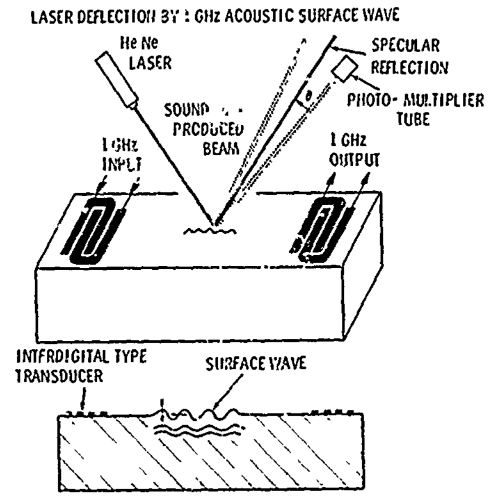
propagate as a volume wave inside a single crystal solid or as a surface wave on an optically polished surface of the solid.

Emphasis on surface transmission has brought closer to reality a long list of electroacoustic components. These microwave acoustic devices can perform most of the functions of purely electronic devices and they can do it in smaller packages, since the acoustic velocity and wavelength are five orders of magnitude smaller than their electromagnetic counterparts.

AFCRL started its microwave acoustics program in 1958 and was then almost alone in the field. It has retained a strong position of leadership since a fundamental part of present research consists of a search for optimum microwave acoustic materials. In this connection, AFCRL in 1970 published a 350-page *Microwave Acoustics Handbook* (AFCRL-70-0164) which gives the properties of all presently known acoustic materials and which can serve as a basic guide for researchers in this expanding field.

ACOUSTIC SURFACE WAVES: During the period, the Laboratory developed a new technique for measuring the microwave acoustic surface wave losses in microwave acoustic materials. As the waves propagate along the surface of a material, they diminish in strength. The basic measure of merit of a microwave acoustic material is therefore its loss rate with propagation distance. Loss rate varies with material. Loss rates also result from microscopic pits and defects, thermal scattering, and foreign substances on the surface of the material. Measurements at AFCRL of the temperature dependence of the attenuation have shown thermal scattering to be the dominant loss mechanism on carefully polished and cleaned samples of lithium niobate, currently the best performing microwave acoustic material.

The AFCRL measurement technique uses a one-millimeter diameter laser beam directed at the surface of the material at roughly a 45 degree angle. The surface wave acts as a moving diffraction grating which reflects the light into a number of sidelobes at angles prescribed by scattering theory. This deflected light is detected by a photomultiplier. The technique was used to measure the surface wave attenuation of lithium niobate at various frequencies up to 3.5 GHz by scanning the laser along the material. The results show that the loss per wavelength was very much lower than for electromagnetic waves



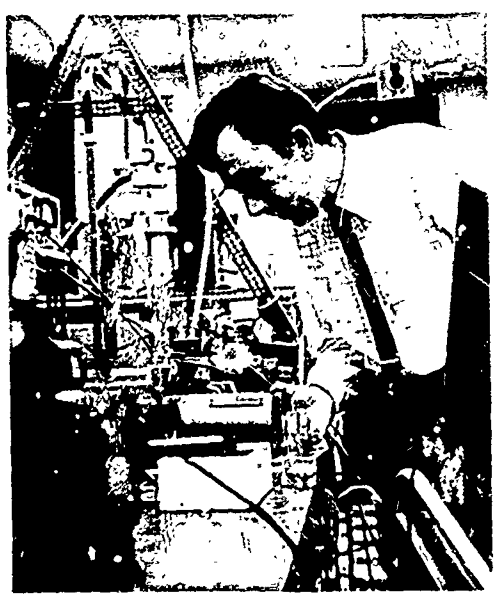
Diagrammed here is AFCRL's laser deflection method for measuring the acoustic surface wave losses on lithium niobate at microwave frequencies.

in a coaxial cable The AFCRL laser technique is becoming a standard method for analyzing the properties of microwave acoustic materials.

In addition to propagation loss measurements, the laser system is being used to investigate beam steering losses and nonlinear effects. Beam steering arises when surface wave transducers are not properly aligned with the pure mode crystalline axes of the substrate and cause all or a significant part of the acoustic energy to miss the output transducer. This can be a dominant source of insertion loss unless understood and properly corrected for. Nonlinear effects arise because the acoustic energy is concentrated within about one acoustic wavelength (about 4 microns at 1 GHz) of the surface. The research on these nonlinearities has resulted in efficient harmonic generators, acoustic limiters, mixers, and has shown the possibility of parametric amplification.

The AFCRL research program has produced design data necessary for the fabrication of any microwave acoustic device. The orientation dependence of the velocity on 22 different anisotropic materials has been computed and assembled in the *Microwave Acoustics Handbook* noted earlier. A highlight of this work is the discovery of a new 41.5 degree orientation of lithium niobate which has higher piezoelectric coupling than any other previously known orientation and has lower beam steering.

MAGNETIC SURFACE WAVES: A magnetic surface wave is defined as a magnetic disturbance along the surface of a saturated ferrimagnetic crystal—such as yttrium iron garnet (YIG), Energy is transferred along the surface from one lattice site within the crystal to a neighboring one via the quantum mechanical exchange force between electron spins. The characteristics and properties of such a mode of propaga-



AFCRL sponsored the development of the first YIG crystals grown in this country and since has conducted continuing investigations into the application of these ferrimagnetic crystals in devices.

tion were recently predicted by AFCRL scientists.

Macroscopically, the magnetic surface wave shares certain common features with the Rayleigh acoustic surface wave. That is, wave amplitudes decay rapidly within a few wavelengths from the crystal surface while successive phase fronts lie in the surface plane and propagate at a velocity less than that of the bulk wave velocity.

In a magnetic wave, the magnetization vector precesses about a dc magnetic biasing field with the tip of the vector describing an elliptical path in a plane perpendicular to the surface and to the biasing field. The relative elastic displacement of a lattice point, due to a propagating Rayleigh acoustic surface wave, undergoes a similar elliptical motion. Unlike surface acoustic waves, however, magnetic surface wave propagation is non-reciprocal, dispersive, and tunable via the biasing field. These properties may be used to advantage in constructing microwave signal processing devices such as isolators, circulators, switches, variable delay lines and filters. Both magnetic and acoustic surface waves are compatible with integrated circuit technology.

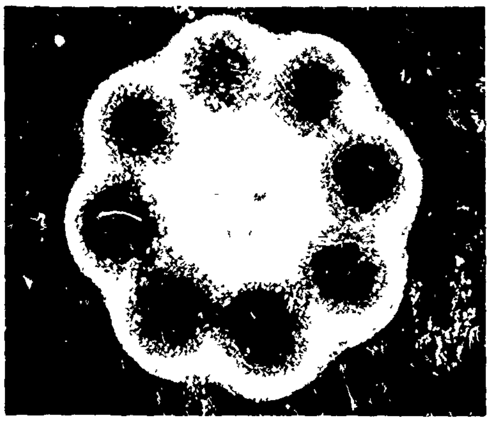
MICROWAVE ACOUSTIC "DOUBLE-QUANTUM" DETECTION: Microwave acoustic volume waves (phonons) have usually been detected piezoelectrically. The output of a piezoelectric detector depends on the phase, as well as the amplitude, of the wavefront at the detector. Since spurious effects, chiefly non-parallelism of the end surfaces, cause the wavefront to strike the piezoelectric transducer at an angle and partly cancel itself out, there is an inherent error in measuring attenuation. "Double-quantum" detection, on the other hand, yields a signal which depends only on the energy of the phonon pulse. It produces an exponential decay pattern and allows more precise attenuation measurements.

The detector consists of a resonant cavity placed on the sample rod in which the phonons propagate, so that the reflectivity of this cavity to microwave electromagnetic energy (photons) can be monitored. When the photon plus phonon energies add up to the Zeeman energy splitting level of paramagnetic iron impurities in the sample, a change in reflectivity is observed for each phonon pulse. Thus, a quantum of sound plus a quantum of electromagnetic energy are required for detection; hence the term "double-quantum."

This technique has additional advantages over piezoelectric detection. It simplifies fabrication since no transducer is required. Furthermore, detection occurs only for the proper combination of frequencies and magnetic field, so that it is possible to tune the detector by varying the field.

The "double-quantum" interaction also allows amplification of the phonon pulse with photon energy. Preliminary evidence indicates that this may be useful in microwave acoustic device technology by allowing direct acoustic amplification in a delay line. This effect can be explained by a Raman type transition in which a higher frequency photon is absorbed and a lower frequency phonon is emitted. Phonon detection due to this type of transition occurs at a lower magnetic field than that at which a photon and a phonon are simultaneously absorbed.

ANTIFERROMAGNETIC AND NUCLEAR SPIN-WAVES: The Laboratory has succeeded in exciting volume spin waves of definite quasi-momentum (k value) by the parallel pumping technique in antiferromagnetic media. This result can



When a crystal resonates, thus emitting EM energy in the microwave region, the energy does not emanate uniformly over the flat surface of the crystal. To measure the pattern of emissions over the crystal face, liquid crystal detectors can be used. Such detectors mirror the areas on the crystal face with sharp fidelity.

greatly extend the delay time of delay lines.

The experiment was performed using the low magnetic anisotropy antiferromagnetic compounds cesium manganese fluoride ($CsMnF_3$) and rubidium manganese fluoride ($RbMnF_3$). Low anisotropy—not usually found in antiferromagnets—means that the resonance frequencies of the spin system lie in the microwave region rather than in the millimeter wave region. This means that conventional microwave circuitry may be used, which is an advantage when a parallel pump instability must be detected. Also, when the anisotropy is low, the spin system can be "flopped" in low magnetic fields and this means that conventional electromagnets may be employed. In contrast, the observation of spin waves by parallel pumping in the more usual antiferromagnetic systems would have required much higher frequencies and magnetic fields.

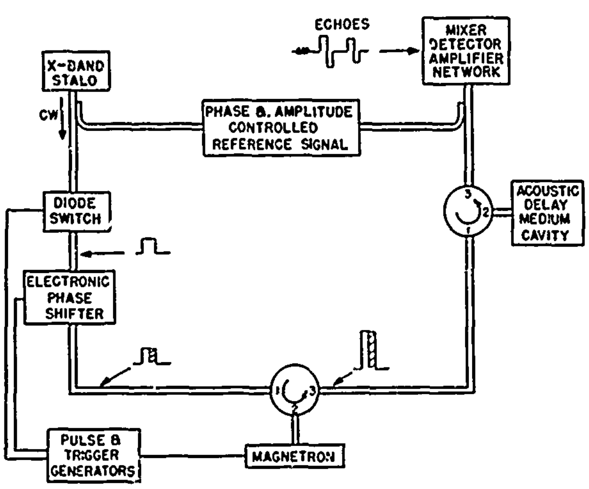
The "flopped" configuration implies that the antiferromagnetic spin waves precess in highly elliptical orbits. This is a necessary condition for success of the parallel pumping technique, which is really a method of spin wave amplification. By measuring the amplification threshold, the relaxation rates of the spin waves can be obtained. These rates have been measured over wide temperature and magnetic field ranges in $CsMnF_3$ and $RbMnF_3$.

A further consequence of the low anisotropy mentioned earlier is that the nuclear spin system is strongly coupled to the low-lying antiferromagnetic spin waves by virtue of the hyperfine interaction. This coupling induces low velocity spin waves in the nuclear spin system. Such spin waves have been excited for the first time, again by parallel pumping, in $CsMnF_3$ and their relaxation rates have been measured and compared with theory. The low velocity of these nuclear spin waves implies that, in a delay line application, long time delays are easily achieved.

MAGNETICALLY TUNABLE FILTERS: In past reports, two new microwave filters, developed at AFCRL, have been described. One used a high dielectric material, the other a ferrimagnetic substance in the resonant structures. Although both devices represented improvements in microwave filter technology, each had its limitations. The dielectric resonator had only a narrow tuning range while the magnetic device was limited in its power handling capability.

A new hybrid filter has been developed which, partially but significantly, removes both of these limitations without sacrificing filter performance. Operation of the device, in the form of a magnetically tuned band pass filter, is based on the coupling of the electromagnetic dimensional resonant modes of the dielectric resonator with the gyromagnetic resonance of YiG. The two materials are bonded together. The external dc magnetic field is used to change the resonant frequency of the hybrid device and the tuning range is about five times as broad as that obtained with the dielectric alone. The power handling capability is two watts; a significant improvement over the 10 mW capability of the YiG alone. Such hybrid filters have been built in the laboratory, operating in the S, C, X and K_u bands, at insertion losses of less than 2 dB. Filter materials including rutile, strontium titanate and temperature compensated rutile ceramic have been used successfully.

INJECTION LOCKED MAGNETRONS: The Laboratory has demonstrated that a magnetron can be locked in frequency and phase—with pulse-to-pulse coherence—to an external oscillator having an injection power 40 dB below the magnetron's output power. This input-output power ratio is 20 dB better (a hundred fold improvement in the state-of-the-art) than ratios previously attained in injection locked magnetron systems.



Diagrammed here is AFCRL's injection-locked magnetron. Pulse-to-pulse coherence to an external oscillator having an injection power of 40 dB below the magnetron output power has been demonstrated.

Injection locked pulsed magnetrons date back to the early days of radar so the concept as such is not new. The high performance achieved by AFCRL, however, has already led to the reappraisal of the magnetron as a radar power source. One manufacturer, Varian Associates, soon after the announcement by AFCRL, began to market the component.

The technique of injection locking consists of injecting input power from a low power oscillator into the interaction circuit of a second, higher power oscillator. When the two output frequencies become sufficiently close, the higher power device locks or synchronizes to the lower power device and a single output frequency is produced. Coherence is said to occur when the phase of the reference signal (injection signal) is preserved in the transmitter pulse (magnetron pulse).

A second phenomenon, locking bandwidth as a function of injection ratio was also studied. Long-term frequency stability, less than 1 part in 10^6, was observed. This indicates that the frequency stability of a locked magnetron is essentially that of the injection source. Coherence is maintained, without locking, on a pulse-to-pulse basis, provided the magnetron is initially started from the injection signal.

This work has led to the discovery of two new capabilities of particular interest to the Air Force. The first concerns phase pattern control. Changes in the phase of the entire injection pulse or portions of it are preserved in the output of the injection locked magnetron. This is in addition to the pulse-to-pulse coherence which is also preserved. Thus phase control at relatively high output power levels can be obtained by phase shifting at the much lower power levels (approximately 40 dB below the output) of the injection pulse. The second capability deriving from this work was the generation of a "Lashinsky Spectrum" containing simultaneous amplitude and frequency modulation.

The two results have clear systems application. A coherent radar system employing an injection locked magnetron with phase pattern control (pulse coding) could greatly reduce the system's complexity and at the same time give improved range resolution, reduced clutter, and lessen the radar's vulnerability to jamming. Injection locked magnetrons have additional applications in pulse coherent transponders, such as those used in missile systems, pulse doppler radars, MTI radars and IFF.

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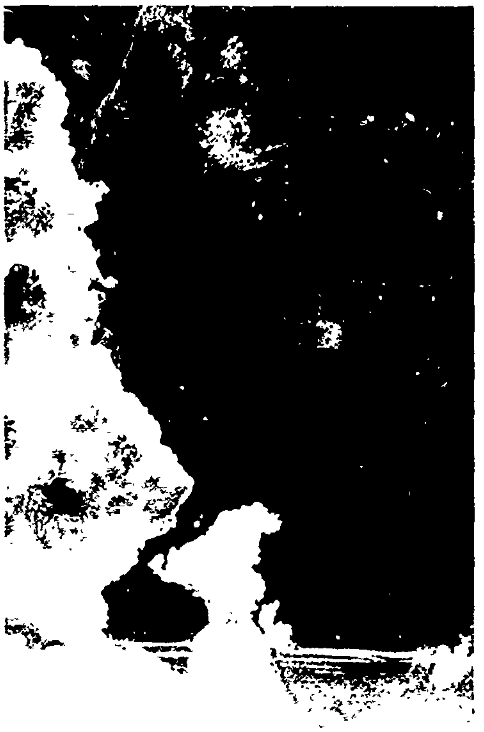


Clouds — their majestic sweep across the sky, their sometimes explosive growth to heights above 50,000 ft, the infinite variety of their shifting patterns — are the most visible and familiar manifestation of dynamic meteorological phenomena.

X Meteorology Laboratory

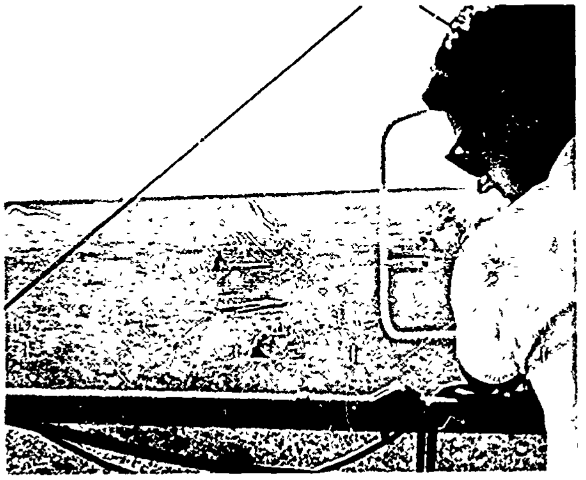
Weather research for the Air Force is centered in AFCRL's Meteorology Laboratory. The program of this Laboratory is based upon well-defined Air Force needs, needs that have historically involved aircraft operations, but that extend across the spectrum of Air Force missions—missile operations, radar surveillance, satellite reconnaissance, and all other operations where the state of the lower atmosphere is a factor. The general goals of this research are improved weather forecasting, limited weather modification, and detection of clear and cloudy air turbulence.

More specifically, the program of the Meteorology Laboratory includes the form and growth of cloud and precipitation mechanisms; the development of techniques of contrail suppression; the development of methods of dissipating warm fog and modifying the growth of convective clouds; the determination of the nature of turbulent transport of heat, momentum, and water vapor to and from the earth's surface; a search for methods of detecting and predicting clear air turbulence; and the determination of the role of atmospheric ozone in the heat budget of the upper atmosphere and as a tracer of upper air motions.

The program also includes the construction and testing of numerical models with which to predict the larger scales of motion in the troposphere and stratosphere as well as the investigations of ways of incorporating data from meteorological satellites in weather analysis and in the prediction of tropical systems, particularly those which are characteristic of Southeast Asia.

For this research, Laboratory scientists often find it necessary to develop special instrumentation for probing the atmosphere as well as methods for processing and displaying the research data. Since, in many cases, conventional sources of data are inadequate for research purposes, a substantial part of the Laboratory effort is devoted to observations. Many of these observations are unique and many require field programs.

Field trips often involve the Laboratory's C-130 instrumented aircraft which is a frequent participant in national multi-agency weather research programs. During the summer months, instrumented trailers are usually taken to the Laboratory's field site at Liberal, Kansas, for micrometeorological studies of small-scale processes in the lowest layers of the atmosphere. The largest single field expedition during the period was Project Haven Hop, in January and February 1970, a program in which the Air Weather Service, FAA, NASA, and the Army, joined the Laboratory in an extensive clear air turbulence observational program. During the six-week observational period several aircraft and a 12-site network extending from Delaware to North Carolina was set up, with activities centered at the Wallops Island, Virginia radar facility. This facility, described in the following section, is jointly operated by AFCRL and NASA, and is one of the Meteorology Laboratory's most important remote bases of operations.



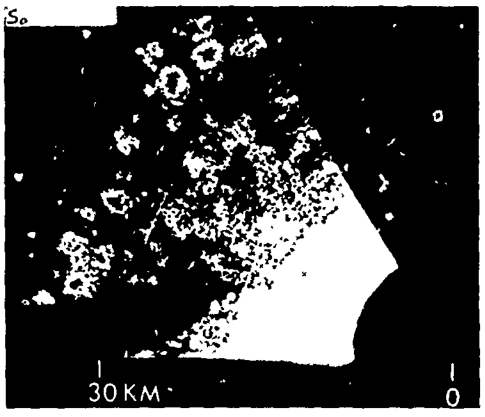
Micrometeorological research has been conducted for many years at a site located on a broad, flat wheatfield near Liberal, Kansas.

WEATHER RADAR TECHNIQUES

The weather radar program at AFCRL is centered at two locations. The primary site is the one at Sudbury, Massachusetts, where work is focused on the observation of precipitation systems and on the development of better weather radar and display systems. Here local thunderstorms and large convective systems are observed to learn more about their structure and dynamics and to deduce the fields of vertical and horizontal winds, wind variability, and moisture content. Five weather radars are in operation at Sudbury. Three of these, a 10-cm FPS-6, a 3.2-cm CPS-9, and a 0.86-cm TPQ-11, are standard radars, although experimental modifications have been made to each. The fourth radar is an experimental APQ-70 system, operating at 1.86 cm. The fifth radar is a nonstandard radar, designated the Porcupine Doppler radar.

The second site is located at Wallops Island, Virginia. The program at this site is sponsored jointly by AFCRL and NASA and is carried out with the help of the Applied Physics Laboratory, Johns Hopkins University. At the site are three high-resolution radars operating respectively at wavelengths of 71.5, 10.7, and 3.2 cm. Dish size for the first two is 60 feet; for the third, 34 feet. The very sensitive Wallops Island radars are used to investigate structures and phenomena in the clear atmosphere, the most important of these being clear air turbulence (CAT).

CONVECTIVE PATTERNS IN THE CLEAR ATMOSPHERE: During conditions of strong surface heating and light winds, sensitive 10-cm radars reveal thermal-like structures in the clear air, which are 1 to 3 km in diameter and several hundred meters in height. Echoes from



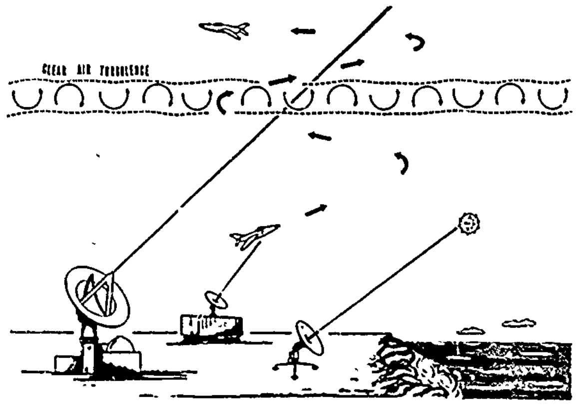
Radar echoes from clear air convective cells at 10.7 cm are seen in the donut-shaped reflections.

clear air convective cells in horizontal section are shown in the accompanying PPI photo. The echoes arise by virtue of the scattering from variations in refractive index. The echo structure displays the typical doughnut-type shape with circular or elliptical echoes and echo-free centers. The radar outlines the boundary of the cell, where the refractive index variability is large; when the radar is scanned in azimuth, a doughnut-shaped echo results. The flow within the convective cell is upward in the center; the relative flow around the periphery is outward and possibly downward.

The cells generally originate from a surface layer several hundred meters thick which forms over the heated land area. In 20 minutes the cell may develop to a mature stage with tops extending to a height of 2 km. In the mature stage the cell domes lose their connection with the lower environment, their bases tend to close, and the cells develop into expanding, oblate spheroids, which later dissipate, breaking up into fragmentary parts.

On occasion, the tops of many of the convective cells may be associated with developing cumulus clouds, although evidence of the detailed correspondence is missing. But the echoes seen in the photograph are not due to particle scatter, as can be shown by multiwavelength radar measurements. Presumably, drag forces around the updraft induce turbulent stirring which results in enhanced refractive index variability where the rising moist air contrasts markedly from the drier environment. The refractive index variability is mainly due to water vapor fluctuations; temperature differences are essential only in providing the buoyancy that establishes the flow.

RADAR INVESTIGATION OF CAT: Powerful radars at wavelengths of 10 cm or longer can detect horizontally stratified layers in the clear atmosphere. The backscattering originates from zones of enhanced refractive index variability created by turbulent mixing of the mean gradient of potential refractive index. When water vapor gradients are strong, as in the lower troposphere, modest stirring results in radar returns, and the



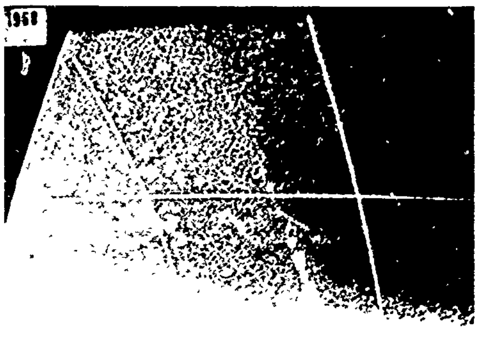
At the Wallops Island site, experiments frequently involve CAT observations with ground-based radars while an aircraft flies through the region observed by the radar.

turbulence may not be very noticeable to an aircraft. The stratified layers correspond to zones of enhanced static stability although water vapor fluctuations may dominate the backscattering in the lower few kilometers of the atmosphere. Presumably, the vertical temperature structure is significant in providing stable zones, where moisture contrasts are accentuated; the stable zones are then outlined as stratified echoes mainly from water vapor perturbations due to small-scale turbulence.

Evidence is now available that the stratified echoes at higher altitudes generally are associated with pronounced vertical wind shears. Marked turbulence is also present in the vicinity of these layers, as evidenced by an increasing number of joint radar and aircraft studies of CAT. These studies were preceded by the radar detection of the tropopause and the prediction that these echoes were associated with significant CAT. The basis of this prediction was the thesis that strong mixing is required for radar returns from temperature perturbations when the water vapor contributions to the refractive index variability are negligible.

Support for this thesis was provided by flying aircraft into regions of clear air radar echoes above 3 km. All clear air radar echoes were associated with at least some degree of turbulence. Not all of the turbulence found by the aircraft was detected by radar, however, but strong CAT was consistently more likely to be detected than weak turbulence. The indications are that strong CAT at high altitudes is generally associated with zones of increased refractive index variability and enhanced radar backscattering. Therefore, if radars of extreme sensitivity are employed, an operational ground-based CAT detecting radar system may be feasible.

Radar echoes from regions of CAT are generally quite patchy and often of a transitory nature, which is consistent



The 10.7 cm radar at Wallops Island detected at a height of 11.3 km the strange clear air structure appearing as a braided structure. The horizontal reference is 12 km. The braided structure occurred at the height of the tropopause.

with the general character of CAT as deduced from aircraft probes. Clear air radar returns frequently display wave patterns in regions of significant CAT. The range-height indicator photo on this page shows an example with two, apparently intermingling, waves in a clear air layer above a thick cloud deck. It is believed that this pattern is representative of the final stages of an overturning gravity wave and is the structure responsible for billow clouds which are sometimes observed at the crest of the waves. With the Wallops Island radars, several similar cases were observed in the winter of 1968-1969 during joint radar and aircraft studies of CAT. When probed with aircraft, these layers always outlined regions of significant CAT. Therefore, it appears that radar signatures from specific structure in clear air layers may offer the prospect of ground-based radar detection of CAT.

HAVEN HOP: The most intensive CAT observation program carried out to date was conducted during a six-week period, January 12 through February 21, 1970, when AFCRL was joined by the Air Weather Service, FAA, NASA, Army and the National Research Council of Canada in a program to observe the origins, movements and severity of clear air turbulence. The atmosphere between 10,000 and 45,000 feet was monitored. Activites centered at Wallops Island, Virginia.

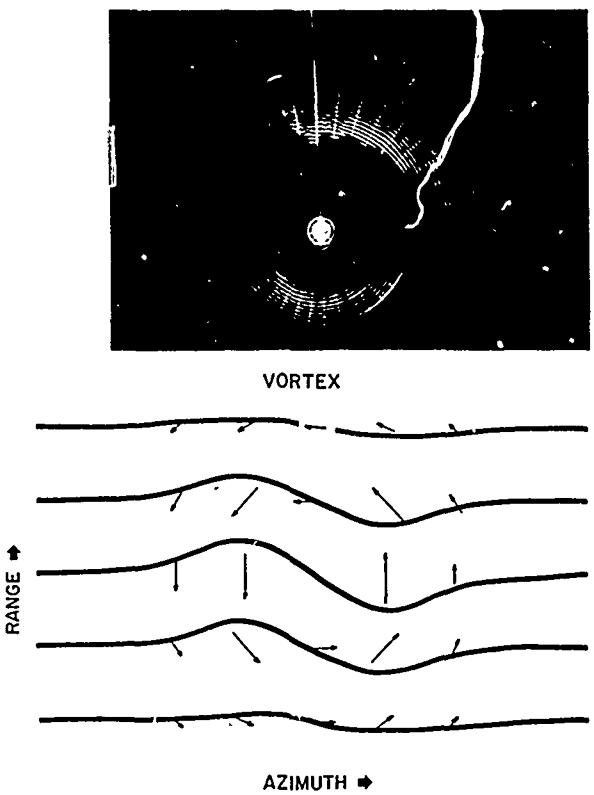
Purpose of the program, with the nickname HAVEN HOP, was to define techniques leading to CAT forecasting and to better methods of CAT detection. The Wallops Island radars, instrumented aircraft, and upper air rawinsonde soundings served as the basic data gatherers. HAVEN HOP represented an extension of the radar investigations of CAT discussed in the above section.

In addition to the continuous observations made by Wallops Island radars during the HAVEN HOP program, the program involved instrumented RB-57 aircraft flights into regions of CAT to check radar observations against severities measured by the aircraft. T-33 aircraft made similar penetrations and also carried instruments to measure temperature, pressure, dew point, and wind velocity and gustiness. During CAT observation periods, rawinsonde balloons were launched at two-hour intervals throughout the six-week observational period from eight stations of a 12-site network, and at six-hour intervals at the other four. This rawinsonde network extended from Delaware on the north to Cape Hatteras, North Carolina, on the south, and from the coast westward to Huntington, West Virginia.

PLAN SHEAR INDICATOR: A new technique for detecting severe turbulence in storms and for displaying this turbulence on a radar PPI was developed by the Meteorology Laboratory during the reporting period. When used at large air terminals, this technique would enable air traffic controllers to guide aircraft around the hazards of severe cloudy-air turbulence during the critical letdown and climb phases of the flight.

The system is called the Plan Shear Indicator (PSI). It uses a Doppler weather radar and a coherent memory filter coupled with an ordinary PPI scope. The coherent memory filter is the key component in the system. Essentially, it is a specialized spectrum analyzer having the capability of producing Doppler spectra at all radar ranges almost simultaneously.

The PPI display from a conventional weather radar tells little about internal wind velocities. Only the large silhouettes of storm systems is seen. More sophisticated Doppler systems can detect wind fields within storms, but they



The Plan Shear Indicator display distinguishes between the smooth arcs of the echo to the south and the wavy arcs of this storm north of the radar. The smooth arcs indicate relatively homogeneous flow while wavy arcs just to the right of the North marker are indicative of a cyclonic vortex of the type diagrammed below.

sacrifice real-time display capability because of excessive data processing time.

On AFCRL's PSI display is seen the same cloud system, but instead of the solid silhouette, the storm is represented by discrete lines. The lines are arranged in concentric arcs out from the radar location. These lines represent range-gated intervals of about a half mile separation. But they also represent wind velocity information. In other words, range and velocity information share the same coordinate on the PSI display. Where there is a sharp change in wind direction or velocity, the lines at the range interval where the change occurs will be distorted.

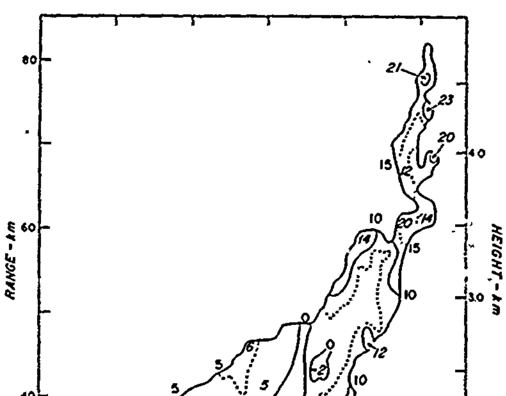
The alterations in the lines forming the picture of the storm are generated by the spectral analysis of the detected radar signal. The spectral data are used to position a particular range arc on the PPI. If the winds are moving away from the radar at a given velocity, the line will be displaced inward toward the radar with an increment depending on its velocity. If the wind is moving toward the radar, the line is displaced outward. Severe localized turbulence results in spectral broadening (because the radar cannot resolve details in this turbulence) and this tends to thicken the line.

Wind shear, turbulence, sinks and vortices can all be interpreted by the pattern depicted by the lines. A wind shift line of the type which might accompany a frontal passage is seen as a sharp displacement cutting across several lines. A vortex is seen as a wave-like structure in several parallel lines. This structure is produced as the winds move toward the radar at one edge of the vortex and away from the radar at the opposite edge.

The system has been tested against several local storms in the vicinity of AFCRL's Weather Radar Site at Sudbury, Mass., with excellent results. The Sudbury test radar operates at 5.4 cm wavelength and has a range of 88 miles.

CLOUDY AIR TURBULENCE: When Doppler radar, more than a decade ago, was first utilized for observing atmospheric wind structure, meteorologists were excited by cw-Doppler measurement of 200 knot winds in a tornado. With the development of accurately ranging pulse Doppler, velocity ambiguity limitations deflected the trend of research toward the more gentle widespread stratiform storms. Recently, however, AFCRL meteorologists have learned how to interpret velocity information despite the ambiguity problems, and many thunderstorms have been studied.

In one thunderstorm which passed over AFCRL's Sudbury, Mass., radar site, detailed vertical velocity spectra were recorded throughout the height and duration of the storm. This particular storm produced no hail or damaging winds at the ground, but the rain was very intense and lightning was frequent. Some of the velocity spectra, however, were surprisingly broad. The wide spectra were found at middle altitudes in the storm (mostly between 6 to 10 km) and were concentrated in the vicinity of the strongest updrafts. Computations conclusively demonstrated the presence of severe turbulence in more than one percent of the observations.



This chart shows a storm in cross section taken with a radar scanning at an elevation angle of 3 degrees. Numbers indicate radial wind speeds relative to the mean motion of the storm. The two prominent negative maxima, −9 and −5 m/sec, are suggestive of western branches of moderate vortices.

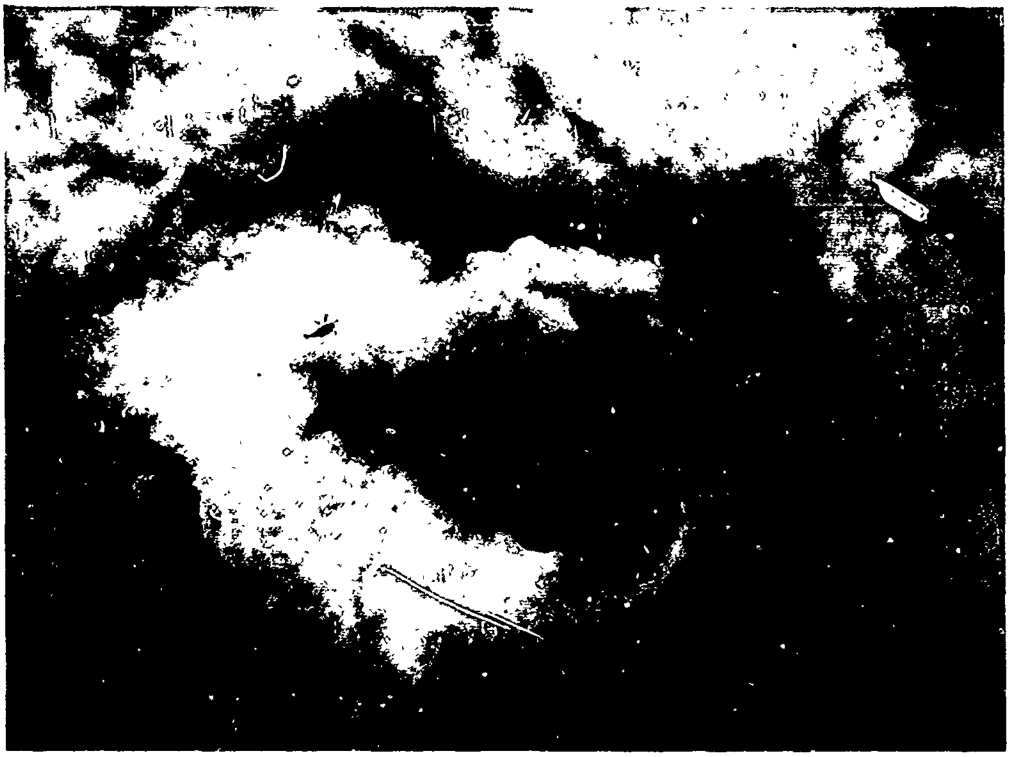
Moreover, vertical velocity variances in excess of 4 m^2 sec^{-2}, which occurred in over 4 percent of the storm, indicated hazards to aircraft in the form of damaging hail or turbulence, or both.

CLOUD PHYSICS

Cloud, fog, and precipitation have historically been major obstacles to Air Force operations. To the old problem of landing aircraft at fog-bound airports, newer problems have been created by sophisticated technology. Penetrations of cloud and precipitation at high speeds cause excessive erosion, solid-state components are more sensitive to cloud-created electrical phenomena, and clouds limit the use of certain optical and radio frequencies.

The AFCRL program in cloud physics falls in three areas. In the first lies the problem of fog. Here the concern is with the processes of fog formation and natural dissipation and with techniques for modifying and dissipating fog artificially. In the second area of investigation, studies are aimed at determining the evolution of convective clouds, the precipitation mechanism, and the feasibility of modifying such clouds and associated precipitation processes. In the third area are the problems associated with static electricity and lightning. Here the problem is the fundamental one of understanding the generation processes and the details surrounding natural discharges. As our understanding increases, the identification of potentially hazardous flight conditions will improve.

In recent years, much of the research in these areas has involved computer simulation of fog, cloud and precipitation processes. Instrumented aircraft have a prominent role in AFCRL's cloud



Helicopters were used in two major series of experiments devoted to warm air fog clearing. The technique is one in which drier air from above the fog layer is forced into the layer by the downwash of the helicopter blades.

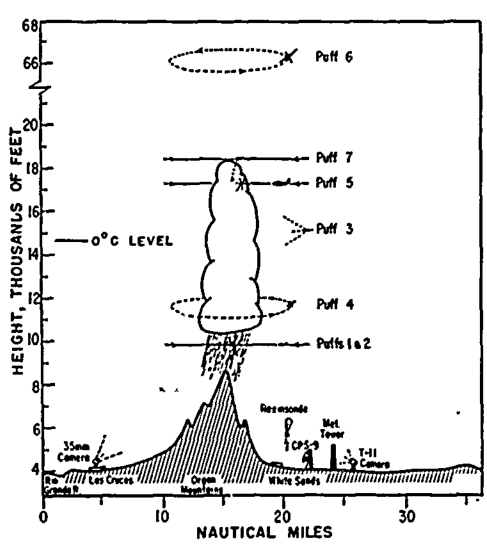
physics program. An Air Force C-130 is extensively instrumented with non-standard custom-developed devices. Smaller aircraft are also used for special programs, and several large helicopters have also been called upon in the development of fog dissipation techniques.

CUMULUS CLOUD MODIFICATION: In the summer of 1968, the Meteorology Laboratory, together with the Army and Navy, undertook a large field experiment in the southwest to obtain quantitative data on the effectiveness of cloud seeding. The program, designated Cloud Puff III, was under AFCRL field direction. The experimental approach was to seed certain clouds, while selecting other clouds having comparable characteristics to serve as controls. All seeding was done with silver iodide aerosols. The development of each cloud was then measured and the effects of seeding evaluated. Another purpose of the test was to evaluate the predictive ability of a numerical cumulus cloud model.

AFCRL's C-130 and another aircraft in the test fleet were used to measure the meteorological variables inside and outside of test and control clouds. Ground-based and airborne radar information, photography and radiosonde data were extensively used.

A unique feature of the field trip was the use of a computer at the site to evaluate quickly the preliminary results of the tests and to utilize a numerical cloud model as a part of the daily operation. The cloud model, based on the early morning balloon sounding, predicted the heights of the tops of modified and unmodified clouds as a function of updraft radius.

Flight operations were conducted on 14 days and cumulus clouds were found on all days. Results indicate that the numerical cloud model—that is, the computer prediction of cloud development and growth based on an initial set of conditions—is a useful operational tool. However, the degree of success depended on the representativeness of the initial set of conditions for a given day with respect to temperature, winds and relative humidity. The computations showed that on certain days seeding should produce large modification effects and that when conditions were right, an explosive growth of clouds should be noted after seeding. But for most days, the computations showed no appreciable difference between seeded and control clouds. Future efforts will be directed toward comparison of the computer results with the much less definitive and more complex cloud observations.



This sketch shows how observations were made during Project Cloud Puff III, a cloud seeding study jointly conducted by the Army, Navy, and Air Force in New Mexico in the summer of 1968. A total of seven aircraft (each bearing a "Puff" code number) were sometimes used simultaneously.

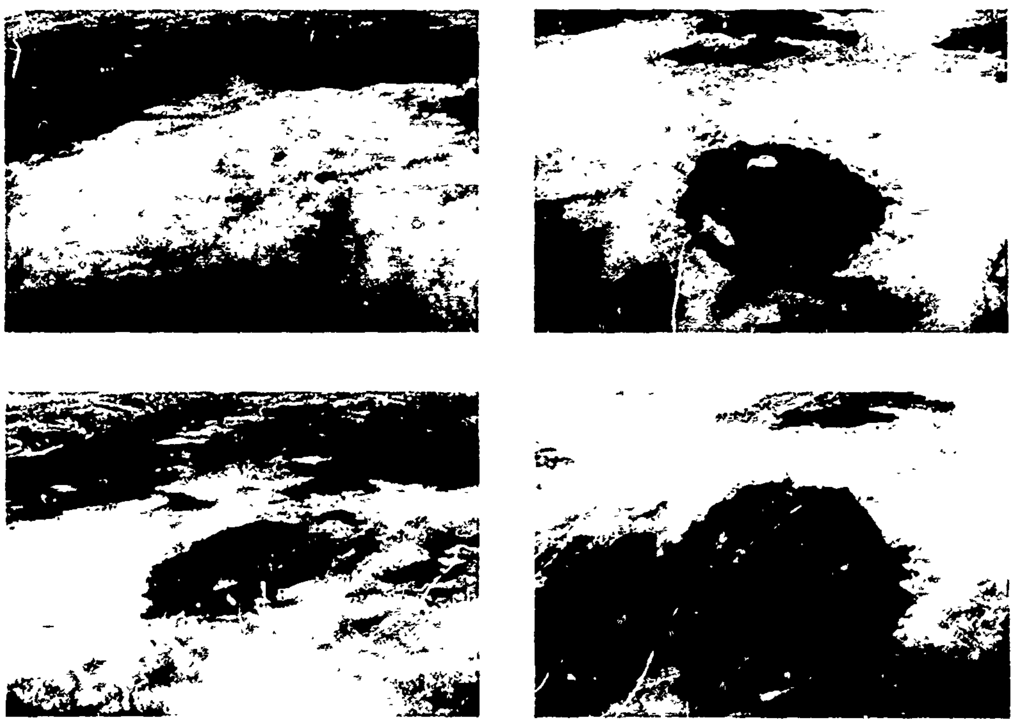
WARM FOG RESEARCH: In the fall of 1967, the Laboratory undertook a reevaluation of techniques for dissipating warm fog. The deployment of hygroscopic materials—such as pulverized salt—into the fog or stratus appeared to be the most promising technique to investigate. Such materials when falling through the cloud or fog layer extract water vapor causing the fog droplets to evaporate. Additional fog water is removed through coalescence with the hygroscopic materials.

Before field tests were undertaken, a numerical model was developed to simulate fog modification using hygroscopic particles. With this model, it was possible to determine the quantity and sizes of various types of hygroscopic seeding material needed to clear fogs of different liquid water content and drop size distributions. The model study indicated that considerable success can be achieved with reasonable quantities of properly sized hygroscopic material. In general, the smaller the size of hygroscopic particle used, the smaller the quantity of material required but the longer the time it takes to accomplish the clearing.

Field experiments to test the numerical model were conducted in California in the fall of 1968. The seeding agent was sodium chloride—salt. Although some clearing effects were noted, it became quite evident that the lateral turbulent diffusion of the surrounding fog droplets back into the seeded area quickly obscured the cleared area. This factor had not been considered in the numerical model.

A more sophisticated model now being developed will not only evaluate the modification effects of hygroscopic materials but also take into account the lateral turbulent diffusion of both the fog droplets into the seeded area and the hygroscopic particles outward as they fall.

CLEARING GROUND FOG WITH HELICOPTERS: Unwanted cloud droplets can be eliminated from the atmosphere if means are available to lower the humidity. One way is to add a drying agent as described above. Another is to mix drier air with the cloudy air so that the humidity of the resultant mixture is lowered permitting the droplets to evaporate. One practical method for accomplishing this mixing is to fly heli-



These four pictures were taken over a period of six minutes and illustrate the rapidity with which a 500-ft fog layer can be cleared by the helicopter downwash technique. Times of the photograph are respectively 0733, 0736, 0738 and 0739 EST. The hole in the lower right photograph is approxiamtely 2500 feet in diameter.

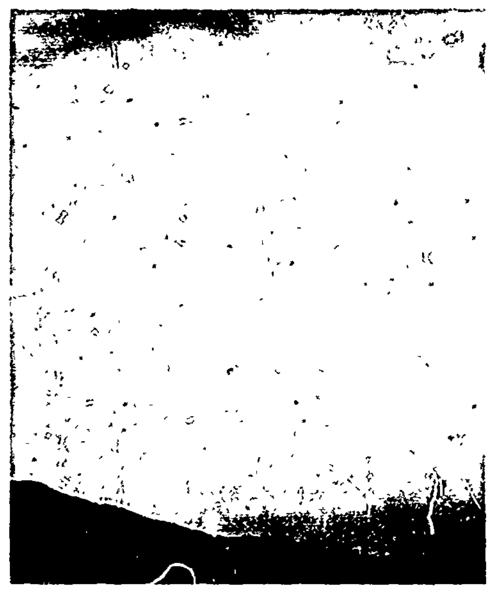
copters slowly across the top surface of a cloud or fog deck an to utilize the downwash action of the rotors to force clear (normally drier) air from above the cloud top deep into the cloud deck. The wake air, on descending, entrains and mixes with the cloudy air and causes evaporative elimination of the cloud.

The Meteorology Laboratory first tested this technique at Eglin AFB, Florida, in February and March of 1968. Very large, HH-53B, helicopters were used to create holes and trails, several hundred feet across, in elevated clouds of the stratus and stratocumulus types.

In later tests conducted at Smith Mountain Lake, Virginia, in November 1968, medium size, CH-3E, helicopters were employed to create clearings in ground fog 150 to 200 feet thick. The helicopter flew an outward-expanding spiral path at an altitude about 100 feet above the fog top at an airspeed of 25-30 knots. The hole was expanded to about a 3/4 mile diameter after a few minutes. In contrast to the hygroscopic particle experiments noted above, the fog didn't reform within the clearing. On another occasion, two CH-3E helicopters cleared a 400-foot wide strip 5000 feet long in a 350-foot deep layer of fog within 13 minutes.

The AFCRL experiments demonstrate that for fog roughly less than 500 feet thick and characterized by little wind and wind shear, clearing can be accomplished with small to medium sized helicopters.

THUNDERSTORM ELECTRICITY: The physical mechanisms for the formation and concentration of electrical charge centers in convective clouds is only dimly understood in spite of continuing studies in many of the world's atmospheric research centers. Through its research in this field, the Meteorology Laboratory hopes to uncover clues for predicting lightning discharges to or near aircraft—or to missiles during ground handling or passage through the atmosphere. Aircraft, with increasing amounts of high resistivity materials such as titanium and high strength plastic materials in their structure, coupled with solid state electronic systems and flight instrumentation, are especially vulnerable to the effects of static electrical discharges and lightning.



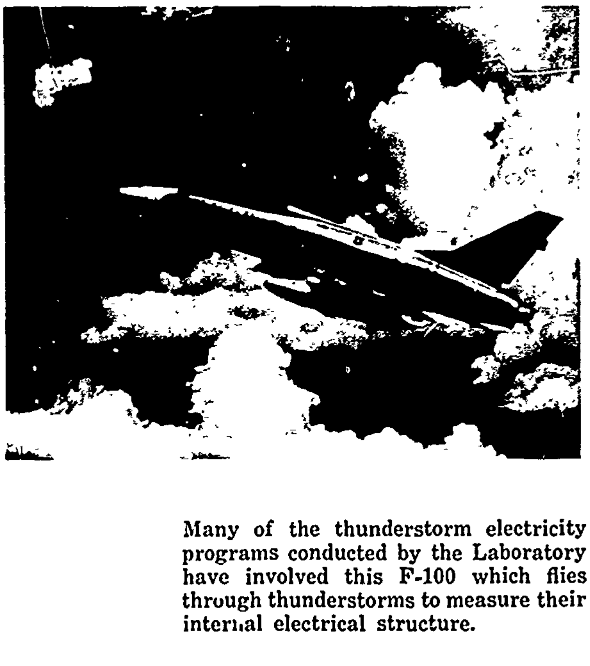
The physical mechanisms for the formation and concentration of electrical charge centers in convective clouds is only dimly understood. The Meteorology Laboratory is searching for clues for predicting lightning discharges to or near aircraft or to missiles passing through the atmosphere.

The AFCRL program has the objective of identifying—as a basis for prediction—those conditions likely to produce lightning discharges. Basic data on the electrical structure of storms and the characteristics of lightning strikes to aircraft were obtained by flying aircraft into and around large convective systems. Such experiments were conducted in Florida and Oklahoma. Flight data were correlated with surface electric field data.

One of the significant findings is that when the aircraft enters a dissipating storm it can trigger a sudden field disturbance initiating a lightning leader and stroke through the aircraft even though the electrical charge centers in the convective cloud have decayed to the point where natural lightning activity has ceased. This means that the pilot flying in clouds and using his radar to avoid the more turbulent cloud cores may find himself subject to unexpected discharge encounters as dangerous to the newer aircraft as the turbulence he is trying to avoid.

ATMOSPHERIC MODELING

Atmospheric circulations and weather result from the interplay of many physical and chemical processes. These interrelated dynamically and thermodynamically varying processes are extremely complex and subtle. To analyze the interplay of the key physical factors, however, the researcher can simulate the condition he wishes to study on a computer using mathematical models. The design of such models is an intrinsic part of studies of atmospheric dynamics at AFCRL and elsewhere.



Many of the thunderstorm electricity programs conducted by the Laboratory have involved this F-100 which flies through thunderstorms to measure their internal electrical structure.

The models basically are systems of partial differential equations expressed in terms of observed meteorological elements and quantities derived from them. Integration of the equations—some of which are nonlinear—expressed in finite-difference form requires the use of computers. The solutions themselves are predictions of the state of the atmosphere at various times in the future. The predictability of atmospheric circulation patterns and atendant weather phenomena in this dynamical approach is strongly affected by the manner in which key physical factors are incorporated in the models, the degree to which the finite-difference equations represent the differential equations, and the speed and storage characteristics of the computer.

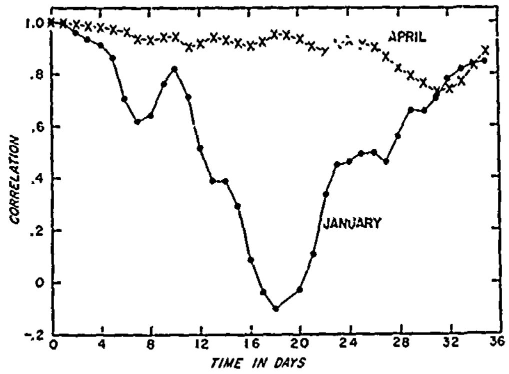
AURORAL HEATING: An auroral disturbance may heat the upper atmosphere with the effects translated to low atmospheric levels some one to two weeks later. This means that auroral heating could have some detectable effect on the earth's weather.

Because the evidence is indirect and empirical, there has been a strong reluctance on the part of meteorologists to accept its reality without a corroborating theoretical foundation. Consequently, a number of years ago, AFCRL developed a model based upon the equations of motion, the continuity equation, the hydrostatic equation and the first law of thermodynamics to study the effects on the large-scale atmospheric circulation caused by auroral heating.

The equations are solved through a network of about 2000 gridpoints covering the region from the North Pole to 30 degrees N latitude in 30-minute time steps. Since the model extends vertically from the ground to auroral heights, the vertical dimension was treated parametrically in order to reduce the computational effort. A full report of this work appears in an AFCRL publication (Environmental Research Papers, No. 294, November 1968).

The results indicated that significant changes in the large-scale tropospheric circulation of the model can be produced by the type of upper level heating introduced. Furthermore, the changes are consistent with what was expected on the basis of empirical studies. Nevertheless, because the model is only a crude approximation of the real atmosphere, certain improvements were necessary before it could be concluded that the response of the model circulation to auroral heating simulates the real atmosphere.

An improved model developed by the Laboratory during the reporting period removes the restriction imposed by the vertical parameterization and substitutes a multi-level configuration. This new model not only removes the restraints inherent in the earlier model, but also permits the investigation, in addition to auroral heating, of other important diabatic processes in the atmosphere, such as frictional heating, radiative heating, and water vapor.



Correlations between the computed values of the vertically integrated stream field for the "heating" and "no-heating" cases of January and April are plotted.

RESEARCH ON NUMERICAL ANALYSIS: Numerical methods of the type described above have become a widely used analytical tool in recent years. But often the results take into account only the dominantly large-scale effects. One numerical analysis problem that arises in the solution of nonlinear systems of equations is that a spurious growth of the short wavelength components may often arise as a result of the numerical integrating procedure. In fact, for the commonly used centered time and space differing scheme, the spurious growth of the short waves may cause the calculations to become unstable and "blow up" after a relatively few time steps. Various procedures have been used to control this growth.

A Fourier analysis of the predicted fields is performed and the spectrum is truncated at some wave component. This procedure is effective but costly in terms of the computational effort involved. It would probably be preferable to express the differential equations themselves in spectral form and circumvent the problem by considering only waves longer than a certain limiting size. Another procedure is to build a large internal viscosity into the system of equations. This procedure is simple and effective but arbitrarily alters the physical system under investigation.

Considerable effort has been devoted

to the search for stable finite-difference schemes which satisfy certain integral constraints. Some of this work was described in the previous AFCRL *Report on Research.* Recently, considerable success has been obtained with the use of the so-called box method. In this method, values for the interior of a box are expressed in terms of values on the surface in such a way as to satisfy the integral requirements. Such methods are relatively simple and have been used very successfully in a number of applications. However, the procedure itself does entail considerable "smoothing" in that the values in the interior of the box are expressed in terms of values on the interfaces by averaging between adjacent boxes.

Other finite-difference schemes which are subject to instabilities due to the spurious growth of short-wavelength oscillations have been shown to be very satisfactory if some weak smoothing is performed to limit the amplitude of such components. It therefore appears that some level of smoothing or filtering is necessary either explicitly or implicitly as part of the integration procedures. This means that the filtering procedure be designed to suit the application and that the full effects of the filtering be understood, since some procedures which appear to be "ideal" may be completely altered by boundary effects.

AFCRL has developed a simple method for designing smoothing and filtering operators for a variety of specific applications and purposes and has pinpointed some of the pitfalls that may arise in practice. One involves a smoothing operator applied over a 24 grid-interval domain. Assume, for example, that the initial data contain waves of 2, 3, 4, and 8 grid-intervals. The operator is designed to remove 2 grid-interval waves, damp the 3 and 4 grid-interval waves, and leave the amplitude of the 8 grid-interval wave intact. In the case where the boundary conditions are periodic, the smoothing operator is well-behaved, without spuriously explosive results.

Other work in numerical analysis consists of the development of new methods of numerical solution of differential equations. One of these is a method for transforming the three-dimensional problem to a number of two-dimensional relaxations. The advantage of this transformation is two-fold: it allows a theoretical estimate of the optimal value of the relaxation factor, otherwise inaccessible, and it furnishes more efficiency, less effort and higher accuracy in the numerical computation.

THE HURRICANE MODEL: Of the several numerical models of atmospheric dynamic processes under study, the model that has been given most intensive and complete treatment is a model designed to investigate the conditions under which hurricane-like disturbances will form. Until recently, the model did not consider certain small-scale processes. The model assumed that certain initial conditions prior to hurricane formation somehow came into existence, possibly due to small-scale effects. Starting from this initial state, the model predicted the formation and motion of a hurricane-like disturbance. While many features of a real hurricane were reproduced, many, such as the warm core, were not.

It is thought that large groups of cumulonimbus clouds provide c - tively the energy needed for the development of the initial state referred to above. Furthermore, continuation of such convective activity leads to the formation of the warm core. Since the scale of this process is much smaller

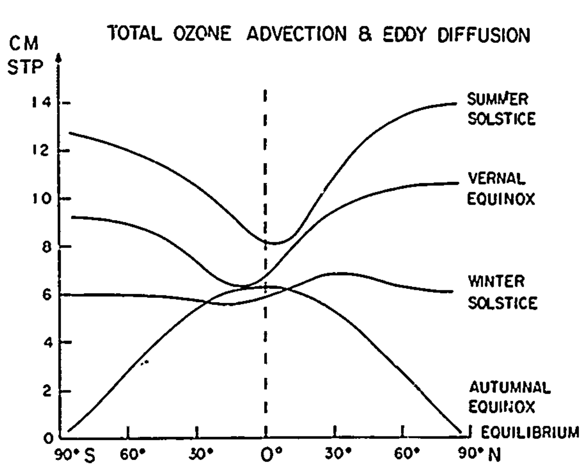
Hurricanes have for many years been the subject of mathematical models at AFCRL. The models are designed to investigate the conditions under which hurricanes form and develop.

than the scale of the developing hurricane, attempts to incorporate the physics of the convection process in detail lead to monumental computational problems. Accordingly, much attention is being given to "parameterization" of the convective processes—that is, to the expression of such proceses in terms of the larger-scale motions. Since the necessary energy comes from the release of latent heat carried into the atmosphere through the planetary boundary layer, one way of parameterizing the convective motions is to assume that the total heat released by these motions in a vertical column is proportional to the vertical motion at the top of the boundary layer.

AFCRL is currently following this line of investigation, and has incorporated a version of this type of parameterization in order to test whether it is possible to compute a storm evolution with more realistic characteristics.

MODEL FOR OZONE CIRCULATIONS: Ozone, of interest to meteorologists because it is the chief source of radiative energy in the stratosphere, can also be used as a tracer of stratospheric circulations. The total ozone content of the Northern Hemisphere increases by a significant factor during the period November through March. Of this overall increase, the most rapid rise in the ozone content occurs in the high-latitude lower stratosphere. This additional ozone most certainly does not originate by photochemical processes in this region. One must postulate then a circulation mechanism that transfers ozone from the middle (or low) latitude upper stratosphere to the high latitude lower stratosphere during the winter months. In earlier studies of the ozone distribution, it was always assumed that the ozone content was in photochemical equilibrium—that is, no transfer processes were acting. While such calculations give the correct vertical distribution of ozone, they give a reversal of the horizontal distribution.

The Meteorology Laboratory has devised a 22-level atmospheric model to study the interaction and transfer process. The model not only allows for the calculation of the change in ozone content due to photochemistry and transfer, but also for change of temperature due to absorption by ozone, by cooling due to long-wave radiation, and by heat transfer. Calculations are made in a meridional plane extending from pole to pole, and from the earth's surface to 65 km. This model predicts the change of the 24 hour average of ozone in the meridional plane, and reconstructs the spring buildup in high latitudes. Calculations were made both with and without effects of diffusion, so that the relative importance of transfer by the mean motions and by diffusion may be assessed.



The distribution of total ozone by latitude as computed from a model which includes transfer of ozone by the mean motion and by eddy diffusion is shown.

Later in this chapter, the Laboratory's ozone observational program is reviewed. Such observations, of course, provide the numerical model builder with the essential data for verifying numerical model results and for refining the model itself.

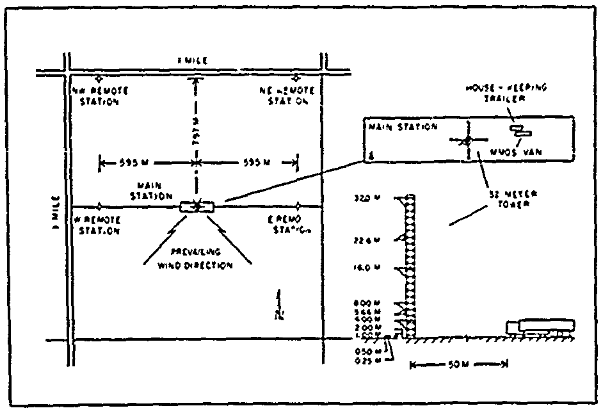
ATMOSPHERIC BOUNDARY LAYER

There are some meteorological processes which by their form and magnitude are characteristic of the first mile or so of the atmosphere, the region which meteorologists refer to as the boundary layer. For example, the turbulent transport of kinetic and thermal energy between the earth's surface and the free atmosphere is of basic physical importance in the understanding of large-scale atmospheric motions. In general, these turbulent transports are effective in transporting heat to and from the earth's surface and is transporting momentum towards the earth's surface to overcome the earth's frictional drag on the overlying air motions. It has become apparent that incorporation of the knowledge of the effects of these processes in numerical weather forecasting models is an essential ingredient for improving 24 to 48 hour weather forecasts.

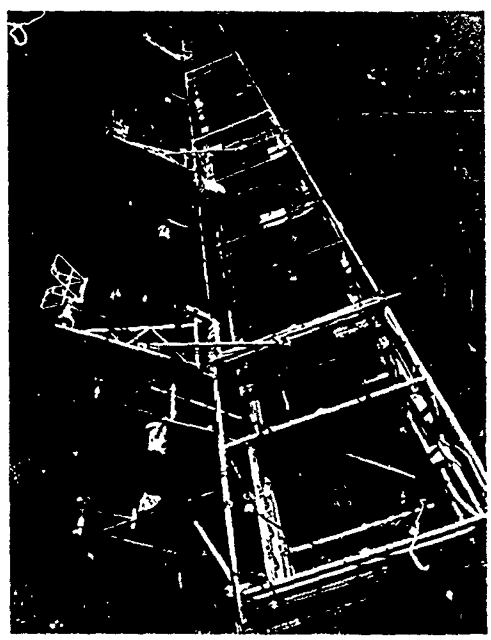
THE KANSAS FIELD SITE: Since 1965, AFCRL's boundary layer research has centered around a field site in southwestern Kansas. Here, on a broad flat obstruction-free wheat field, the Meteorology Laboratory has installed a variety of instruments to obtain detailed microscale information on such parameters as winds, temperatures, moisture and the vertical turbulent transport of momentum, heat, and water vapor. Three field trips were made to the site in the summers of 1965, 1967 and 1968.

The whole problem of turbulent transport is an extremely complex one. The most promising approach is to investigate the most simple, yet non-trivial physical situation in the atmosphere, the case where the turbulent flow properties are uniform in the horizontal. Thus, only vertical gradients are required for the most part in characterizing the flow.

Accordingly, the experimental site in southwestern Kansas was chosen for its close approximation to a uniform flat plane. A 32-meter tower was erected on the site, a semi-permanent fixture complete with commercial power and signal cables enclosed in conduits. The logistics problem of preparing for an experiment was thus reduced to transporting a trailer carrying a computer-controlled data acquisition system from Bedford, Mass., to Kansas; mounting the various wind, temperature, and moisture sensors on the tower; and connecting the appropriate sensor cables. All the sensors are calibrated in the Laboratory's calibration facility consisting of a wind tunnel, temperature bath, humidity chamber, and associated control electronics.



The micrometeorological site in Liberal, Kansas, is diagrammed in this schematic.



At intervals along the 32 meter tower at the Kansas field site are located a variety of meteorological sensors.

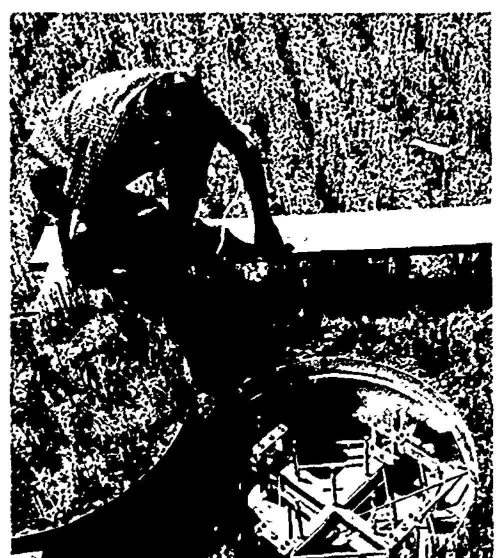
THE 1968 EXPEDITION: The 1968 expedition was particularly successful on a number of counts. The sensor inventory was much better than in previous years, and, in fact, exceeded that of any other known similar experimental program. Heat and momentum flux were measured with sonic anemometers and platinum wire thermometers at three levels on the tower, 5.6, 11.3 and 22.6 meters. An Australian scientist joined the AFCRL group with two drag plates designed to measure the frictional drag right at the earth's surface. Hot-wire anemometers were used at the same levels as the sonic anemometers to obtain high-frequency information on the wind fluctuations and, in particular, to provide an estimate of the rate of viscous dissipation of the turbulent wind field. Wind and temperature profile measurements were also made.

With respect to instrumentation, a surprising discovery was that extreme precision in orientation of the sonic anemometers is required to measure momentum flux. Tilt of the anemometer out of the vertical by more than 0.1 degree can cause errors as much as 100 percent in extreme cases and, quite commonly, as high as 30 to 40 percent.

Of particular interest is the behavior of momentum and heat flux as a function of height during all stabilities. For a uniform flat plane, these fluxes are assumed to remain constant with height within the first 30 meters or so. But dependable experimental verification of this assumption had not been obtained prior to these experiments. In general, fluxes are indeed constant with height to within the experimental capability to measure them, which is to an accuracy of plus or minus 20 percent. Under unstable conditions, however, the momentum flux is not so easily characterized. It sometimes increases with, decreases with, or is constant with height for individual, 15-minute averaged estimates of the flux.

Examination of the characteristics of the transport processes during these

The interior of the trailer showing portions of the data acquisition system used at the Kansas site is shown in the upper photo. Below a scientist is shown readjusting an instrument used in the measurement of the earth's drag on the atmosphere.



periods has revealed the occasional presence of large bursts of momentum and heat transport that last for 30 seconds or so. These tranports are ten to 20 times greater in magnitude than the transports occurring between the bursts. They occur at intervals of 10 to 30 minutes. These bursts have a tremendous influence on the temporal and height variability of the momentum flux, making it necessary to average the fluxes over a long time period (an hour or so) before statistically stable estimates of momentum flux can be obtained.

The Muirhead K300-A/1 photofacsimile recorder is shown with gray-scale simulator and image density calibrator installed. The crater current-signal amplitude curve can be seen on the scope of the simulator.

SATELLITE METEOROLOGY

Since about 1965, the extraction of meteorological information from satellite pictures has become routine and satellite data are now being used in increasingly sophisticated ways. At Hanscom Field, the Meteorology Laboratory routinely receives direct transmissions from the various weather satellites and uses them in investigations designed to enhance their usefulness in forecasting. During the period, satellite data have been used in conjunction with all other types of available meteorological data in synoptic, dynamic and statistical studies.

SOUTHEAST ASIA STUDIES: The Air Weather Service (AWS) in Southeast Asia (SEA) uses direct satellite transmissions as part of its weather forecasting mission there. AFCRL is assisting AWS personnel in SEA through a research program designed to obtain maximum value from satellite photos. During most of the report period, visits were made to bases in SEA by AFCRL, contractor and AWS satellite meteorologists to instruct personnel in the application of their research results.

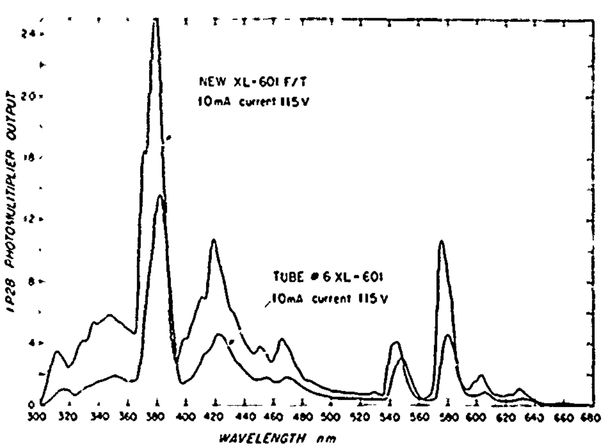
AFCRL research is conducted along synoptic and statistical lines. The synoptic work has concentrated on the identification of circulation regimes antecedent to or associated with clearing weather over target areas. Identifiable synoptic features have been found that give 24 hours or more of advance notice of clearing. The key to the forecasting is the identification of the main circulation features of this area, such as the subtropical ridge, monsoon trough, and the buffer circulations between the Northern and Southern Hemispheres.

Statistical work emphasizes the forecasting of comparatively fair periods as against convectively active periods during the southwest monsoon season.

Significant correlations have been demonstrated between the location of clouds on a satellite video or IR picture and the rainfall over the next 24 to 72 hours in the vicinity of the radar.

One study that related wind speed at 1.5 km altitude to the height of convective clouds proved of particular value. There appears to be a critical wind speed for each particular observing station which separates days of light to moderate convection from those of intense convection in which the cloud tops exceed 40,000 feet. The thicker clouds occur when the wind is less than the critical speed. Forecasts of 18 hours based on these observations were correct 65 to 85 percent of the time, depending on the station.

AUTOMATIC PICTURE TRANSMISSION: One problem with weather satellite photos is the varying quality of the output of different satellites. Lack of contrast, resulting in a gray, washed-out appearance, sometimes obscures valuable detail. AFCRL has completed a study of weather satellite picture quality, has identified the factors involved, and has shown this quality can be enhanced at the receiver with a little effort.



Many factors are involved in obtaining sharp, high resolution photos from satellites, some requiring only simple adjustment and calibration of ground receiving equipment. For example, it is seen in this plot that the spectral response of two satellite transmission tubes is quite different, but this difference can be reconciled by adjustments in the ground receivers.

Without equipment redesign or modification, much can be done to improve weather satellite pictures from APT (Automatic Picture Transmission) recorders. The Air Weather Service operates a sizable number of these APT recorders, particularly in Southeast Asia. Poor picture quality is often the result of imprecise calibration and lack of understanding on the part of the operators of the factors affecting picture quality.

For example, the operator should know that aging of the vidicon camera in the satellite not only changes the dynamic range of the video signal but that the loss of sensitivity is more severe at low brightness levels than at high brightness areas of the picture. To compensate for vidicon degradation, the quality of pictures can be restored by proper adjustment of gray scale compensation circuits in the recorder.

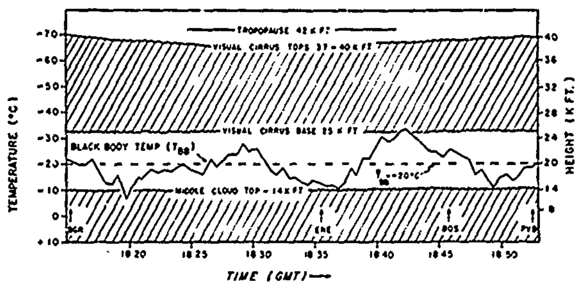
Aside from the report of this work which can serve as a kind of manual, training classes have been held at AFCRL and in the field to insure that AWS personnel understand the system. It is now routine to have at least one AWS officer in Vietnam who has been at AFCRL to receive training in the process for obtaining optimum picture quality.

To ease the job of calibrating the recorder and making adjustments by less skilled personnel, AFCRL has designed a special attachment to the APT equipment which allows an oscilloscope display of the relationship between input signal and marking current. This equipment was provided to AWS units in SEA. The Laboratory has also instructed NASA in its calibration techniques. In addition to optimizing the use of existing equipment, the Laboratory has provided guidance and assistance to the Electronic Systems Division (ESD) of the Air Force Systems Command on the design of future readout equipment.

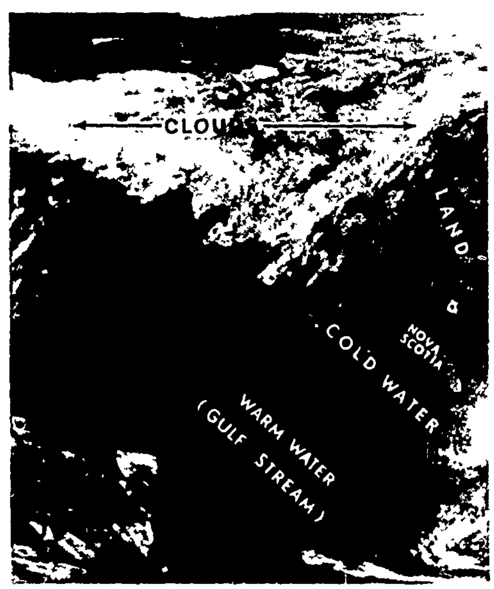
INFRARED STUDIES: An investigation into the radiative characteristics of jet stream cirrus using an instrumented U-2 aircraft has been completed. The conclusions reached were that the radiation data in the 8-13 micron "atmospheric window" gave little information as to absolute cloud height or temperature. In the accompanying illustration cloud layers are indicated by hatching and the radiometric blackbody temperature by the curved line near 20,000 feet. As can be seen, the radiometer places the cloud tops between 14,000 and 25,000 feet, while the observed tops were between 37,000 and 40,000 feet. Errors of this size are not uncommon.

In addition, the results indicate a very wide range of values of emission and transmission for cirrus clouds in the 8-13 micron window region. It is clear that the blackbody assumption in this region as it pertains to cirrus cloud regimes must be abandoned.

A technique was formulated to improve cirrus height and temperature estimates by categorizing the radiation measurements and assigning an effective cirrus emission-transmission factor.



Aircraft radiometric measurements made between Providence, R.I., and Bangor, Me., are shown here. Although temperatures at the top of the cirrus layer were about −65 degrees C, the transparency of the cirrus led to erroneous radiometric temperatures about 45 degrees C too warm.



This infrared photograph was taken during a satellite pass over southeastern Canada. The whiter the area, the colder the temperature of the radiant surface.

UPPER ATMOSPHERE STUDIES

Weather is a tropospheric phenomenon, with the major meteorological events—winds, rain, temperature change, cloud formation and so on—taking place within a narrow shell extending from the ground up to the tropopause between about 12 and 18 km. Above the tropopause is the relatively stable stratosphere. Defining just how stratospheric processes influence the earth's weather is a major category of meteorological research.

Interest is focused on ozone and large-scale circulations. To the meteorologist, ozone is one of the atmosphere's important constituents. It is a highly efficient absorber of solar energy, contributing more than 80 percent of the heat in the atmosphere. It controls the earth's heat balance, keeping the earth's temperature in reasonable equilibrium throughout the year. The Meteorology Laboratory is interested in ozone circulations and the photochemistry of ozone formation. Earlier in this chapter, numerical models of ozone circulations were discussed. This section reviews the Laboratory's observational programs. Another upper atmosphere observational program discussed in this section is the detection of winds at altitudes between 80 and 120 km using meteor trails as tracers.

METEOR TRAIL ANALYSIS: A typical meteor enters the earth's atmosphere at a speed of 40 km sec^{-1}, leaving an ionized trail. Special radar sets detect these trails and use them as tracers to investigate the earth's environment in the 80 to 120 km altitude range. One of the programs in the Meteorology Laboratory is a unified, coordinated effort to improve radar observing techniques, to automate the data reduction, and to provide a description of the neutral atmosphere.

The AFCRL meteor trail radar operates at a frequency of 36.8 MHz. Antennas consist of Yagi arrays that operate in association with a ground plane —a wire grid suspended about ten feet off the ground and measuring about 40 by 50 feet. Data are recorded and processed automatically by the system.

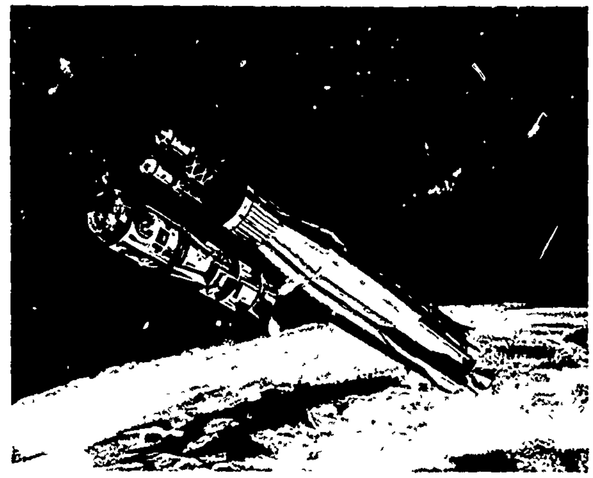
A copy of the AFCRL computer-controlled radar meteor trail system has been built by the Army and is being installed for environmental support at the White Sands Missile Range. Stanford University has designed and is assembling for AFCRL a more sophisticated system employing recent advances in electronic detection and packaging. This new, compact prototype system is truck-mounted, is less expensive than previous systems, and will cost less to build, operate, and maintain than present radiosonde systems.

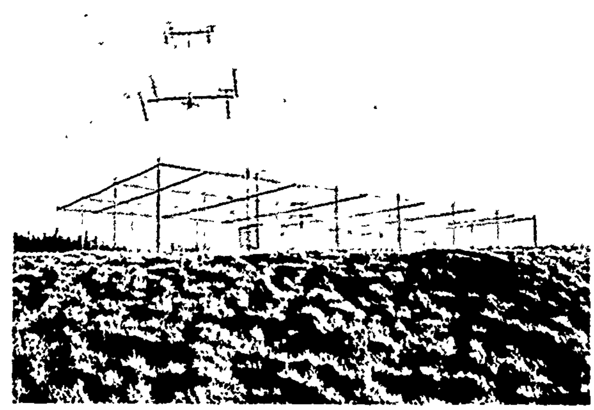
The AFCRL systems at Durham, New Hampshire, and Stanford provide data for in-house research. A maximum rate of 400 usable observations per day are obtained by each radar which can operate both day and night, regardless of weather, to define the prominent tidal wind oscillations and prevailing wind components. Observations reveal that the semi-diurnal wind oscillation is stronger and more regular than the diurnal oscillations, but there is a large amount of variation in the individual measurements. No significant correlation has been found between the wind variations in the 80 to 100 km altitude range and anomalous solar activity. Although echo decay rate variations are known to be closely related to variations of atmospheric density and although significant decay rate variations have been observed, the state of the art does not permit good estimates of the density variations. Large density variations are significant for aerospace operations and might explain some of the lower thermosphere satellite observations which are at variance with the theoretical models.

The major obstacle in obtaining accurate data has been the calibration of the antenna systems. A small beacon in satellite OV1-17, which was put into orbit on March 18, 1969, is being used to calibrate the antenna systems and thereby provide greater resolution of echo heights. Preliminary results are very encouraging.

RADIATIVE AND CIRCULATION PROCESSES: Using the wealth of ozone data gathered in recent years by the AFCRL ozonesonde network covering North America, the Laboratory has attempted to define the radiative and circulation processes in the upper troposphere and lower stratosphere. The high resolution ozone measurements have enabled the Laboratory to explore the nature of atmospheric motion systems in a way not previously possible.

Of particular interest and importance are the striking fluctuations in the ozone concentration of the lower stratosphere, which are characteristic features of mid-latitude ozonesonde observations in the cold months of the year. These large variations occur as wave disturbances of varying scale and act upon the strong gradients of ozone that are maintained in the stratosphere. Descriptions and understanding of ozone-circulation relationships are obtained through analysis of the distribution of ozone mixing ratio with respect to potential temperature. Ozone mixing ratio is a conservative parameter following the air motion below about 20 km while diabatic temperature change processes are relatively slow in the upper troposphere and lower stratosphere. Thus, air parcels conserving ozone are constrained essentially to move along or move in translation with isentropic surfaces for several days or more. Isentropic excursions of ozone-rich air from the north and ozone-poor air from the south into intermediate latitudes, often in very thin layers, are readily identifiable in the winter and spring ozonesonde data.

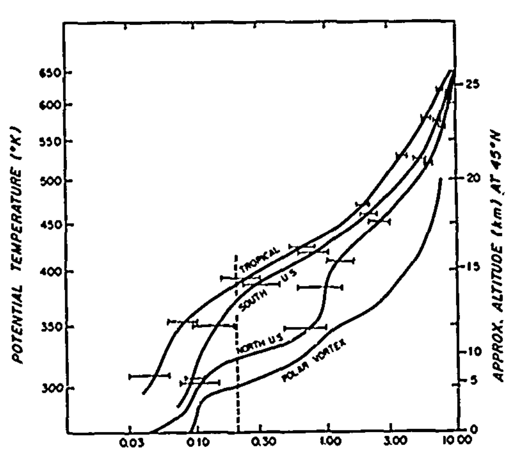




The OV1-17 satellite launched in March 1969 carried a beacon for calibrating the AFCRL meteor trail radar systems at Durham, N.H., and Stanford, Calif. One of these systems is shown in the lower photograph.

Average meridional cross sections of ozone vs. potential temperature were calculated from network observations made during the years 1963 through 1967, a data base of over 2000 ascents made with Regener chemiluminescent and Brewer-Mast electrochemical ozonesonde instruments. These charts provide a working climatology of ozone that may be used to help diagnose synoptic-scale events. The mean meridional ozone gradient is a minimum near the 650 degrees K potential temperature surface (approximately 25 km). Above this level, the ozone concentration is strongly influenced by photochemical processes, which produce and maintain the largest amounts near the equator. The average meridional ozone gradient is reversed at lower atmospheric levels where the distribution is controlled by transport processes. In the winter and spring months, the largest ozone values are invariably found within the cold polar vortex as it moves about in the arctic region. In the lower stratosphere, a strong ozone gradient persists between the vortex center and the anticyclonic or equatorward side of the polar jet stream. Thus, the observed changes in ozone structure near the tropopause provide a close look at circulation mechanisms which lead to broad meridional excursions of polar and subtropical air masses and lead to the interchange of air between the stratosphere and troposphere.

Invasions of ozone-rich stratospheric air into the troposphere are easily detectable, even though the resultant perturbation amplitudes are usually small because of rapid erosion and dilution by mixing processes in the troposphere. Extrusions totally imbedded within the troposphere seldom have ozone amounts exceeding 0.3 parts per million, which corresponds to the amount normally found only a few hundred meters above the tropopause. The preferred region for transport out of the stratosphere is at the base of transient wave troughs on the poleward side of the jet stream.



This chart shows the average concentration of ozone vs. potential temperature for the spring season as calculated from the AFCRL ozonesonde network.

OZONE PHOTOCHEMISTRY: From a seed planted by Sydney Chapman almost two decades previously, the "classical" theory of ozone in the earth's atmosphere came to full flower in the late 1940's. In this view ozone is depicted as the result of photochemical reactions involving only allotropes of oxygen. It is in photochemical equilibrium in the upper stratosphere, but in the lower stratosphere it is conservative for all practical purposes, and its distribution there is governed by circulation processes. The intermediate altitudes, where the characteristic times of photochemistry and circulation are comparable in magnitude, are the source regions for the ozone that percolates down into the troposphere, where it is destroyed.

This theory was well received and remained essentially free from challenge until the early 1960's when it became evident that the theoretical values of equilibrium concentration are consistently and significantly higher than observed values. Two developments led to this adverse reappraisal: revised values for certain of the photochemical rate constants and better observations of ozone.

Among various attempts to patch up the theory, the one that has attracted principal attention amounts to a major overhaul. It postulates that compounds of hydrogen are present in the reaction scheme and are the dominant agent for destroying ozone, thereby lowering markedly the equilibrium values. Since these compounds are derived from atmospheric water vapor, the new model has been dubbed the "wet" model.

A consequence of the wet model is a sizable reduction of the photochemical relaxation time. This would imply that the source region of ozone is much lower in altitude than previously held and would raise some doubt as to whether ozone is truly conservative in the lower stratosphere.

However, according to recent studies by Meteorology Laboratory scientists the proponents of the wet model may have jumped from the frying pan into the fire. The wet model is found to under-predict the observed values by even more than the dry model over-predicts. What's more, the lower values of relaxation time turn out to be adventitious and not the result of an instrinsic difference between wet and dry models. When the observed values are correctly predicted, the relaxation time is essentially the same whether the wet or dry model is used.

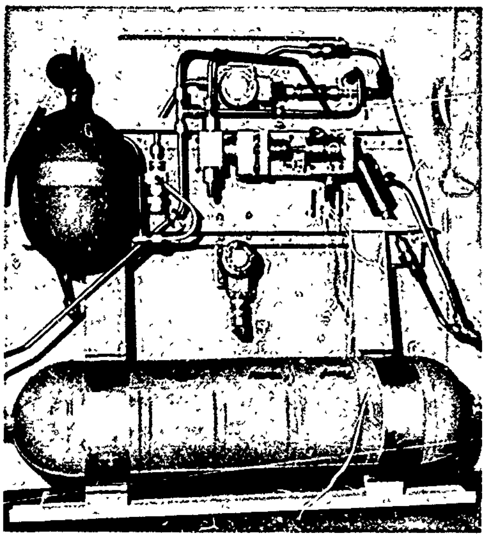
A dense, smoky exhaust is deliberately created in this J-69 jet engine, preparatory to tests of methods for suppressing the visibility of the exhaust. Tests were conducted at AFCRL.

CONTRAIL SUPPRESSION

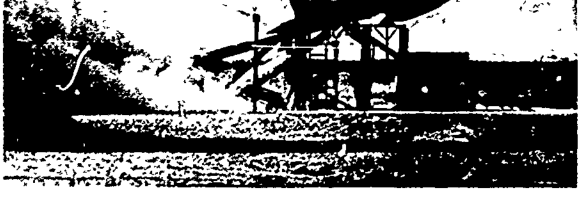
AFCRL's research in contrail suppression dates back well over ten years. This early research led directly to the development of a suppression system that was incorporated into operational aircraft. With the program successfully concluded, no further work was done for several years. Then, during the present reporting period, a new Air Force requirement for contrail suppression arose and AFCRL was asked to reopen its program. This program is carried out under the title "Aerosol Interactions" because the approach to the problem is to produce combustion products—aerosols—sufficiently small in size so as to be invisible. At the conclusion of the present reporting period, AFCRL had again satisfied the new Air Force requirement and the program was again being phased out.

FUEL ADDITIVES: The best—and only practical—way to mask the contrail of a jet is to prevent the water produced by combustion from condensing into particles above a certain critical size, a size no larger than 0.25 micron. In AFCRL's earlier approach, noted above, chemicals were injected directly into the aircraft exhaust where they evaporated to form sulfur trioxide nuclei. The present approach is to add chemicals to the jet fuels. While the earlier technique was effective, it required relatively complex injection equipment which had to be operated in conjunction with highly corrosive chemicals.

During the reporting period, laboratory tests were conducted on the conversion of various types of sulfur compounds to sulfur trioxide during the



Aircraft contrails can be suppressed by injecting chemicals into the aircraft exhaust. One such injection system is shown here. The bottom tank contains the suppressing agent. Upper left is the pressurizing tank.



This BQM34A drone was flown at Holloman AFB, N. M., to test AFCRL-developed methods for suppressing contrails.

combustion. Because such chemicals are corrosive, particular care was taken to evaluate possible damage to engine parts during this test program. The results of this laboratory work have been verified in a flight test program conducted at Holloman AFB, N.M., using the White Sands Missile Range. Two BQM34A target drones are flown in each test mission, one with and one without the sulfur compound additive.

The tests were successful for the development of a high altitude suppression system. At high altitudes, contrails suppressed more effectively than in the earlier exhaust injection system, but there is no system weight to impose a range penalty on the aircraft. The heat loss of the fuel due to these additives is extremely small. Maximum range penalty to an aircraft is estimated at below 0.5 percent compared to the 3 percent and higher from conventional contrail suppression systems.

For lower altitude contrail suppression, an extremely promising technique is the use of sulfur dioxide-sulfur trioxide gas mixtures injected directly into the exhaust. Because the material is injected as a gas, no complicated equipment is required for droplet breakup and evaporation.

METHODS OF EXHAUST GAS ANALYSIS: Contrail suppression depends on the production of sulfur trioxide in the exhaust to control the condensation of the water particles. For a given quantity of fuel additives, one wishes to maximize the production of sulfur trioxide in the jet exhaust. In view of the complexity of the reactions within the tailpipe and the fact that all reactions occur at extremely high temperatures, measurements of the concentration of reactive exhaust gas components posed a problem.

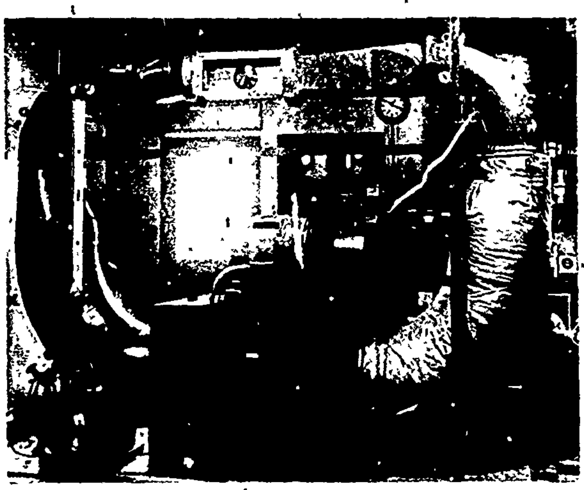
The problem was solved by installing

in the laboratory a small jet engine, equipped with silencers and other necessary soundproofing. With this engine, tests can be made by introducing sulfur compounds through injection in the exhaust or by the use of fuel additives. A portion of the exhaust gases are passed through a heated tube into an ultraviolet spectrometer. The amounts of sulfur dioxide and sulfur trioxide are measured by UV absorption techniques. With this laboratory engine, one can evaluate the effectiveness of contrail suppression materials in the laboratory and confirm the results with a minimum of flight testing.

WIND TUNNEL MEASUREMENTS: Not only does one wish to maximize the production of sulfur dioxide in the jet exhaust, one must maximize the breakup of these materials into small droplets if one is to achieve an optimum contrail suppression effectiveness.

In normal operation, droplet breakup decreases with an aircraft's altitude because the density in the exhaust of the gases which control breakup decreases with increased altitude. The complexity of factors involved in droplet breakup led to the need for a theoretical framework, and experimental checks on various theoretical models.

To obtain the experimental data, the Laboratory undertook a series of wind tunnel tests. In this wind tunnel, a range of densities and Mach numbers can be simulated. High-speed cameras photographed the breakup of the droplets. The camera unit consists of five cameras used in conjunction with high-speed light sources to produce exposures on the order of 20 nanoseconds. The time between exposures can be varied from approximately 10 and 400 microseconds. All five cameras are focused on the same volume within the test section and it is possible to follow single droplets in the breakup process. The wind tunnel has been successfully operated at densities corresponding to altitudes of 40,000 to 60,000 feet. Several preliminary breakup models have been developed as a result of this program.



This subsonic wind tunnel was used in studies of droplet breakup. Reducing the size of exhaust particles is the basic approach to reducing contrail visibility.

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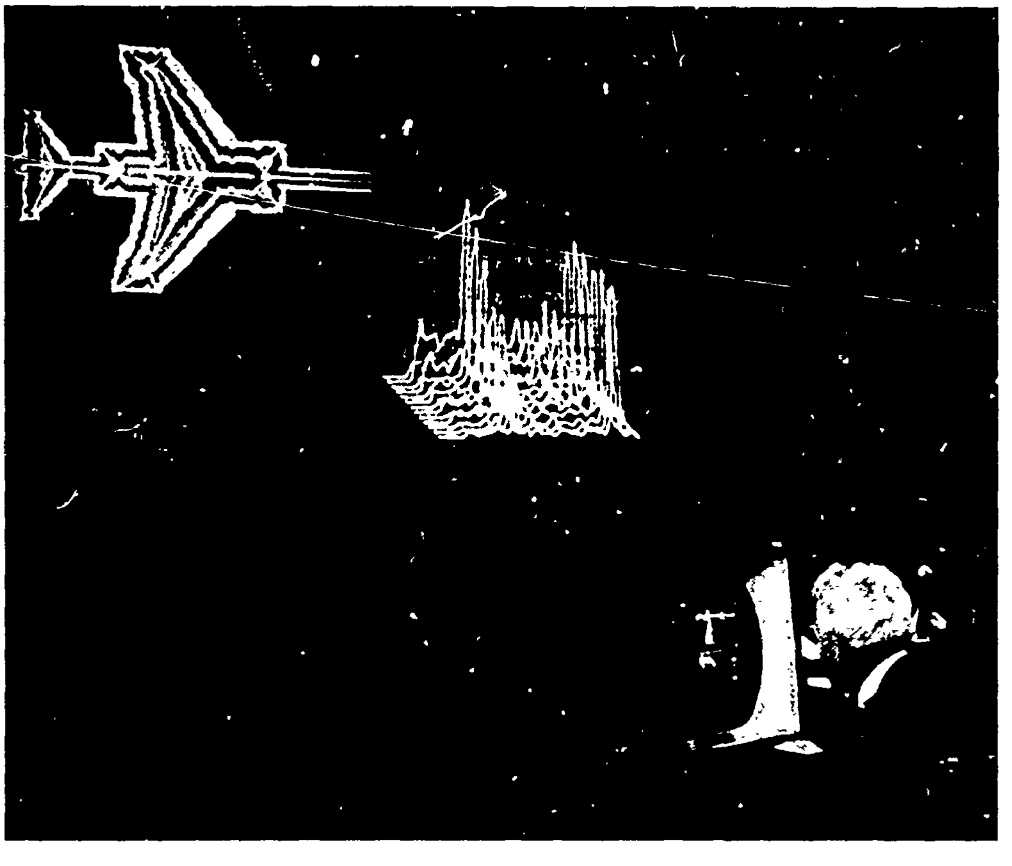
Research in the Data Sciences Laboratory ranges across a wide spectrum of programs — automatic computer recognition of aircraft, speech bandwidth compression, logic network design, multisensor signal processing, and error correcting coding.



XI Data Sciences Laboratory

Broadly defined, the program of the Data Sciences Laboratory involves the automatic processing, filtering, interpretation and transmission of information. These functions are indispensable parts of practically all Air Force electronic systems. The task of the Laboratory is to anticipate the needs of the Air Force for new and improved technologies, to evaluate these needs against current research in the computer sciences, to identify important areas insufficiently emphasized, and to conduct research responsive to Air Force needs.

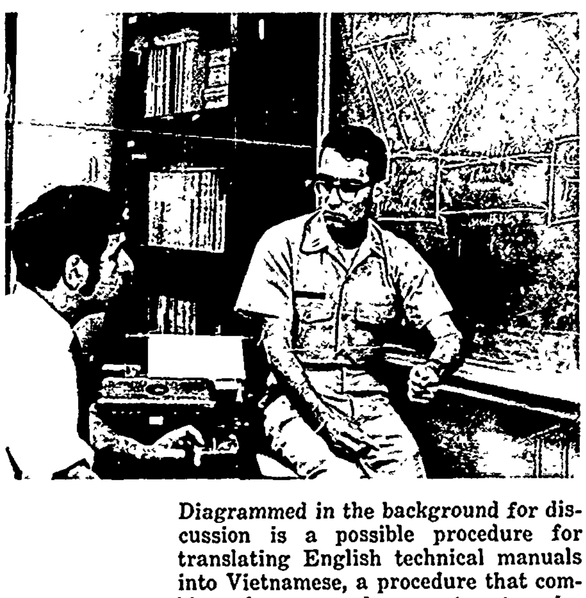
Computer software—the languages and programming procedures that will make it easier for man and machine to interact and communicate—forms one sphere of Laboratory activity. Another is research in circuit theory and logic networks that may lead to more efficient computer designs. Hundreds of circuit functions can now be incorporated on a single small chip. These high-density circuit packages represent a new technology, one embodied in the term large-scale integration.

Another division of the Laboratory's effort is that of using existing computers for more sophisticated tasks. One such task is the automatic identification, recognition, and classification of sensor inputs of all kinds. The inputs may be of great variety—photographs, human speech, radar, or infrared signals. Techniques for the real-time extraction of meaningful data—signatures otherwise buried in the flood of data from sensors—are of fundamental Air Force importance.

Apart from research directly related to computers, the Laboratory conducts research in speech processing and in analog and digital data transmission. The speech research program has several goals, among them being the reduction of bandwidth needed to transmit voice messages and more secure voice communications. Analog and digital data transmission research is limited primarily to methods for encoding analog and digital data to assure the error-free transmission of data even when circuits are noisy and degraded.

COMPUTER LANGUAGES AND PROGRAMMING

The fourth generation of computers will be the first big technological event of the 1970's. A new computer generation has come along every six years or so, with the first characterized by vacuum tubes, the second by transistors, and the third by small-scale integration of logic circuits.



Diagrammed in the background for discussion is a possible procedure for translating English technical manuals into Vietnamese, a procedure that combines human and computer translations.

The fourth will be characterized by large-scale integration through which computers will be realized capable of many times the work and speed of computers of the present generation.

Software development, the crucial problem in realizing the potential performance of these new computers, has not kept pace with hardware developments. The lag is relative, not absolute. Looking back, it can be seen that much distance has been covered since the 1950's when a computer program had to be written, step by laborious step, in the internal instruction code of the machine. The introduction of the programming languages—COBOL, LISP, FORTRAN, and so on—permitted the user to instruct the machine without the necessity of first learning the internal code of the machine he was using.

Software development has presently reached great heights of sophistication and complexity, with some programming procedures being beyond the comprehension of any one person. For these highly complex programs, there is no objective method for gauging whether they are optimum, merely efficient, or inefficient. Part of the problem is due to the absence of an underlying theoretical base. AFCRL is studying methods for gauging the relative effectiveness of software programs. In the distant future is the prospect of programs framed in a natural language—a modified version of English, for example. AFCRL is already looking toward this horizon.

COMPUTER LINGUISTICS: A natural language computer program must rest on the linguistic base of the language, taking into account underlying structure and logic. Through the study of the deep underlying constructions of language, linguists believe that it may be possible to define the very limits of the human ability to communicate. Modern linguistics is a far journey from simple rules of grammar, but rules of grammar are the essential starting point.

Several years ago, AFCRL took an early initiative in studying the linguistic requirements for programming a computer directly in English. This led to the formulation of some of the first notations (rules or algorithms) for helping a computer cope with English grammar. The study was subsequently summarized in the AFCRL report "Syntactic Analysis" (AFCRL-67-0305).

Programming in a natural language is a multilayered problem. One problem is simple ambiguity of the type found, for example, in the sentence "The boy looked over the wall." Did he peer over it, or did he examine it? Such simple ambiguities are easily resolved.

The real problem in constructing a computer grammar is that a sentence can be constructed in many different ways to express the same thought. The interchangeable use of the active voice and the passive voice is an example. The key to the AFCRL notation system is that it readily permits the computer to transform a particular sentence from active to passive or from passive to active without loss of the intended logical relationships of the words.

Special notations were formulated for a variety of sentence types. Among these are sentences with many embedded components such as "The girl likes the boy that works in the store that is owned by the man." Humans quickly sort out, categorize and assign relationships among such strings of words. Computers, with a very limited capability to learn or to reinforce their performance through experience, must view each new sentence presented as a new experience.

PARSING EFFICIENCY: When two different programming rules may each be used in a given situation, it would be assumed that the most efficient of the two would be used. An unresolved problem, however, is that of judging the relative efficiency of algorithms (rules of procedures). Recent work at AFCRL attempts to find some answers. Questions which need to be answered are, for example, "Does algorithm A always take fewer steps to finish its job than algorithm B?" Many fine points need to be pinned down to make this question precise, such as what operations are to count as "steps," but the flavor of the problem should be evident.

One such question has been successfully attacked in the Data Sciences Laboratory. It is concerned with algorithms for parsing context-free languages. It was shown that for one class of algorithms known as bottom-to-top (BT) algorithms, the maximum number of steps can be defined, in the sense that parsing steps are never more than a constant factor times sentence length. For another class known as top-to-bottom (TB), no such relationship is known and the number of steps may be much greater.

Along the same line, work is also being done on questions of absolute efficiency, such as "What is the smallest number of steps required as a function of its length to parse a sentence (with the theoretically best algorithm)?" Such problems are being attacked both directly and by looking for possible changes in the grammars of the languages that may improve parsing efficiency without compromising the power of the grammars.

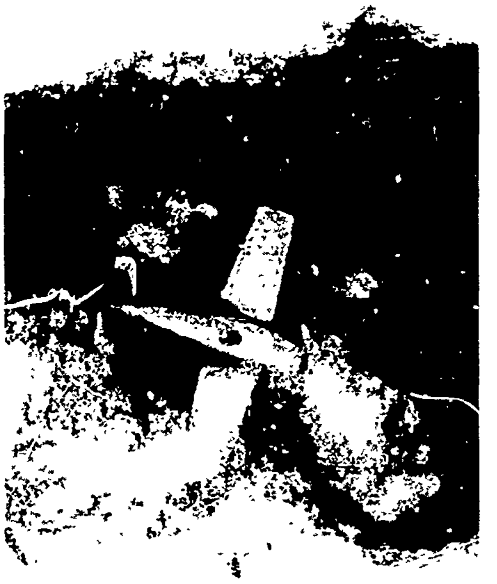
COGNITIVE PROCESSES

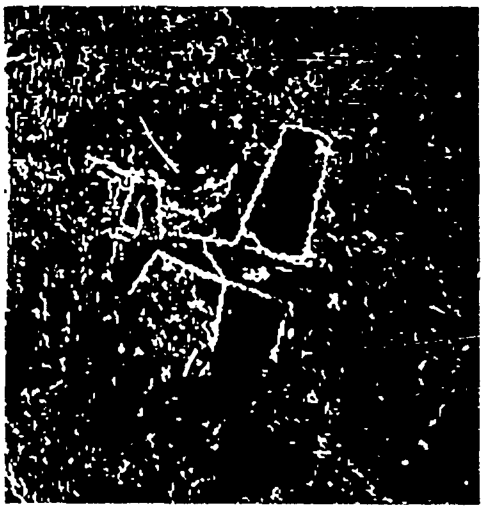
The ability to sense, recognize, analyze, and assess the environment—the cognitive processes—is essential to an animal's survival. Modern command, control, and management systems extend man's sensing capability but at the same time tax his ability to recognize, analyze, and assess. A much larger part of this cognitive activity must be mechanized if man is to cope with increasingly complex situations. Unfortunately, what man accomplishes with relative ease—examining his sensory inputs for invariant characteristic "patterns," putting them in the context of his mental model of the world, and arriving at an assessment of a situation as a prelude to decision—the computer can do only laboriously, if at all. Conceptualization of the problem as a basis for computer implementation demands penetrating and creative insight.

Objects, situations and physical processes can be described in a multiplicity of ways. But most frequently, one seeks sets of invariant attributes which describe the pattern or process in the simplest and most effective way according to a set of specified criteria. This is not a simple task except, perhaps, when the data have definable statistical properties. Part of the problem is that the choice of the attributes most effective for classification depends not only on the nature of the input data but also on the subjective point of view of the classifier. This choice of proper attributes is not obvious.

In complex situations, there are usually very few clues to attributes that describe best, from a classification point of view, a particular pattern. Often it is necessary to transform the pattern (or data) into several radically different configurations in order to bring out hidden features.

PROCESSING OF PHOTOGRAPHIC DATA: Pictures and other visual images are the raw product of photoreconnaissance,





One approach to the automatic machine analysis of reconnaissance photos is to first simplify the original photo (above) by edge enhancement, an intermediate stage of which is shown below.

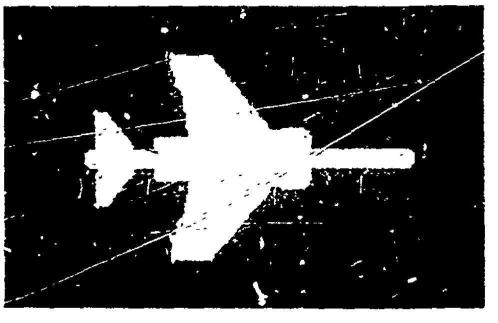
weather observations, mapping, and data recording. The sheer volume of picture material that must be viewed and analyzed in many Air Force operations has led AFCRL to investigate procedures whereby at least part of the job of the human photointerpreter can be mechanized.

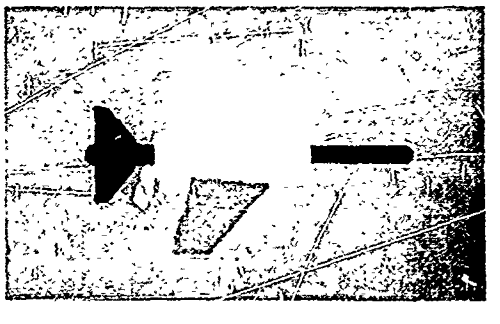
The results expected from such automated picture processing systems vary widely dependent on the application; they may range from the task of detecting only the presence of certain objects in a picture (e.g., are there missile sites in this aerial photo? or are there cancerous cells in this microphotograph?) to a comprehensive analysis of a photograph through a question-answer dialogue between photointerpreter and the machine.

Quite obviously, the computer must process the "raw" input picture before it can perform a sophisticated analysis or answer questions about it. These processing operations serve a variety of purposes, among them the removal of picture noise. This can be done by distorting contrasts, or by enhancing all edges to produce a product that looks like a line drawing. Or the computer can be instructed to enhance only those features of a prescribed geometry. In these approaches, the enormous redundancy characteristic of an unprocessed image is reduced.

Several computer programs have been developed at AFCRL for transforming raw pictures into computer-acceptable form and for extracting significant features. Two examples are given in the accompanying sequences of pictures. The first series shows how a gray-scale photograph is converted into a stereotype suitable for computer analysis. This example demonstrates how the automatic processing sequence extracts, from an extremely fuzzy and noisy original, a particular feature of interest—in this case, the aircraft wings. (The medial axis transform operation whereby this extraction is made has been described in the previous *Report on Research.*)

The second set of pictures illustrates the processes of translating human concepts of shape into a form suitable for computer manipulation. Four arbitrary shapes are identified to the computer using a special representation that is easy for a computer to use. Then a simple language is used to instruct the computer to assemble the shapes in different sizes and orientations. In one configuration the shape is that of a jet aircraft. The sentence used by the computer to construct the silhouette is the machine's "name" for that object. Interestingly, the concept of "name" in this sense points up something of the difference





Part of the research in automatic photointerpretation involves the manipulation of shape information. In this case, the F-4 silhouette, above, was constructed by machine from three simple shapes appropriately scaled and oriented, as illustrated by the lower scope photo.

between a man's and a machine's cognitive processes. The name 707 conjures up a detailed picture of a specific aircraft in man. He then can describe it in an infinite number of ways. The computer recognizes the aircraft only if the image is consistent with a fixed property list of descriptions in the computer memory.

GENERAL DESCRIPTION OF COMPLEX PATTERNS: In dealing with complex patterns, such as aerial photographs, conventional pattern classification schemes are often inadequate. The complexity of the pattern may swamp the fixed property list approach usually employed in such classifications, or the desired processing may not be a simple classification of the pattern into one of a pre-selected set of categories. More complex manipulation is often called for, such as finding all instances of a specified sub-pattern which may be defined in terms of, say, certain specified relationships between pattern constituents.

A promising approach to such problems developed at AFCRL consists of constructing a "description" of the pattern in a form convenient for further computer manipulation. This description is the result of an analysis of the pattern in terms of a set of hierarchical definitions specifying sub-patterns and how they are composed to form larger ones. The process is in some respects analogous to the syntactic analysis of sentences, where the complex pattern corresponds to a sentence, the set of definitions to a grammar in terms of which the analysis is carried out, and the resulting "description" of the pattern corresponds to the linguist's "structural description" of the sentence.

A "language" for such definitions has been designed and a corresponding analysis program implemented (in LISP) and tested on a variety of pattern classes. Present work is directed toward generalizing the pattern description formalism itself, constructing a more efficient program, and applying the scheme to more "real-life" classes of patterns, by interfacing the analyzer to existing picture preprocessing systems. A further area of interest is "grammatical inference" for such picture grammars; that is, a procedure capable of automatically generating a grammar to describe efficiently the structure of a given set of examples of patterns.

AUTOMATIC CHARACTER READING: Automatic reading of the highly stylized letters and numbers on credit cards and bank checks is now a routine part of the business economy. But automated schemes for reading conventional type fonts and hand lettering are less advanced—although some do a creditable job in handling a given type font of uniform size and orientation.

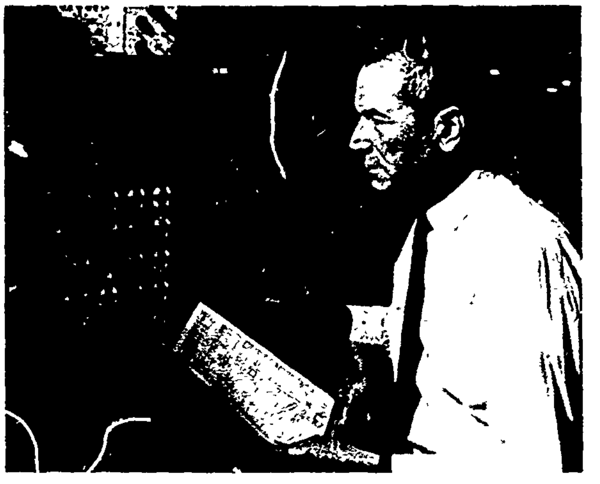
For several years, AFCRL has worked on a character recognition scheme that could read a variety of type fonts and sizes even in the presence of smudges, mutilations and improper registration. It should also be capable of accepting hand lettering with reasonable constraints. A basic purpose of this research is to develop a method whereby textual material could be read directly from a printed page as a computer input. The AFCRL scheme is one in which the character to be identified is inscribed on a matrix, or an array of cells. It makes no difference whether the pattern line-width extends across one or several cells. Tests of the letter for its characteristic identifying features are performed by the background cells—that is, by those cells that do not contain any part of the pattern.

Each of the background cells makes, with the help of its neighbor cells acting as a miniature computer, its own measurements from its own particular perspective. One can visualize this operation as drawing horizontal and vertical lines through a particular interrogating cell to form a cross. The cell then can be considered as having four arms extending to the left, up, down, and right. The object is to count how many lines in the pattern forming the letter are intersected by each of the four arms.

To take a simple illustration, if the letter O is presented for identification and the cell called upon to make an interrogation is located anywhere inside the letter, each of the four arms would intersect one line. But obviously the same result would obtain for a point inside the letter D. Such ambiguities are resolved through tests from other points (or cells) in the background of the letter.

Encoding the results of the measurements is rather straightforward. Each of the four arms determines one of four code digits for the particular grid cell through which the cross is drawn. If the arm intersects the pattern's line once, the code is 1; if two or more times, the code is 2; and if not at all, the code is 0. Thus in the example above the code for the point measurement is 1111. The sequence of the digits in the four-digit code always begins with the left arm, then the upper arm, the lower arm and finally the right arm. For a point in the upper cavity of the letter M, for example, the code would be 2012. For clean letters, this particular code, 2012, is in fact unique for the letter M. No other letter has it.

Tests of the system have been carried out by computer simulation. With simulation, not only can characters of various fonts and sizes be tested, but recognized in the presence of smudges and other "noise" as well. Using AFCRL's 7090-7044 computer, tests of a random assortment of 21,000 letters were made with an overall error rate of 2.4 percent. Identification speed is still relatively slow—50 characters per second—but by means of decision tree schemes and by special hardware implementations, speed increases by several orders of magnitude are believed possible.



Preprocessing for automatic character recognition can be demonstrated on this light array in which the investigator can see the imprinting of the letter on a matrix and the results of subsequent transformations on the letter.

MULTI-SENSOR DATA INTERPRETATION: To the technically untutored, waveforms seen on an oscilloscope—electromagnetic, biological (a heartbeat or an electroencephalogram) or acoustical (speech or a seismic disturbance)—all appear similar. Similarities do in fact exist and these can be used to advantage. A major Data Sciences Laboratory program is devoted to the questions: "What are the common characteristics of all sensor measurement processes?" and "How does one extract only essential attributes from the torrential flow of information contained in the waveform produced by a particular sensor?"

On the color display of the Experimental Dynamic Processor, the results of a complex statistical target signature classification procedure are being examined by scientists who can communicate interactively with the processor. Anomalies in the performance of the target classification procedure can be quickly identified and corrected using this interactive capability.

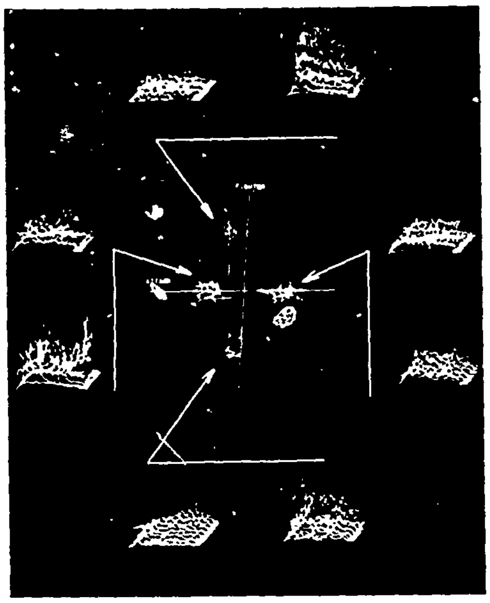
While it is commonly argued that the human is very good at pattern recognition and data interpretation, this is only true of sensor data corresponding to certain optical and acoustical stimuli for which the individual has built up a background of experience. Even here, the individual usually sees what he "wants to see," hence spoofing and deception are easily achieved, as many deliberately ambiguous patterns clearly demonstrate. For the vast bulk of signal data from a growing variety of military sensors, such as multi-spectral, phased-array radars and infrared devices, there exists no "human" experience to aid in interpreting the data. Moreover, the data must be reduced, interpreted and decisions made on a time scale which is usually too short for human response.

Fortunately, advanced signal processing methods. based upon abstract mathematical procedures, and implementable through the use of modern micrologic technology, hold the promise of achieving high levels of confidence in interpreting the data from multiple sensors. In particular, one method developed at AFCRL, is based on techniques which were originally evolved in quantum mechanics to describe the interaction between sensing devices and the process being observed. Basically, the techniques provide a mechanism for extracting minimal sets of invariant attributes from the measurement process. The procedure used is derived from a small family of principles, the most important of which are: 1) reproducibility of extracted attributes, 2) mutual exclusiveness of the attributes, and 3) completeness of the set of extracted attributes.

The power of the technique has been demonstrated in the processing of speech signals. From the continuous flow of information in the raw speech signal, key invariant structures were extracted for transmission and reconstruction. In these tests, bandwidth compression by a factor of five with negligible distortion was demonstrated.

Attribute extraction procedures may eventually be incorporated into modularized signal processing devices of relative simplicity that could operate with a variety of Air Force radar or infrared surveillance and tracking instruments. These modules would reduce the data from different sensors to a suitably standardized or "canonical" format, based upon the automatic isolation of critical invariants needed to describe the data sources. By systematically consolidating the data from multiple sensors, the potential exists for achieving very large savings in the bandwidth needed to both transmit the data and to store it for later reference.

Most of the attribute extraction research is performed on AFCRL's Ex-



Noisy time-varying signatures of the head and tail aspects of four different aircraft are shown around the periphery of this representation. Using a statistical analysis procedure, these radar target signature data are consolidated into the format shown in the center. The location of the resultant traces gives a clue to aircraft identity.

perimental Dynamic Processor DX-1. The DX-1 Computer is a memory-sharing, polymorphic digital processor with special microprocessing and on-line display generating features. Although it is now eight years old and relatively slow, it is still a highly versatile instrument, one in which man and machine have a good and direct rapport.

During the reporting period, this machine was used to investigate the signatures of a variety of sources. For example, is the radar signal from a B-52 distinguishable from that of a 707, and to what extent can the radar signatures of fighters and fighter-bombers be unambiguously distinguished? The same data reduction and interpretation system has been applied to the classification of acoustic signature data.

The color display on the DX-1 System provides an excellent tool for use in examining the performance of various advanced target signature categorization procedures. In particular, by consolidating each signature into a single point in a complex N-dimensional space, the behavior of whole families of signatures from different sources can be studied by observing the behavior of color-coded clusters of points projected on the computer-controlled display. This approach has proved of exceptional value to systems analysts and designers, and is being copied at a number of other defense research laboratories.

SPEECH AND DATA TRANSMISSION

The research covered in this section deals with electronic communications—with techniques for transferring information efficiently and reliably. Most of the research involves digital techniques.

Speech is the basic information transfer mechanism. AFCRL has supported

Speech intelligibility is a subjective factor. Tests for intelligibility are conducted in AFCRL's sound room, part of the speech research facilities.

a strong speech research program for many years. This program has two parts. The first involves experimental equipment for the manipulation and processing of speech signals for economical, reliable and secure transmission. The best known equipment for achieving this is a class of equipments known as vocoders. The second part is more fundamental, involving basic properties of speech, the physiology of speech production, and its perception. Both efforts have common goals: to reduce the bandwith needed to transmit speech signals, and to lay the groundwork for automatic recognition and identification of spoken messages.

Other Laboratory programs relating to communications are concerned with the encoding and transmission of digital data and with information and communications theory.

SPEECH PROCESSING: Speech processing entails the filtering, encoding and digitizing of speech signals into electronically manageable and efficient units for transmission. At the receiving terminal the transformed signals are reconstructed for acoustical reproduction by a voice synthesizer. With processing, the bandwidth needed to transmit the message is reduced. For example, the bandwidth used to carry an ordinary telephone message is about 3000 Hz. With speech processing techniques, the same message can be carried by a bandwidth of less than 600 Hz. Thus with bandwidth compression, five times as many messages can be carried over a given channel.

Much of the research in speech processing is focused on vocoders, equipments which perform two basic operations. They separate the various frequency components of the basic speech signal by filtering, and they convert the signal to digital form for more efficient transmission. There are several classes of vocoders; AFCRL has placed emphasis on channel vocoders. Channel vocoders presently provide highly intelligible speech and useful speech compression factors. But voice quality and naturalness are still lacking. During the reporting period, AFCRL's vocoder was subjected to comparative tests for voice quality with vocoder systems developed by others and was found to be equal and superior to any in existence.

Although vocoders have been introduced into operational systems, special problems still exist and must be resolved before they can be more universally adopted. One of these is the use of these equipments in a noisy environment—in an aircraft, for example.

SPEECH PATTERN MATCHING: The best 2400-bit-per-second channel vocoders available can transform analog speech signals to digital form with only minor losses in intelligibility, speaker identity or the tonal nuances that convey much extra-verbal information. The fidelity, in fact, approaches telephone quality.

AFCRL has shown that the output from a channel vocoder can be processed through another stage, leading to a further bandwidth reduction by a factor of three to five. The technique is one of speech pattern matching. A set of reference speech signal spectra is stored and when a speech waveform matches one of the stored patterns, a relatively simple code for that pattern is transmitted. The original pattern can then be reconstructed at the receiver.

The intelligibility of words reconstructed from these patterns must in the final analysis be judged subjectively. For this reason, AFCRL arranged through one of its contractors for listener tests to be made. As guides for scoring, a set of diagnostic criteria was

VOICING	DENT - TENT	GOAD - CODE	VAST - FAST
NASALITY	NEED - DEED	MOSS - BOSS	KNOCK - DOCK
SUSTENTION	FIN - PIN	VOTE - BOAT	THIN - TIN
SIBILATION	JOT - GOT	SEEM - THEME	CHAMP - CAMP
GRAVENESS	BID - DID	MODE - NODE	POP - TOP
COMPACTNESS	CAST - PAST	YAWL - WALL	SHED - SAID

Shown here are examples of word pairs used in the Diagnostic Rhyme Test for measuring intelligibility.

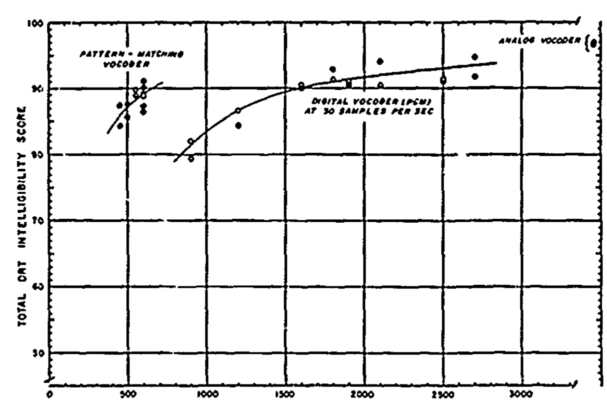
adopted. Tested were six fundamental components of intelligibility: voicing, nasality, sustention, sibilation, graveness and compactness.

A large number of rhyming word pairs were formulated as a means for testing how well each component was replicated. Each rhyming pair differed only by the single component being tested. An example of a word pair used to measure sustention is the pair, "fin-pin." The initial consonant of "fin" is sustained while that of "pin" is abrupt. Examples of other word pairs in which the first word is representative of the quality being tested are: for voicing, "dot-tot"; for nasality, "mend-bend"; for sibilation, "seem-theme"; for graveness, "weed-reed"; and for compactness, "kit-pit." Purpose of the tests was to see how often a word was confused with its mate. Words were presented individually to the listener, not as parts of sentences.

A reasonable initial assumption was that, as the number of stored reference patterns increases, confusion between words in a pair would decrease. The number of stored patterns was varied through 12 increments ranging in number from 497 to 3996. Corresponding data rates over this range are 450 to 600 bits per second.

Contrary to expectations, the listener tests showed that the pattern-matching technique is relatively insensitive to the precise number of stored voice patterns. Overall intelligibility scores (the percent of words identified correctly) ranged from 82.6 percent for 497 voice patterns to 91.9 percent for 3996 patterns. But within this overall score, some of the six intelligibility components were easily processed to produce words that are immediately clear. Others proved more difficult. Sibilation test pairs—"jest" and "‹ ıest," for example —were rarely confused. Taking the mean scores for all the tests, the results were: for sibilation, 97.9 percent; for nasality, 95.1 percent; for compactness, 93.0 percent; for voicing, 88.4 percent; for graveness, 86.7 percent, and for sustention, where the listener had to distinguish between such pairs as "vote" and "boat," the result was 67.0 percent.

The AFCRL group is highly encouraged by these results. Improvements are likely in all six intelligibility categories, and data rates can possibly be reduced by about 30 percent by a coding



In the upper right of this chart the intelligibility of an analog vocoder (or an ordinary telephone) is depicted. The digital vocoder approaches this intelligibility with a much slower bit rate. But with a still slower bit rate, AFCRL's pattern-matching vocoder (upper left curve) yields exceptionally high intelligibility.

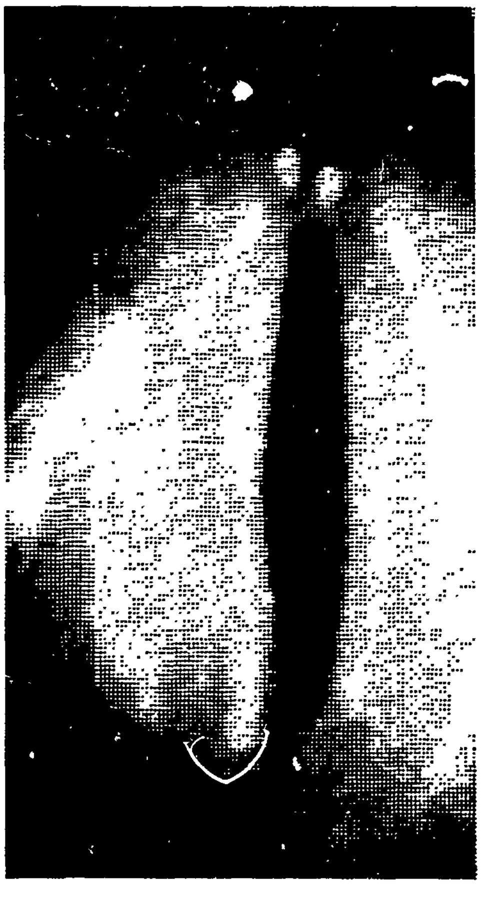
scheme that takes into consideration pattern probabilities.

Looking further ahead, the AFCRL group believes that data rates can be furthered lowered—to perhaps 200 bits per second—by reducing redundancies in the time domain. The data flow would be compressed during transmission, and expanded again to normal speech rates at the receiver. Last, and perhaps farthest on the horizon, the pattern-matching technique can lead to peripheral equipment for the generation of a voice output from a computer system.

SPEECH PERCEPTION: An effective voice communication system must be capable of transmitting all those attributes of the input utterance that are necessary to achieve complete intelligibility. Considerable effort has therefore been placed on attempts to identify invariant acoustic patterns for the basic sounds of speech.

Recent research at AFCRL and elsewhere has shown that the task is not simple. Human speech perception is not simply the recognition of a sequence of sound patterns strung out in time and perhaps modified somewhat by individual human differences. Rather, there is interaction among the sounds themselves, along with overlays due to linguistic and emotional considerations. Further, the perceptual processing humans use for speech sounds seems to be organized differently from the processing of non-speech sounds, such as music. In particular, consonantal sounds appear to be perceived as speech, while vowels have some apparent perceptual attributes of non-speech. The perception of consonants and vowels embedded in various noises has been studied in detail at AFCRL, with several interesting results.

First, consonants are much more easily perceived than vowels at the same signal-to-noise ratio—an advantageous situation since consonants are the primary conveyers of speech intelligibility. Second, noise interferes with the perception of vowels and consonants in different ways. Also, different parts of the speech spectrum contribute disproportionately to vowel and consonant perception. Vowel identification is easier at the lower frequencies in speech, the same region that contributes the most to speech energy, but apparently not to the information transfer. Finally,



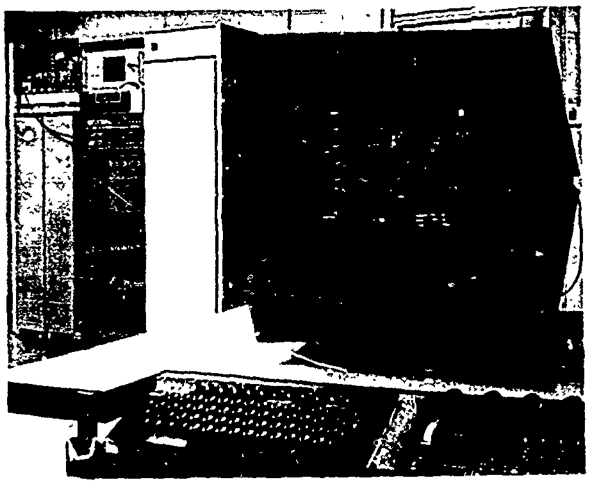
High-speed motion pictures of the vocal cords (a frame of which is shown here) are later processed by a computer to study the basic parameters of speech production — glottal opening, the amount of air passing through the vocal cords, and vocal cord vibrations.

not only are there fewer errors in consonant perception versus vowel perception, but the variability is less as well.

An optimized speech filter developed by AFCRL takes advantage of these phenomena and achieves in the order of 50 percent savings in signal power without loss of intelligibility. Curiously, the filter deliberately distorts the signal to degrade fidelity to achieve this beneficial result.

MECHANISMS OF SPEECH PRODUCTION: Clues to the development of improved speech processors and synthesizers may be found in the study of the mechanism by which speech sounds are produced—that is, the human vocal cords. For voiced sounds, the area of the glottal opening (the opening between the vocal cords) as a function of time, is the determining factor. Knowing the glottal area as a function of time, one can compute the volume velocity of the exhaled gas as a function of time with comparable accuracy. The volume velocity is the function of interest, since it constitutes the actual sound source for voiced speech. High-speed motion pictures of the glottal area provide the basic data for this research. The glottal area is derived from each frame with computer assistance. Both the photography and data reduction were greatly improved during the reporting period.

The sharpness of the glottal edge in the photographed image was improved by lighting the vocal cords from below rather than from above. The translucent properties of the skin were used with light passing through the anterior tracheal wall below the larynx. To achieve this has required using the brightest and coolest light, the widest lens aperture, and the fastest film. Lighted in this way the vocal cords are seen in silhouette, and the edges are much more sharply defined.



A computer and a voice synthesizer are used to reproduce speech. One of the sets of control signals for a formant speech synthesizer is displayed on the scope of the controlling computer. The voice synthesizer is in the center rack in the background. The right-hand rack contains the multiplex D/A converter that forms the interface between computer and synthesizer.

For data reduction, a computer program was written that determines the edges by automatic means. Pertinent parts of the image of the glottal opening contained on one frame are scanned and digitized. Initially, the operator sets two segments of one scan line so that one segment spans each of the two glottal edges near the middle of the image. The computer looks for the greatest change in density along each segment by ascertaining positive or negative peaks in the density derivative. The two selections thus made tell the computer where to look in the next line above, and the machine continues examining upward, line by line, until the two edges converge. The edge points are smoothed to a realistic contour. This technique, together with that for improving the edge sharpness in glottal photographs, is pointed toward automatic reduction of glottal area data at a very rapid rate.

ANALOG DATA TRANSMISSION: Pulse code modulation (PCM) has long been used as a method of digitally transmitting analog signals. In this method of transmission, the analog waveform is sampled, or measured, many times each second, and the value of each sample is then transmitted digitally. It has been recognized for some time that the value of the sample at a given time is strongly constrained by the values which precede and follow it. This would make it possible, in principle, to transmit the waveform with a smaller number of bits per second than that dictated by the product of the number of samples per second and the number of bits used to represent each sample.

AFCRL is currently investigating techniques for digitizing simultaneously samples from several data sources such as pressure, temperature, and velocity gauges to achieve minimum data rate. This simultaneous digitization would permit lower transmitted bit rates because improbable combinations of samples could be quantized more coarsely. Furthermore, initial theoretical studies have indicated that, surprisingly, the design problem of minimum-error quantizers for multi-sample data may be easier than for single sample quantizers, and further that quantizer operation which changes according to slow variations in the source characteristics may be possible.

ERROR CORRECTING CODES: When certain kinds of digital data must be sent over channels that are noisy and imperfect, and it is essential that the digits received be precisely those that are sent, automatic error detecting and correcting codes must be used. Such codes consist of a string of information

Sophisticated mathematical codes are necessary to assure error-free transmission of digital data.

bits followed by a number of code or parity check bits. For example, four information bits may be followed by three parity bits which can detect and to some extent correct errors in the four information bits. There can be an infinite number of codes—and many thousands in several major code classes have, in fact, been developed. The development of a good code, like an exercise in cryptography, requires mathematical logic, patience, and often spontaneous and creative insight.

As a measure of the mathematical complexity of these codes, it should be noted that once a good code is discovered, there is no easy way of judging, except in a qualitative way, just how efficient it is. Nor is there any way of comparing the efficiency of one good code against that of another good code. (An efficient code is one that can detect and correct errors using a small number of parity bits relative to information bits.) In this connection, an AFCRL contribution of classic importance was the proof established during the period that one family of codes, the Golay codes, are the only perfect codes for their parameters. This result will have great impact on coding theory.

One reason that error correcting or detecting codes is not in more widespread use is that their use calls for prohibitively complex encoding and decoding equipment. AFCRL has designed and constructed a fail-safe decoding device that can automatically detect virtually all errors and correct most of them. Large codes can now be used because the complexity of the AFCRL device increases only linearly with the length of the code word, whereas other coding and decoding techniques increase in complexity exponentially with the length of the code word.

Briefly, the principle of the decoding method is to erase all binary digits likely to be in error and fill in the resulting blanks with digits that satisfy *all* the parity check equations, if possible. If this is not possible the word is then rejected. The equipment is presently under test and has shown excellent performance.

IMPLEMENTATION

Implementation refers to research that may lead to more efficient and economical computer designs. Efficiency is measured in many dimensions—speed, versatility, memory, ease of fabrication, low power requirements, compactness, and so on. For the Air Force, reliability is a parameter of special importance. The machine in an Air Force system must often operate in environmental extremes and in the presence of ionizing radiation.

In the closing years of the 1960's, integrated circuits of the third computer generation were marked for replacement by devices of high complexity with circuits per chip numbering in the several hundreds, an order of magnitude advance over relatively simple integrated circuits. Large-scale integration had emerged as a key term. The circuitry designer was suddenly presented with a new range of choices—and complexities. More and more he sought computer assistance in evaluation of circuit design, giving rise to the term, "computer-aided design."

A great variety of circuits can be designed to perform a given function. When a circuit has been designed, with or without the aid of a computer, how does the designer know that his design is the best possible design for a particular function? There are few guidelines that tell the designer his circuit is opti-

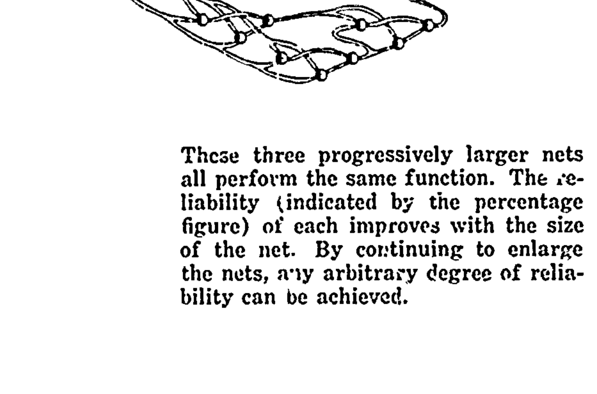
Electronic programmable desk calculators are ideal tools for examining problems in electrical network theories.

mum. Circuit theory deals with this matter.

CIRCUIT THEORY: This research is not concerned with specific circuits but with extending circuit theory and deriving new network principles. AFCRL has emphasized, in particular, the problem of finding objective methods for selecting the optimum circuit to fill a particular requirement. The approach is to express the desired network behavior mathematically for computer-assisted analysis. The resultant product is an enumeration of all possible networks having the desired characteristics.

For this analysis, AFCRL often uses small desk electronic calculators for which it has evolved a number of specialized programs. The big advantage in the use of these calculators is that, unlike the larger computers, they are always available to the designer. Their use obviates demands for time on larger laboratory computers. The special programs formulated by AFCRL for network analysis by electronic calculators have been compiled in an AFCRL inhouse report.

Scores of individual network problems have been analyzed using these calculators, one of which, by way of example, is the following: The input impedance of a network can be represented as the quotient of two polynomials which differ at most by 1 in their order. If they are of the same order, they are referred to as "bi-order functions"; if they differ, a function of order 1 can be split off, leaving a bi-order function. It has been shown that from the general bi-order function a specific one can be derived that has an extremely simple realization in the form of a single terminated T circuit section.



These three progressively larger nets all perform the same function. The reliability (indicated by the percentage figure) of each improves with the size of the net. By continuing to enlarge the nets, any arbitrary degree of reliability can be achieved.

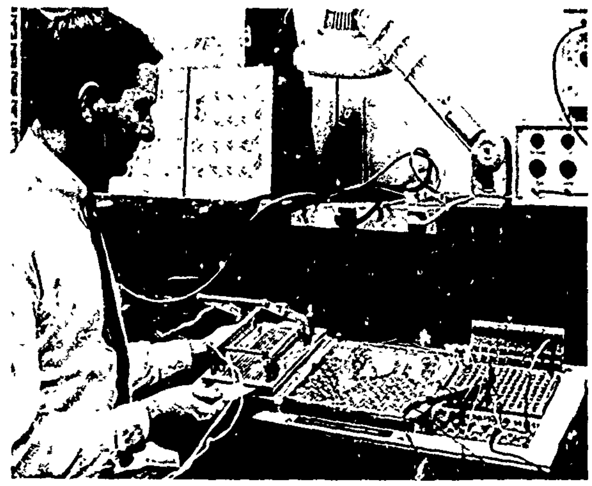
LOGIC NETWORKS: Large-scale integration has created a range of problems for the designer. For example, assuming that a maximum number of functions per chip is in fact desirable, what functions should be integrated into the chip? Another problem has to do with standardization. Because a near-infinite number of circuit designs can be fabricated, efficiency dictates the need to restrict the inventory of different integrated chips required to build a machine. Custom designed chips produced in small numbers are prohibitively expensive, while chips, even very complex ones, become quite inexpensive if produced in large quantities. On the other hand, the more complex the function of a chip, the more specialized it becomes. So the designer attempts to achieve maximum functional flexibility in standardized chips.

Further problems are: reliability of arrays consisting of less than perfect elements; the sequential behavior of such arrays due to the finite switching speed of the constituent elements; the restrictions of the chip geometry that dictate which elements in a common neighborhood will communicate with each other, and finally, the adaptation of electronic techniques to satisfy the requirements and constraints of the above conditions.

AFCRL programs in logic networks cover various aspects of all of these problem areas. Polyfunctional nets have been given special attention. These are nets that can perform many functions depending on the set of functions assigned to their constituent elements. AFCRL's work is dominated by two basic questions. Given an arbitrarily large net, what is its overall function set under all possible sets of function assignments to the individual elements? What happens to the overall set of functions if the net is composed of unreliable components? These two questions are closely related; once it has been determined what the set of functions is that a given network performs for all possible function assignments to its constituent elements, one needs only to interpret an element failure as one of the function assignments possible to an element. With known failure probabilities, the reliability of the entire net can be computed.

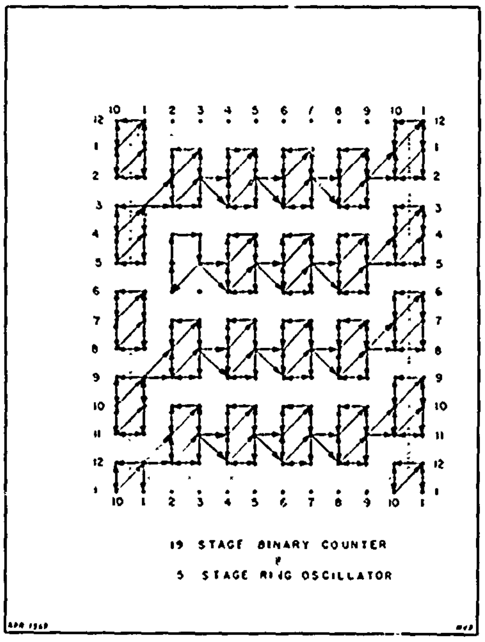
The previous *Report on Research*, in a discussion of homogeneous iterated nets, noted that arbitrarily reliable nets can be constructed from arbitrarily unreliable elements. More recently, researchers at AFCRL have discovered the existence of polyfunctional nets with other, attractive properties: "perfect" nets which, for every function assignment among the elements, produce a different output function, thus displaying the maximum possible in versatility. On the other end of the spectrum is an "ultrastable" net that, regardless of the element function assignment, always produces the same output function—that is, nets that are infinitely reliable.

This research received a new impetus



Holes in this computer card control the active interconnections between 120 NOR logic elements contained within a 120 node eight-neighbor array.

from study of *The Two-Valued Systems of Mathematical Logic* by Emil Post. The research reported in that book was performed in 1926 and published in 1940. Because of its archaic terminology and difficult style, it has been essentially inaccessible to network theorists and logic designers. A complete reorganization and rewriting of the book was undertaken in the past year by an AFCRL scientist. This work is now essentially complete. It contains Post's material in modern terminology with most of the proofs redone to achieve clarity of expression and ease of application. In addition, some results of AFCRL's research have been included. This book will be of particular importance to logic designers since it specifies the nature of the building blocks needed to realize any of the closed sets of two-valued functions with an appropriate network. Applications to the convergence problem in polyfunctional nets are expected to develop since the function set of such a net is closed whenever the element function sets are closed.

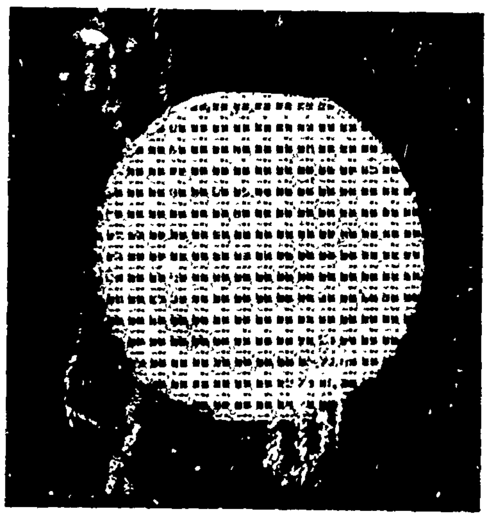


The realization of a 19-stage binary counter and a 5-stage ring oscillator embedded in a 120 node eight-neighbor NOR network is illustrated. The arrows indicate that a light-controlled connection has been made.

REGULAR, MODIFIABLE NETS: The preceding section dealt with logic networks as rather abstract theoretical structures. Before these ideal structures are applied to the microminiaturized computer circuitry, some facts of life must be taken into account.

In large-scale integration, a large number of gate circuits are put on a single chip of semiconductor material to form the equivalent of what previously was a sizable computer module. As noted earlier, the larger the integrated module on a single chip, the more specialized it becomes, where the goal is always flexibility. Specialized chips sacrifice many of the advantages expected from large-scale integration. Another problem is that of limited yield in large structures. The probability of faulty circuits occurring in a large chip is very appreciable and it is economically unfeasible to discard all but the perfect chips. Therefore, faulty circuits have to be located by testing and, by a technique called discretionary wiring, bypassed. Thus, each chip created in this manner becomes a custom-made component which runs contrary to the basic philosophy of LSI. Finally, there is the fact that a complex integrated module can have only a limited number of input and output connections to communicate with the outside world. To transform a given logic design into an efficient integrated structure requires, therefore, skillful partitioning of the basic logic structure.

AFCRL is concerned with all three of these problems. To start with the last one, the partitioning problem, two modern computer designs, one for a small machine, the other for a very large ma-



This silicon wafer contains hundreds of arrays of silicon photodiodes and p-MOS transistors. Such arrays can be diced out to be mounted individually, or the arrays can be interconnected to form a large-scale integrated array. Light impinging upon appropriate locations in the array can be made to control the circuit function of the array or serve as data input.

chine, were analyzed to find out how they can be partitioned into a limited number of different module types that can be realized by large-scale integration. The results of this study should give significant direction to the organization of future generations of computers. The other problem, that of dealing with chips containing faulty elements, has led to a study of techniques of fault-detection, location and repair.

The problem of creating large logic arrays of maximum flexibility is in the forefront of AFCRL's research efforts. The approach is to assume regular logic arrays containing large numbers of identical logic elements arranged on a rectangular grid. It is further assumed that each element in the array can communicate only with elements located within its "neighborhood" which may extend somewhat further than the nearest neighbor elements. These assumptions assure that the array is easily manufacturable by integrated circuit techniques and avoids different circuit types on the same chip. The overall function of the resulting network is determined by the function performed by the individual elements and the connection pattern linking the elements together.

One approach taken at AFCRL to flexible networks is the control of the network interconnections using light-sensitive components in each element. The network function can then be changed by letting different light patterns impinge on the array to change connections among the elements. Integrated logic elements having this feature have been developed under AFCRL contract.

Light-sensitive arrays of this kind can be modeled by a computer. The Laboratory has developed a number of computer programs for these modeling studies. Faulty elements can be simulated, and studies of the repair or bypassing of these faulty elements can also be made. The goal of this work is that of specifying a network function to the computer and permitting the computer to formulate a light pattern that changes the interconnections so as to realize this function.

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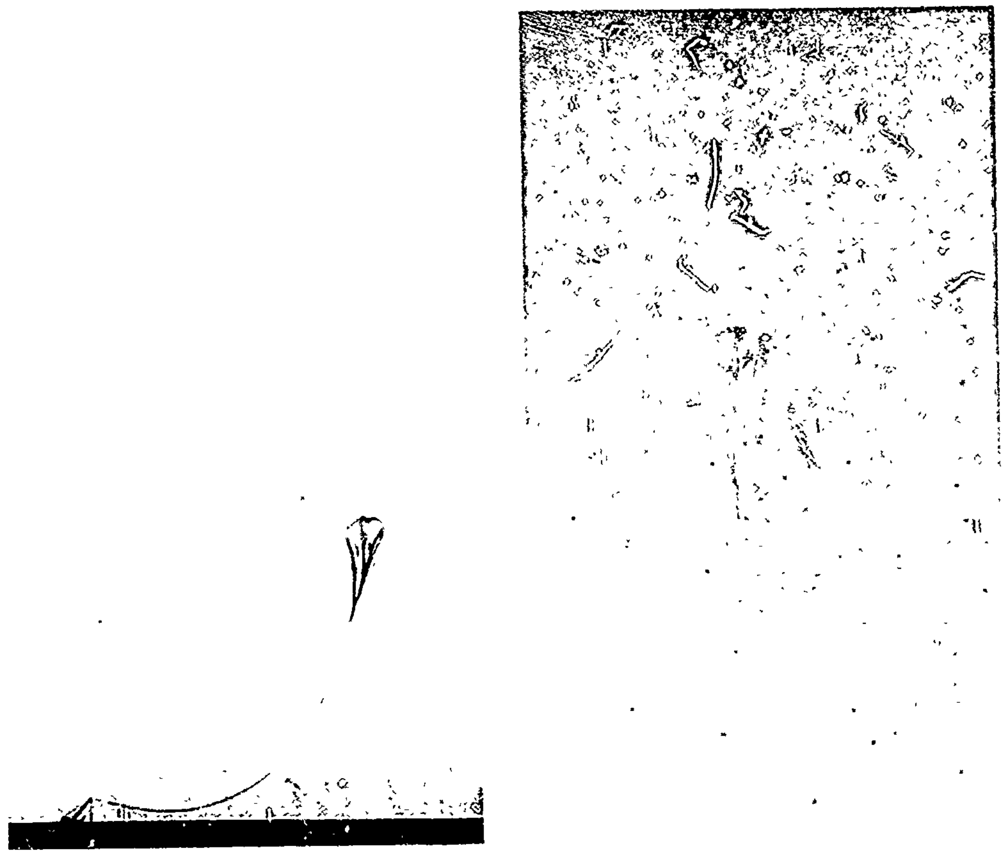
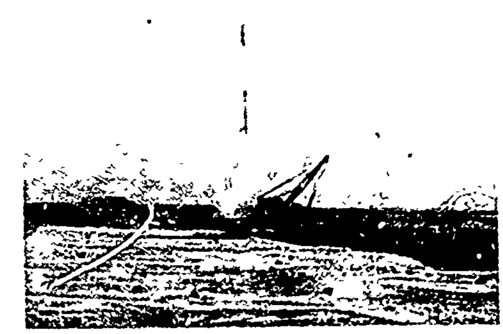




Just before launch, the crane moves up under the rising balloon and when the balloon is vertical, it is released. This particular balloon was launched on September 11, 1968, and established a record for the highest altitude ever reached by a research balloon — 160,000 feet.

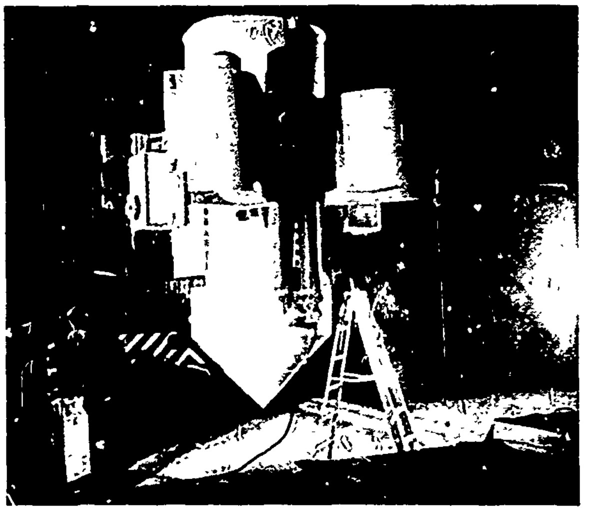
XII Aerospace Instrumentation Laboratory

In the preceding chapters of this report, frequent reference was made to balloon, rocket and satellite experiments. The Aerospace Instrumentation Laboratory manages the research vehicle program for AFCRL. It serves as a consultant to the AFCRL users of these vehicles, as well as to AFCRL contractors and to those in other military and government agencies that call upon AFCRL for balloon and rocket launch assistance. It organizes the ground telemetry network associated with such launches, selects the appropriate vehicle for the experiment, assists in the instrumentation and manages the actual flight and payload recovery.

During the three-year reporting period, the Laboratory launched 166 large research sounding rockets, 277 smaller meteorological sounding rockets and 384 large plastic balloons. The Laboratory also designed and managed the launch of three AFCRL instrumented satellites. Several new balloon records with respect to size, altitude and payload weight were set by the Laboratory during the period. On November 6, 1969, the Laboratory launched the largest balloon (34 million cubic feet) ever sent aloft and it carried the heaviest balloon payload package (13,800 pounds). The altitude record was set on September 23, 1969, when a balloon was sent to 161,000 feet. For its balloon activities, the Laboratory operates two permanently staffed launch sites, one at Holloman AFB, N.M., the other at Chico, California.

In addition to the research vehicle activities, the Laboratory develops and often procures for the Air Weather Service new meteorological equipment. The 277 meteorological sounding rockets noted above carried payloads for meteorological equipment developers. In recent years, the Laboratory has placed particular emphasis on the development of lightweight portable weather equipment for use in Southeast Asia. The meteorological equipment development program, in general, is not confined to any one particular specialty, but includes every meteorological sensor or equipment that might augment the mission of the Air Weather Service.

On June 13, 1970, one of the Laboratory's large branches, the Design Climatology Branch concerned with global climatology, was transferred with no change of function to AFCRL's Aeronomy Laboratory. The research conducted by the Design Climatology Branch is covered in Chapter VIII.



AFCRL launches balloons for many agencies. This balloon payload package, a NASA cosmic ray experiment designated CRISP, was the heaviest payload ever carried aloft by a balloon. It weighed over 6 tons.

ROCKET AND SATELLITE PROGRAMS

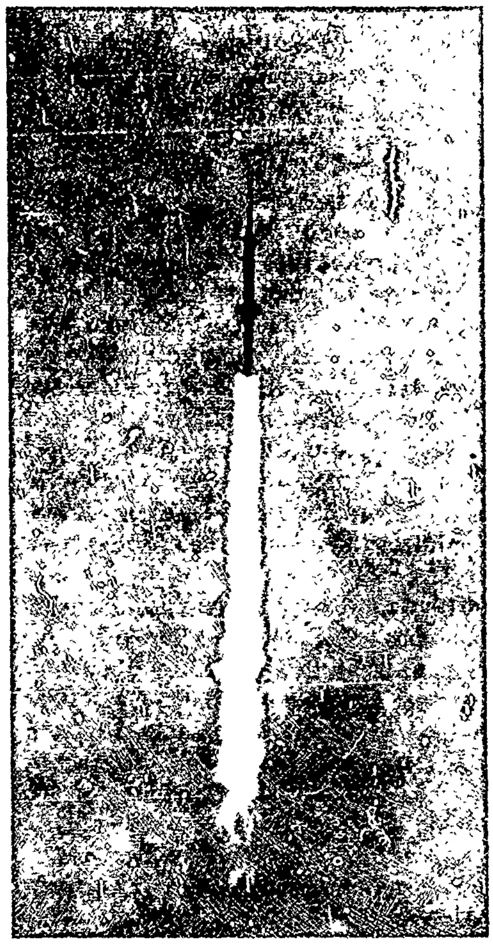
The Aerospace Instrumentation Laboratory manages the AFCRL research probe program. Management of the program has many facets including vehicle selection, range scheduling, structural design, payload integration and fabrication, and systems for data transmission and decoding.

Most of the rockets launched during the reporting period were launched from three primary ranges—Eglin AFB, Florida; White Sands Missile Range, New Mexico; and Ft. Churchill Range in Canada.

The largest single rocket program of the three-year period took place in early November 1969 when some 19 AFCRL sounding rockets were launched as part of a 35 vehicle interagency program in a six-day period from Ft. Churchill to investigate the terrestrial effects of a solar proton shower. Much of the logistical and operational planning for the overall program was accomplished within the Laboratory, as well as the engineering and field services for the AFCRL commitment.

Another event of geophysical interest was the solar eclipse of March 7, 1970. The Laboratory was instrumental in the launch of six rockets from a small auxiliary launch site controlled by Eglin AFB and of three rockets from Wallops Island, Virginia. The determination of launch azimuth and launch time for each of these rockets was preplanned through the computer simulation methods developed within the Laboratory.

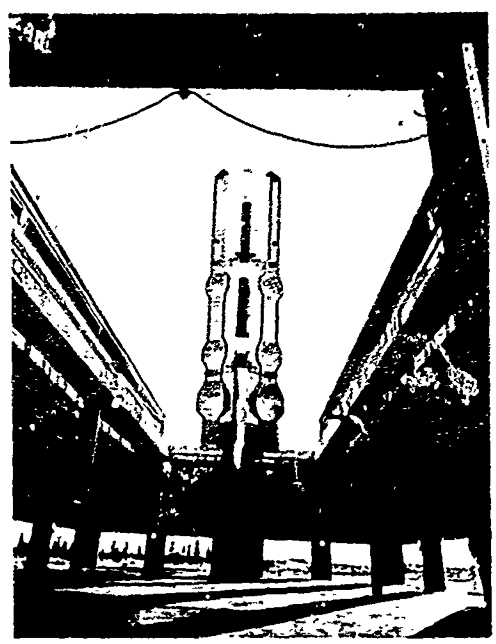
Launches were also made from Puerto Rico, Hawaii, and Brazil, emphasizing



The Aerospace Instrumentation Laboratory manages AFCRL's rocket program, a responsibility that includes payload assembly, rocket selection, data collection, and range scheduling.

the versatility of the rocket probe as a research tool. Launches made outside standard missile ranges are sometimes necessary because of geographical considerations or because the experiment is conducted in association with some special facility. For instance, the launchings in Puerto Rico were conducted in conjunction with ground-based measurements by the huge radio telescope at Arecibo, whereas the instigation to utilize the Barreira do Inferno Range in Brazil was its proximity to the geomagnetic equator.

ROCKET FLIGHT DYNAMICS: Two problem areas of sounding rocket flight dynamics have received special attention from the Laboratory. The first consists of the erratic and unpredictable roll rates observed on some flights. The typical sounding rocket is caused to roll about its longitudinal axis by canted fins at the base of the vehicle. On a nominal flight the roll rate remains proportional to the vehicle velocity. However, on some flights the observed roll rate has demonstrated almost an inverse proportionality to velocity, decreasing during periods of acceleration and increasing during deceleration. Several possible explanations of the



This four-stage Javelin rocket is shown prior to launch from the Ft. Churchill Research Range in Canada. It reached an altitude of 500 miles and was instrumented to measure magnetic fields.

anomaly have been explored, but definitive relationships are not yet complete. Analytic expressions have been developed describing the effect on individual fins of vortices trailing back from the nose of the vehicle. The investigation into the nonlinear aerodynamics is necessarily complex and involved but will provide a description of what happens to an unsymmetrical finned vehicle at an angle of attack.

The second problem area manifests itself as a rapid generation of a large angle of attack without significant altitude loss or destruction of the vehicle. The large angular deviations from pure rolling motion are obviously undesirable from an experimenter's point of view. As well as investigating analytically the possible causes of the anomaly, an empirical solution to the effects of the anomaly is being attempted. A spring-mass-damper installed in the payload will be despun with respect to the vehicle and used to damp out the undesirable transverse oscillations.

OV SATELLITE SERIES: The last of the OV (orbiting vehicle) series of low-cost satellites was launched in May 1969. Fifteen of these satellites were launched during the preceding two years. The Aerospace Instrumentation Laboratory had total responsibility for technical management and experiment integration of three OV spacecraft during the report period. AFCRL experimenters provided sensors for an additional nine which required a lesser degree of technical assistance from Laboratory engineers. All three of the satellites under AFCRL's technical management were successful.

The OV3-6 (ATCOS II) was launched in December 1967 and was still operational on reentry in March 1969, having greatly exceeded its eight month design life. The OV1-16 (Cannonball) satellite presented a design challenge to Laboratory engineers. The density experiment required a very heavy sphere with a maximum mass-to-area ratio, thus greatly restricting volume available for satellite subsystems. The final design utilizing microcircuit techniques and other advanced methods of packaging resulted in a 23-inch sphere weighing 600 pounds. The spacecraft was launched July 11, 1968, and was operating perfectly on reentry 39 days later. Approximately 30 percent of the OV1-16 experiment data was collected by polar stations using AFCRL-provided ground equipment since the National Range stations offered no coverage in this important area of the earth's surface.

The OV5-6, a small satellite to measure solar radiation, was flown piggyback on a Titan III in May 1969 and achieved an orbit of 10,000 by 60,000 nautical miles. As of June 30, 1970, all systems were working well. The satellite has an expected lifetime of 18 months.

BALLOON TECHNOLOGY

The Laboratory has the primary responsibility for Air Force balloon research and development, a responsibility that includes balloon design, balloon system engineering and operational techniques. It launches approximately 140 instrumented balloons each year, most of these from its permanent sites in New Mexico and California. For special observations, launches are made from temporary sites. (One series of five launches for NASA was made from Virginia.) The balloon program during the past three years was characterized by the design and launch of larger and larger balloons to reach higher altitudes or carry heavier payloads.

Balloons launched by AFCRL's balloon group at Holloman AFB, N.M., are sent aloft from this runway.

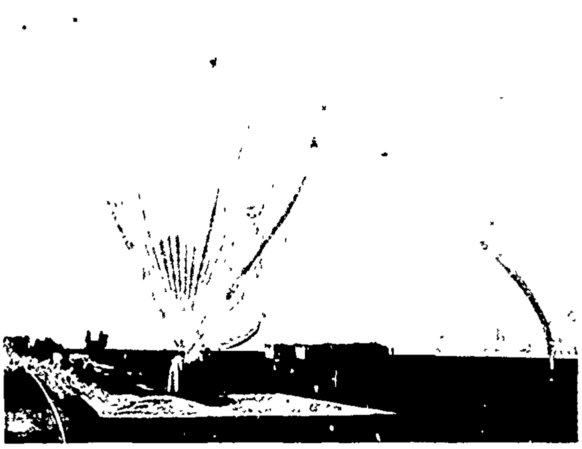
During the past three years a greater understanding of polyethylene balloon films and sealing techniques has led to higher reliability and increased payload limits for low cost polyethylene balloons.

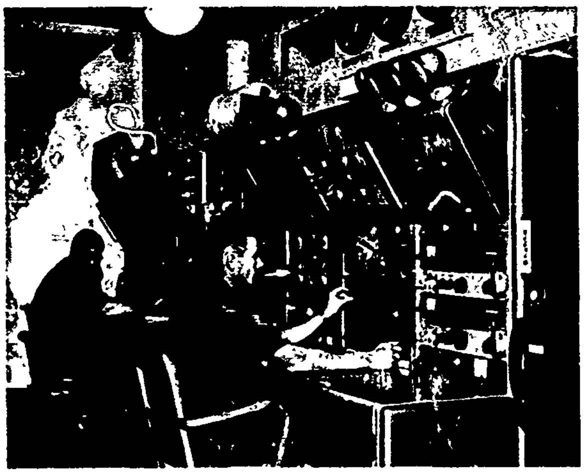
AFCRL tethered balloon systems, extending up to altitudes of 10,000 feet over fixed ground locations, have already been used for drop tests of NASA vehicles and to evaluate communications relay schemes. Soon AFCRL will extend the altitude capability to 15,000 feet. Higher altitudes, possibly in excess of 50,000 ft, appear to be feasible using a more complex system. A study of stranded fiberglas tether cables has resulted in a complete re-evaluation of manufacturing techniques for the very long continuous lengths required for the higher altitudes. Plans for the establishment of a permanent tethered site on the White Sands Missile Range in New Mexico have proceeded through the phase of determining the equipment required for the next several years, the layout design of the complex, and the early stages of construction.

BALLOON MATERIALS: Polyethylene, historically, has been the balloon material of choice. But it is a fragile material, subject to strain and tear, particularly at low temperatures. In recent years, Mylar, reinforced with Dacron threads, has been used for giant balloons—that is, for balloons having volumes of more than 25 million cubic feet. (To an uninitiated observer, the standard five million cubic feet volume balloon appears impressively massive.) Now polyethylene is coming back into favor. The reason is economy. AFCRL studies in materials have produced a safe launch stress theory and discovery of a strength degradation phenomenon which relates low temperature tensile strength to the strain-time-temperature history of the material.

The useful strength of polyethylene film, like most plastics, is a function of its stress history and the temperature, rate of loading and duration of loading for the application under consideration. Engineering design of polyethylene balloons requires that these points be considered. The new safe launch stress theory is an attempt at defining the first phase of an acceptable stress history for a polyethylene balloon. The discovered strength degradation phenomenon relates to the establishment of an acceptable working stress level for a polyethylene balloon during the phase of ascent through the earth's tropopause. These two phases are, as indicated, interdependent, and their relationship is the subject of part of AFCRL's present material research program.

The development of a unique balloon system is now in progress to meet





Balloon inflation and launch take place in the early morning hours when there is usually an absence of wind. Balloon flights are controlled from the command control (below) at Holloman AFB, N.M.

a Defense Atomic Support Agency (DASA) requirement. In addition to including all of the characteristics for adequate balloon design and fabrication to provide the payload-altitude specified, a new material of high electrical conductivity was required. The DASA balloon system is to be inflated with a detonable gas mixture (Methane/O_2 or Hydrogen/O_2), then detonated at high altitude to provide a nuclear blast effects simulant for actual in-flight measurement of re-entry vehicle structural vulnerability. Premature detonation of these gas mixtures by static electrical discharge during the balloon inflation period presents a potential hazard that must be eliminated. Existing large-volume plastic-material balloons necessary for the execution of this simulation technique unfortunately provide a strong source of static electrical generation and accumulation. As a result of investigations and tests by the balloon research group, a tri-laminate (Mylar-Dacron-Scrim-Mylar) with a printed conductive silver grid on both sides was developed to satisfy the known requirements. Through the printed conductive silver grid, continuous paths are maintained and static electrical buildup is minimized and continually bled off as it is generated.

BALLOON ALTITUDE—PAYLOAD ADVANCEMENTS: On September 11, 1968, AFCRL launched a 28.7 million cubic foot volume balloon which reached an altitude of 160,000 feet. This balloon established two records: it was the largest single cell balloon ever launched, and the altitude was the highest ever reached by a research balloon. On September 23, 1969, AFCRL launched a 30.3 million cubic foot volume balloon which reached an altitude of 161,000 feet.

These two flights were made in support of the U.S. Army Electronics Command's Office of Atmospherics Sciences. The payloads included instruments provided by the Army to measure atmospheric composition, pressure, temperature, density, ozone and wind motion near the stratopause. These balloons provided a means for obtaining at-

One of the Laboratory's giant balloons — this fully expanded 28.7 million cubic foot volume balloon — was photographed from the ground after it had reached an altitude of 160,000 ft. It was photographed through a 25-inch telescope.

mospheric data which could be gathered by no other means.

The most ambitious launch ever attempted occurred on April 6, 1970, when AFCRL launched a 47.6 million cubic foot volume balloon designed to reach an altitude of 170,000 feet. Although the launching was a success, the balloon developed a leak which prevented it from achieving its design altitude.

These flights represent significant advances in the thin film balloon technology. The largest polyethylene balloon previously flown was made of 0.75 mil thick material and had a volume of 13.5 million cubic feet. The 47.6 million cubic foot balloon made of 0.32 mii thick material demonstrated the feasibility of fabricating, handling and launching extremely large single cell balloons.

AFCRL established another balloon size record on November 6, 1969 when a tandem balloon system of 34 million cubic feet was launched from Holloman AFB, New Mexico. These balloons were made of reinforced mylar material. The flight was made in support of the NASA-Houston Cosmic Ray Ionization Spectrograph Program.

On July 18 and September 25, 1969, two balloon systems were successfully launched by AFCRL as a part of a

The polyethylene balloon must be carefully removed from packing cases to avoid tearing the material. While the balloon is being layed out for inflation, a scientist prepares the balloon-borne experiment, in this case one requiring cryogenic cooling.

program to replace the reinforced mylar main balloons of tandem balloon systems with lower cost polyethylene balloons in the medium-heavy payload range. The success of these balloons meant the realization of a savings of nearly $100,000 for a balloon system of this size.

On December 6, 1969, AFCRL established another first in heavy payload-high altitude performance by a single celled polyethylene balloons when a 20.6 million cubic foot volume balloon carrying a 4500-pound payload was successfully launched and attained a float altitude of 120,000 ft.

AIR LAUNCHED BALLOONS: During the late 1950's AFCRL undertook a program to develop methods for launching balloons from aircraft. This work produced systems for launching small balloons from fighter aircraft at 45,000 ft, from bomber or cargo aircraft at lower altitudes, and from hovering helicopters. The components of the systems were relatively complex in that the balloons were automatically inflated after deployment from the aircraft.

More recently a DOD requirement arose calling for the launch of large numbers of small balloons from C-130 type cargo aircraft for limited war applications. In July 1968, AFCRL began development of a method for launching fully inflated eight foot diameter polyethylene balloons from a C-130 aircraft while flying at an altitude of 10,000 ft. During December 1968, several discouraging tests were conducted in which the balloons were damaged by turbulent air conditions that existed near the tail of the aircraft. Subsequently, balloon deployment techniques were refined and a disposable nylon cover was provided to protect the balloon until it was far removed from the aircraft. Six test flights in February 1969 at El Centro Naval Air Facility, California, successfully demonstrated the suitability of the system and the simplicity of the launching method.

The technique was further developed to include a balloon to carry 15 pounds to 20,000 ft. Tests were conducted during July 1969 demonstrating the success of this development.

TETHERED BALLOONING: Interest and activity in the tethered balloon field has continued over the past three years. This was evidenced by the attendance at a Tethered Balloon Workshop sponsored by AFCRL and held in late 1967. A stable, elevated platform has many potential scientific and military uses. Major interest now is in altitudes below 30,000 ft. The prospect of placing tethered balloons above 50,000 ft is capturing increasing interest. The program at AFCRL has already established procedures for extending the altitude capability to 20,000 ft.

A study to investigate very high altitudes (in excess of 50,000 ft) was completed in 1968. The purpose of the study was to determine feasibility, define problem areas and provide planning and cost estimates. One significant determination of the study was a requirement for a durable cable with a very high strength to weight ratio. Such a cable would also increase payload capability of low altitude systems. A test program has been established and is now underway to identify cables with a high value of strength to weight ratio and to determine their suitability in tethered balloon applications.

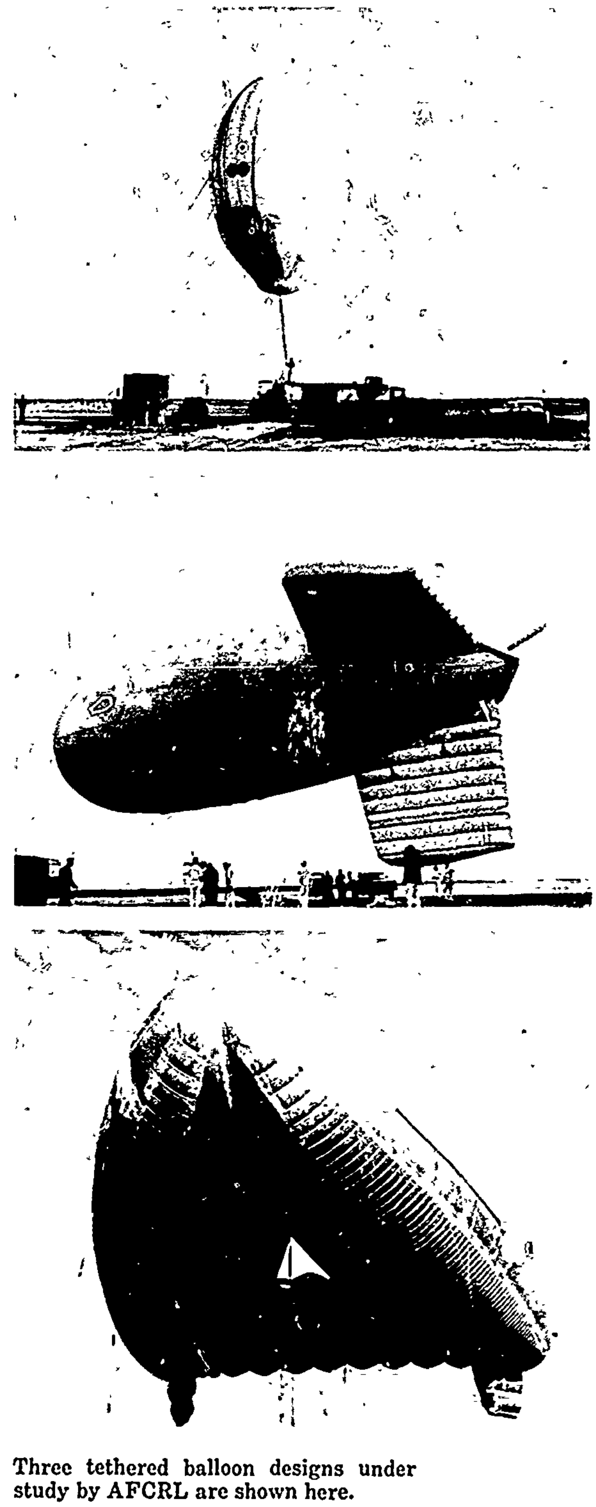
As part of this program, a *Tethered Balloon Handbook* has been compiled and provides a complete review of the literature for the past 100 years, as well as practical and complete up-to-date information on balloons, cables and winches.

An additional effort was the development of a winch specifically for tethered balloon flying. This winch is capable of handling glass tethers as well as steel and can inhaul cable at speeds up to 1000 ft/min. This winch will be integrated into the AFCRL tethered balloon site along with a winch presently under development that will be capable of handling heavier loads. Four large balloons have been added to the inventory. The new winch and large balloon will provide a load lifting capability of 2000 pounds at ground level and 400 pounds at 15,000 ft.

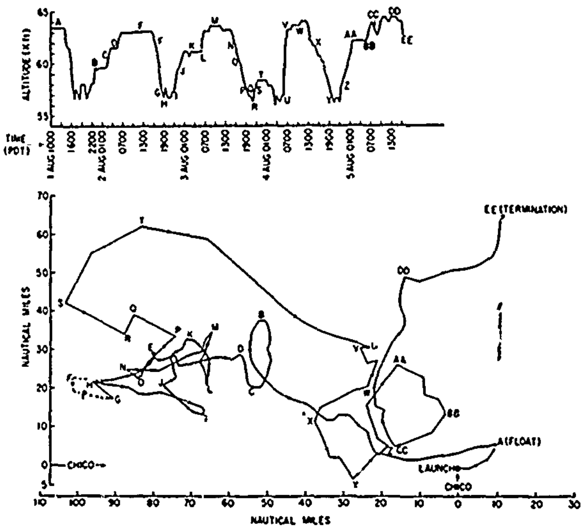
HOVERING FREE BALLOONS: Tethered balloons of the type discussed above have potential uses in military surveillance as radio relay stations and as platforms for scientific instruments. But it is also possible to keep balloons on station in free flight, thus accomplishing the same purpose. By dropping ballast and valving gas, it is possible to adjust balloon altitude up or down in search of winds that will carry the balloon back toward the station when it wanders too far. Because high altitude winds change direction with altitude, the balloon can be maintained within a 50 to 70 mile radius of the ground station for several days.

To evaluate the operational feasibility of a station-keeping free balloon, the characteristic wind patterns as a function of altitude during a given season at a given geographical location must be known. To evaluate the operational feasibility of hovering free balloons it is necessary to formulate a set of probability tables of wind speeds at certain locations.

This is what the Laboratory has done. The ideal wind situation for free hovering balloons is when there exists the combination of westerlies and easterlies with a light wind layer between. This



Three tethered balloon designs under study by AFCRL are shown here.



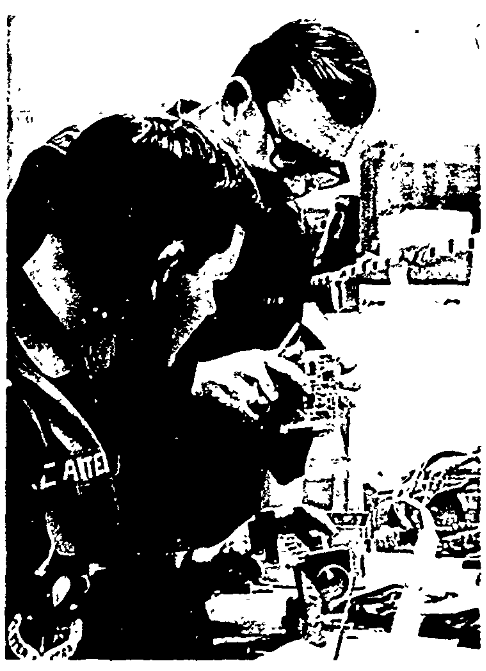
A free balloon can be kept close overhead for several days by proper ballasting and valving to take advantage of winds that will keep it within range. The trajectory of one such 104-hour flight from Chico, Calif., is plotted here. Letters correlate trajectory with time and altitude shown above.

condition is found at about 60,000 to 65,000 ft during the summer over a large area of the world and is usually found the year around in the tropics.

In tests conducted at the Chico, California, launch site, a balloon was kept within a radius of hover of 30 nautical miles for 25 hours and 70 nautical miles for over 72 hours.

BALLOON INSTRUMENTATION: Modular instruments such as programmers, sensors, data encoders, data transmitters, command receivers, ballasting and gas valving devices, power sources, payload separation and flight safety devices saw increasing use during the period. Both designs and techniques for applications were improved.

Long duration flights at the high altitudes generally require the maintenance of an accurate nighttime float level in regions above 100,000 ft. Until recently, aneroid devices have been the accepted standard for establishing a pre-set ballast altitude floor. The simplicity of the aneroid actuated device has made it attractive, but its accuracy is about 1 millibar. This accuracy is entirely unsuitable for ballast floor control at altitudes of 100,000 to 170,000 ft (9 to 0.7 mb). A new ballast floor control has been developed that utilizes either a hypsometer, heat transfer gauge, or capacitance or reactance type of pressure sensor for establishing the reference altitude ballast level to within 1 percent of the indicated pressure level. This unit can also be programmed to provide several discrete levels and thereby yield a step function descent profile when used in conjunction with a gas valve.



A basic goal of balloon instrumentation is to reduce the size and weight of both the experimental packages and control instrumentation.

For large balloon systems flying at altitudes up to 130,000 ft, the weight of the complete flight support instrumentation can be from 50 to 150 pounds without lowering the flight altitude by more than a few hundred feet. At higher altitudes payload weight becomes a critical factor. Support instrumentation was reduced to 22 pounds for the 28.7 million cubic foot balloon that reached 160,000 ft in 1968. To achieve the present goal of 170,000 ft and possibly higher, further weight reduction of modules is required. One example is a newly developed solid state programmer and timer weighing five ounces as a substitute for a four pound standard mechanical unit.

METEOROLOGICAL INSTRUMENTATION

Of the total AFCRL program, the activities reviewed in this section on meteorological instrumentation extend furthest into the development domain of the R&D spectrum. The prototype equipments to be discussed are in some cases only a step away from operational use, and indeed, the Laboratory occasionally initiates procurement actions on equipment it has developed on behalf of the Air Weather Service. The Air Weather Service is the primary customer for the improved sensors and techniques which are the products of this activity.

The AFCRL meteorological instrumentation program is made up of literally scores of individual efforts relating to ground-based and airborne sensors and new sensing techniques. It also includes instrument platforms such as balloons and rockets. Telemetry for acquiring data and even the development of hydrogen generators for meteorological balloon inflation are included in the program. While AFCRL's Meteorology Laboratory (Chapter X) also does a limited amount of meteorological instrumentation development, the purposes are quite different. The Meteorology Laboratory, when it undertakes to develop new instruments, does so for scientific instrumentation purposes rather than for operational purposes.

The DART upper stage has been adapted to carry several different configurations of meteorological sensors. In one model the ROBIN balloon, shown deflated on the desk, is carried aloft and is ejected for density measurements.

Many of the development efforts in progress—efforts relating to pressure sensors, refractive index sounding, temperature, density and wind sensors—will not be noted in this report because of space. The discussion which follows considers some of the major parts of the meteorological equipment program.

SOUNDING ROCKETS: A miniaturized rocket sounding system for measuring upper air winds and temperatures developed by AFCRL to replace the standard ARCAS system is now in operational use in the Meteorological Rocket Network and at all U.S. missile test ranges to obtain meteorological data from 60 km down to balloon altitudes of 30 km. This rocket-boosted system, which is in the LOKI class, is officially known as Meteorological Probe PWN-8B. It utilizes a new, slow descent, extremely stable, ram-air inflated retardation device (STARUTE) which eliminates the excessive fall velocities and wild oscillations inherent in the old parachute and results in a dramatic improvement in the accuracy of the data obtained from the system. The PWN-8B costs only about $800 for the complete vehicle, compared to more than $2000 for the previously-used ARCAS. Its launch conditions are also less restrictive.

A transponder-sonde is currently under development as a meteorological rocket payload in order to obviate the need for radar tracking. To accommodate this new sonde, the LOKI system is being enlarged somewhat. The new system, tentatively called the Super LOKI, will have a higher altitude capability (70 km) and will provide greater system reliability and data accuracy.

The DART upper stage attached to the LOKI booster to form the LOKI-DART is shown within the rocket launcher.

The varied sensing requirements preclude the use of any single vehicle for all soundings. To meet these requirements, several low cost, high altitude meteorological rocket vehicles are under investigation. One vehicle, the SPARROW-ARCAS, has performed well to 150 km and another, the less costly 140 km VIPER-DART, is being introduced into the field operationally.

SOUNDING BALLOONS: Because of their low cost, simplicity and minimal launch requirements, meteorological balloon systems will continue to be used to obtain data from the surface to over 30 km. Such balloons, a standard meteorological item for decades, have been improved to obtain more rapid ascent rates and better cold temperature performance. A joint AFCRL-Army balloon material investigation over the past several years resulted in better balloon films. Prospects are promising for early introduction soon of a balloon that will perform in all climatic regimes, including the Arctic and at the extremely cold tropical tropopause. The goal of a balloon with a fast ascent rate has been reached. A balloon that can achieve an ascent rate of 1700 ft/min or better has been developed. Its cost is excessive, however, and efforts are now aimed at reducing its cost.

HUMIDITY MEASUREMENTS: Investigation of the accuracy of radiosonde humidity measurements has led to the discovery of measurement errors up to 40 to 50 percent in both the military and Weather Bureau sondes. The sensor on these sondes is the carbon element ML-476 which is sensitive to relative humidity of the air. These errors are due to the fact that the element is not in thermodynamic equilibrium with the air stream. The evaluation of in-house designs to correct this deficiency is being carried on in two stages. One is a temporary fix capable of a field retrofit, and the other is a permanent fix involving redesign of the element and the physical configuration of the sonde.

Field testing of AFCRL's balloon-borne optical dew-point hygrometer has led to design changes of this unit to incorporate a variable gain servo loop which has materially improved the response characteristics of the device. Field experiments carried out in conjunction with the ML-476 carbon elements confirmed the errors mentioned in the previous paragraph.

During the last few years this Laboratory has been responsible for the development of a dew point hygrometer which utilizes the absorption of alpha particles to detect atmospheric moisture. Flight testing of the aircraft alpha radiation dew point hygrometer on an Air Weather Service KC-135 was completed during the period. The instrument has proved itself suitable for operational purposes and capable of measuring down to 2 percent relative humidity over the complete flight envelope.

ATMOSPHERIC DENSITY MEASUREMENT: In Chapter VIII covering the Aeronomy Laboratory, it was seen that two large efforts in that Laboratory involved the measurement of atmospheric densities. One technique involved the release of chemicals by rockets and measuring the rate of diffusion of the chemical trail. The other involved a satellite containing accelerometers which measured densities by detecting atmospheric drag on the satellite.

Unlike the Aeronomy Laboratroy, the Aerospace Instrumentation Laboratory is not interested in the characteristics of atmospheric density as such, but in improving the state of the art of density measuring equipment and techniques. One technique that has been gradually improved over the years is the falling sphere technique in which a balloon containing accelerometers is released by rocket at altitude. Density is calculated from the atmospheric deceleration of the sphere. During the reporting period the technique has been refined and spheres were developed for use in small meteorological rockets. Another technique that was adapted by the Laboratory for use in small rockets is rather elegant technically but is nevertheless inexpensive. A pitot tube of the type used to sense aircraft speed draws in atmospheric gases which are passed through a chamber where they are ionized by Americium 241. The ionized gas sets up a current flow which can be interpreted in terms of atmospheric density. The system was tested during the reporting period and was found useful for measuring densities between 30 and 100 km.

Before reviewing a large new ground-based laser system for measuring densities that the Laboratory sponsored in Jamaica during the period, it would be well to look at just why atmospheric densities are of such interest to the Air Force. There is the obvious connection with respect to precise missile targeting and to the plotting of satellite lifetimes and decay. Not so obvious is the extreme variability of upper atmospheric density induced by solar and nuclear events. Atmospheric densities must figure as a parameter in just about every aspect of upper atmospheric and near space physics. Thus to the extent, as

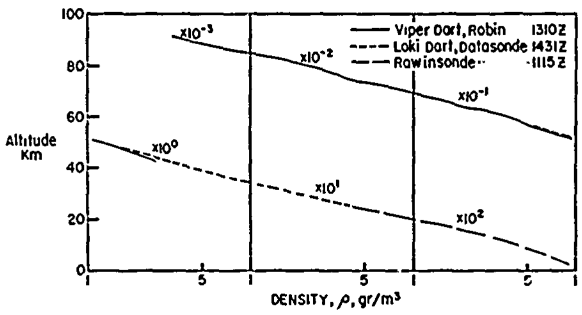


FIGURE 16: DENSITY PROFILE, APOLLO 11 LAUNCH SUPPORT ETR, CAPE KENNEDY, FLA., 14 JULY 1969

Three sensing techniques were used to provide this smooth, continuous density profile from nearly 100 km altitude to the ground on the day Apollo 11 was launched. The ROBIN Falling Sphere covered the highest region, a rocketsonde was used in the mid-region, and a balloon-borne radiosonde was flown through the lowest r·:ion.

has been noted throughout this report, that the Air Force is interested in atmospheric transmission and emissions of optical/infrared radiation (Chapter IV), that it is interested in environmental forecasting (Chapter VII), that it is interested in geomagnetic effects on radio propagation (Chapter VI), that it is interested in long-range weather forecasting (Chapter X), then that is the extent to which it is interested in atmospheric densities.

LASER RADAR DENSITY MEASUREMENT: During the reporting period, AFCRL and the University of the West Indies, Kingston, Jamaica, demonstrated the capability of a laser radar to obtain density profiles of the atmosphere up to 100 km.

The laser system consists of a laser with a 12 joule pulsed output. The pulse of light, collimated with a 15-inch parabolic mirror, is transmitted vertically upwards through the atmosphere. Molecules and aerosols scatter the light, and the backscattered signal is detected by an array of mirrors and a photomultiplier adjacent to the transmitter. The time between transmission of the pulse and reception of the scattered signals gives the heights from which scattering occurs and the received intensity is a function of atmospheric density at these particular heights.

The receiving mirror array consists of an assembly of 30 spherical mirrors, each of 30-inch diameter. They are arranged in the form of a parabolic dish and focused onto a photomultiplier assembly which is mounted on a rigid platform approximately 80 ft above the

AFCRL's laser system for probing the atmosphere, located in Kingston, Jamaica, has a receiving array of 30 spherical mirrors each 30 inches in diameter. Part of this 30-mirror array is shown here.

ground. The technique itself is not original, but the Kingston system is by far the largest and most powerful designed to date, and represents the emergence of the technique into feasibility for both operational and experimental purposes.

The detected laser signal, consisting of scattered light, is extremely weak, and becomes exponentially weaker with altitude. Furthermore, the signal has to be detected in the presence of sky-noise and photomultiplier dark current. Cooling of the photomultiplier and the use of a narrow band optical filter in the receiving system render these problems tractable. The detected photons are counted in 64 range-gated intervals, resulting in density measurement at discrete steps of two and a half km each.

Performance of the system has been checked comparatively against density data obtained by meteorological balloons—or at least up to the altitude maximum of such balloons which is about 30 km.

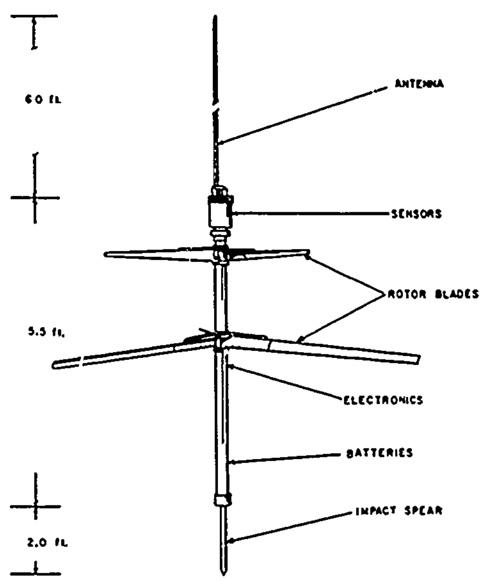
LASER CAT DETECTION: A ruby laser optical radar for clear air turbulence (CAT) detection was developed during the period, but as of June 30, 1970, had not yet been flight tested. Tests will determine if sufficient backscatter returns can be obtained from contaminants of clear air in CAT regions to enable their use as tracers of air motion. A parallel development program, in cooperation with NASA's Marshall Space Flight Center, is investigating the use of a CO_2 gas laser to measure the broadening of the very narrow transmitted spectral line caused by the motion of particles that backscatter the energy to determine air motions.

SURFACE OBSERVING INSTRUMENTATION: The requirement for accurately forecasting the lightning probability hazard at Cape Kennedy was augmented by a similar requirement at most air bases in connection with refueling of aircraft. The difficulty of logistically supporting the off-base stations of a sferics network prompted the development of a lightning ranging and atmospheric electric field indicator that can be used singly or in an on-base network to satisfy the needs of all users.

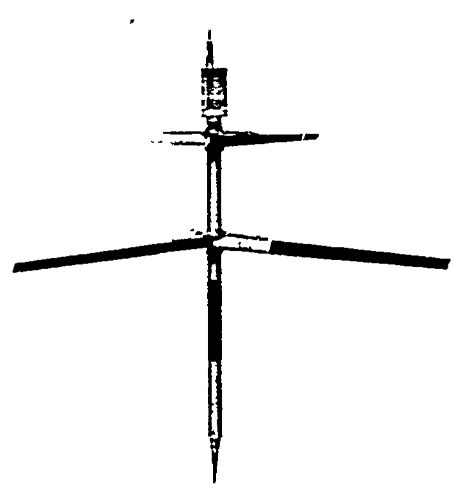
In response to SEAOR 95 for a portable light ceilometer, a model was fabricated which proved the feasibility of such a system. The design, based on the principles of the standard rotating beam ceilometer, contains several unique features that permitted great reductions in size and weight of comparable components. The most significant feature was to use an audio technique to detect the cloud height return. This audio technique permits the replacement of the standard oscilloscope display with a simple head phone set. AFSC is procuring 25 systems based on this work.

Another ceilometer is being investigated that makes use of a switched ruby laser radar that determines cloud height by measuring the transit time of the light pulse to the cloud base and return. This approach avoids the requirement for a measured base line and separation of the transmitter and receiver. Having the transmitter and receiver at the same point greatly simplifies installation and maintenance and permits determination of ceilings at locations where the establishment of a base line is impractical.

In response to a TAC requirement for a covert winds aloft set, a system was devised that uses an infrared source attached to a balloon. The infrared source is tracked by a sniperscope mounted on a theodolite. Presently undergoing tests is a miniaturized, solid state, wind set that will significantly



EROWS



The EROWS (Expendable Remote Operating Weather Station) weighs 55 pounds. Dropped from an aircraft, its spear-like tip embeds itself in the ground and it begins operation automatically.

reduce the weight and logistics problems associated with existing tactical equipment. Operating from only four D cell batteries, the set will provide wind data to remote indicators, located up to three miles away from the observation site, over ordinary field telephone wires.

In the weather radar instrumentation area, the Laboratory assists AWS in correcting difficulties associated with the operational use of the AN/TPQ-11 Cloud Radar and the AN/FPS-77 Severe Storm Radar. Calibration and alignment procedures have been developed for these sets and analyses of cloud records from selected sets have been made to determine techniques for making optimum use of the capabilities of the radars. A scanning, high frequency K_a band radar is being developed to aid in evaluating the effectiveness of seeding operations in fog, and digital integrators are being tested to determine their operational unity in improving the detection of weak weather echoes.

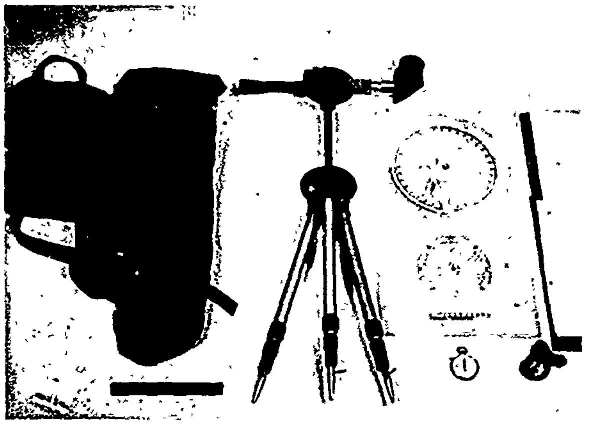
Several efforts that were reported on during the last reporting period have either been terminated or are dormant, pending new advances in technology. The sonic anemometer has been completed, as has the development work on upper air wind detection using meteor trails as tracers. Visibility measurements, using light backscattered from gallium arsenide luminescent diodes, have been terminated. High power laser gallium arsenide arrays which offer a much greater potential are being investigated.

AIR-DROPPED REMOTE WEATHER STATION: In June 1970, AFCRL awarded a contract to Honeywell for the development of an expendable weather station designed to be air-dropped in remote, inaccessible areas.

Designated EROWS (Expendable Remote Operating Weather Station), the weather station looks like a large arrow. It is cylindrical, about eight feet long and six inches in diameter. It weighs 55 pounds. Dropped from the aircraft, it is stabilized and descends to the ground on four rotating blades, each 2.5 feet long. A spear-like tip imbeds itself into the ground, and a 5.7 foot vertical dipole antenna is automatically raised into position.

The four-pound sensor package near the top measures wind speed and direction, atmospheric pressure, temperature, humidity, precipitation and cloud cover. Data gathered by the station is transmitted to a master control through FM telemetry equipment. The battery operated station is designed to operate for at least ten days. One master station will be able to handle data from 30 remote stations. The master unit will include an interrogation module to display the exact status of the EROWS being interrogated. Remote check out of the EROWS can also be accomplished from the master unit.

EQUIPMENT FOR SOUTHEAST ASIA: Several unique items of weather observing equipment were designed and fabricated in-house to meet the unusual requirements of TAC's special operations weather teams. The devices developed are small in size, simple to operate, and expendable. They are also rugged enough for paradrops and do not restrict jumper efficiency. Most important among these items are an expendable weather observation kit, weighing approximately three pounds, and containing all the elements necessary for a complete surface weather observation, and a miniaturized winds aloft observation kit, weighing five pounds, complete with very small throw-away helium cylinders, an extremely lightweight theodolite, and various charts and ancillary equipment.



An example of tactical weather equipment is the meteorological balloon tracking kit (AN/PMQ-10). This kit contains all equipment necessary for measuring winds aloft and is suitable for paradrop operations.

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Appendix A

AFCRL PROJECTS BY PROGRAM ELEMENT

Program Element	Project Number, Title, and Agency		Lab
11321F	*SPECIAL PURPOSE COMMUNICATIONS*	*AFSC**	
	487M	Low Frequency Survival	LI**
61101D	*DEFENSE RESEARCH SCIENCES*	*ARPA*	
	0627	Bilateral Communications Between Men and Machines Through Conversation	LR
	086?	Research on On-Line Computation	LR
	1060	Unconventional Solid State Materials and Devices—Project THEMIS	LQ
	1434	Laser Damage Studies	OP
61101F	*IN-HOUSE LABORATORY INDEPENDENT RESEARCH*		
	ILIR	Laboratory Director's Fund	XO
61102F	*DEFENSE RESEARCH SCIENCES*	*OAR*	
	5620	Growth and Characterization of Advanced Electromagnetic Materials	LQ
	5621	Physics of Solid State Phenomena	LQ
	5628	Communications Processes	LR
	5631	Ionospheric Radio Physics	LI
	5632	Electronic Information Processing	LR
	5634	Research in Quantum Electronics	OP
	5635	Electromagnetic Sensors, Scatterers. Radiators, and Microwave Acoustic Devices	LZ
	5638	Research on Solid State Electronics	LQ
	7259	Remote Terrestrial Sensor Utilization for Systems Studies—THEMIS	LW
	7260	Meteorological and Upper Atmospheric Research—THEMIS	XO
	8600	Energetic Particle Environment	PH
	8601	Geomagnetism	PH
	8603	Infrared and Optical Techniques	OP
	8604	Meteorological Research	LY
	8605	Upper Atmosphere Structure	LK
	8607	Earth Sciences and Technologies	LW
	8608	Solar Plasma Dynamics	PH
	8617	Electrical Structure of Aerospace	LI
	8620	Cloud Physics	LY
	8627	Spectroscopic Studies of Upper Atmosphere Processes	LK
	8658	IR Non-Equilibrium Radiative Mechanisms	OP
	8659	Energetics Processes	PH
	8694	Research in Data Processing Microwave Devices and Optical Devices	XO
	8695	Terrestrial Environment Research	LW
	8696	Atmospheric Environment Research	XO
	8697	Aerospace Research Measurements	XO
	8698	Aerospace Research Measurements	XO
	8699	Space Environment Research	XO
61102H	*NWET*		
	5710	Nuclear Weapons Effects Test	LK/OP/LI/LQ

Appendix A

AFCRL PROJECTS BY PROGRAM ELEMENT

Program Element	Project Number, Title, and Agency	Lab
62101F	*ENVIRONMENT* *AFSC-OAR*	
	4062 Electromagnetic Wave Propagation in Dynamic Situations	XO
	4063 Generation and Propagation of Low Frequency Radio Waves	LI
	4642 Alleviation Techniques for Reentry Plasmas	LZ
	4643 Aerospace Radio Propagation	LI
	6670 Atmospheric Sensing Techniques	LC
	6672 Weather Radar Techniques	LY
	6682 Test Range Meteorological Support	LC
	6687 Aerospace Composition Studies	LK
	6688 Solar Ultraviolet Radiation	LK
	6690 Aerospace Density	LK
	6698 Satellite Meteorology	LY
	7600 Geodesy for Naviguidance	LW
	7601 Electric and Magnetic Fields	PH
	7605 Weather Modification	LY
	7621 Atmospheric Optics	OP
	7628 Terrestrial Geology	LW
	7635 Upper Atmosphere Chemical Processes	LK
	7639 Wave Propagation Studies	LW
	7649 Solar Environmental Effects	LM
	7655 Micrometeorology	LY
	7659 Aerospace Research Instrumentation	LC
	7661 Polar Atmospheric Processes	LK
	7663 Ionospheric Characteristics	LI
	7670 IR Properties of the Environment	OP
	8624 Variability of Meteorological Elements	LK
	8628 Upper Air Circulations	LY
	8666 Space Environment Observing and Forecasting Techniques	PH
	8682 Millimeter Wave Propagation	LZ
62204F	*AEROSPACE AVIONICS* *AFSC-AFAL*	
	4608 Radiation Resistant Solid State Materials and Devices	LQ
	4645 Coherent Optical Device Physics	OP
	5042 High Resolution Radar Technology	LZ
62301D	*DEFENDER* *ARPA*	
	1141 Participation in Secede III Series	LK
	1364 Anomalous Airglow	OP
62403F	*AEROSPACE AVIONICS*	
	4200 IR Signatures	OP
62701D	*VELA* *ARPA*	
	0292 Seismic Research Project Vela Uniform	LW
	0635 Magnetohydrodynamic Wave Propagation in the Ionosphere	LI

62702F	*GROUND ELECTRONICS*	*AFSC-RADC*	
	4600 Electromagnetic Radiation Techniques		LZ
	4610 Information Processes for Communications		LR
	4641 Advanced Data Processing Technology		LR
62703D	*ADVANCED SENSORS*	*ARPA*	
	1300 Airborne Launching of Small Pre-Inflated Balloons		LC
63404F	*SABAR*		
	BLNS Balloons		LC
	RKTS Rockets		LC
	SATS Satellites		LC
64708F	*OTHER OPERATIONAL EQUIPMENT*	*AFSC*	
	1559 Miniaturized Meteorological Equipment		LC
64710F	*INTELLIGENCE/RECONNAISSANCE EQUIPMENT*		
	1085 Have Hue		XO
65701H	*NWET*		
	5710 Nuclear Weapons Effects Test		OP/LI/XO

* Denotes Agency Having Management Responsibility for Program Element.
** See Organization Chart, Appendix C, for Laboratory Title.

Appendix B

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 - JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
5 Jul 67	CHILL	Aerobee 150	Day Airglow (Scanning Spectrometer)	S. Silverman	Success
27 Jul 67	WTR	OV1-86	Earth and Cloud IR/Cosmic Radiation/ Atomic Oxygen	J. Lovett V. Smalley	Success Success
28 Jul 67	WTR	OGO-IV	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success
8 Aug 67	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	J. Manson	Success
15 Aug 67	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	J. Higgins	Success
17 Aug 67	ADTC	Niro	Atmospheric Density (7″ Falling Sphere)	A. Faire	Success
26 Aug 67	ADTC	Niro	Atmospheric Density (Bremsstrahlung)	J. McIsaac	Failure (P)*
5 Sep 67	ADTC	Niro	Atmospheric Density (Light-Scatter)	A. Faire	Failure (P)
30 Sep 67	Wallops Island	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success
2 Oct 67	Wallops Island	Nike Cajun	Antenna Voltage Breakdown	C. Ellis	Success
4 Oct 67	Wallops Island	Nike Tomahawk	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
5 Oct 67	Wallops Island	Nike Tomahawk	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
24 Oct 67	Puerto Rico	Niro	Ionospheric Charged Particle Densities	R. Sagalyn	Success
24 Oct 67	Puerto Rico	Niro	Ionospheric Charged Particle Densities	R. Sagalyn	Success
26 Oct 67	Puerto Rico	Niro	Ionospheric Charged Particle Densities	R. Sagalyn	Failure (V)*
27 Oct 67	Puerto Rico	Niro	Ionospheric Charged Particle Densities	R. Sagalyn	Success
28 Oct 67	Puerto Rico	Niro	Ionospheric Charged Particle Densities	R. Sagalyn	Success
7 Nov 67	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Failure (P)
15 Nov 67	Brazil	Aerobee 150	Equatorial Day Airglow	S. Silverman	Partial
19 Nov 67	Brazil	Niro	Research Payload Water Recovery Test	C. Hoult	Success
22 Nov 67	Brazil	Niro	Research Payload Water Recovery Test	C. Hoult	Success
27 Nov 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Failure
27 Nov 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Failure
29 Nov 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
29 Nov 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
3 Dec 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
3 Dec 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
4 Dec 67	CHILL	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Success
4 Dec 67	CHILL	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Success
5 Dec 67	CHILL	OV3-6	Latitudinal Variations in Neutral and Ion Species/ Electron Density and Temperature/ Atmospheric Density	R. Narcisi J. Ulwick J. McIsaac	Success

CHILL — Fort Churchill, Canada
WTR — Western Test Range, Vandenberg AFB, California
WSMR — White Sands Missile Range, New Mexico
ADTC — Armament Development Test Center, Eglin AFB, Florida
ETR — Eastern Test Range, Cape Kennedy, Florida

*(P) — Payload
(V) — Vehicle

Appendix B

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 - JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
6 Dec 67	CHILL	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Success
6 Dec 67	CHILL	Black Brant	Polar Cap Absorption	J. Sandock	Success
13 Dec 67	WSMR	Aerobee 150	Micrometeoroid Particle Collection	R. Skrivanek	Failure (P)
13 Dec 67	ADTC	Niro	Atmospheric Density (7″ Falling Sphere)/ Chemical Release	A. Faire	Success
13 Dec 67	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
13 Dec 67	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
14 Dec 67	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
14 Dec 67	ADTC	Nike Tomahawk	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Failure (V)
16 Dec 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
16 Dec 67	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
17 Jan 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
19 Jan 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
22 Jan 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
22 Jan 68	CHILL	Nike Tomahawk	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Failure (P)
19 Feb 68	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)/ Ion and Electron Densities	H. Hinteregger	Success
4 Mar 68	ETR	OGO-V	Charged Particles at 0–2.5 keV	R. Sagalyn	Success
15 Mar 68	CHILL	Niro	Magnetic Field Intensities/ Electron and Proton Fluxes	R. Vancour	Success
29 Mar 68	WSMR	Aerobee 150	Atmospheric Absorption/Oxygen Distribution in D and E Regions	F. LeBlanc	Failure (V)
30 Mar 68	WTR	OV1-13	Trapped Radiation Flux	L. Katz	Success
1 May 68	ADTC	Niro	Atmospheric Density (Falling Sphere)	A. Faire	Success
2 May 68	ADTC	Niro	Atmospheric Density (Falling Sphere)	A. Faire	Failure (P)
2 May 68	ADTC	Niro	Atmospheric Density (Bremsstrahlung)	J. McIsaac	Failure (P)
2 May 68	Puerto Rico	Niro	Study of F Region (Chemical Release)	N. W. Rosenberg	Success
7 May 68	Puerto Rico	Niro	Study of F Region (Chemical Release)	N. W. Rosenberg	Success
12 May 68	Puerto Rico	Nike Tomahawk	Study of F Region (Chemical Release)	N. W. Rosenberg	Failure (V)
13 May 68	Puerto Rico	Nike Tomahawk	Study of F Region (Chemical Release)	N. W. Rosenberg	Success
17 May 68	Kauai, Hawaii	Niro	Atmospheric Density (Inflatable Sphere)	G. Faucher	Success
22 May 68	Kauai, Hawaii	Niro	Atmospheric Density (Inflatable Sphere)	G. Faucher	Success
10 Jun 68	CHILL	Black Brant	Polar Cap Absorption	J. Sandock	Failure (V)
11 Jul 68	WTR	OV1-15	Atmospheric Density/Ion Composition	J. McIsaac C. Philbrick M. Smiddy	Success
11 Jul 68	WTR	OV1-16	Atmospheric Density	K. Champion	Success
17 Jul 68	ADTC	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Partial

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 - JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
19 Jul 68	ADTC	Niro	Study of Sporadic E (Chemical Release)	N. W. Rosenberg	Accidental Firing
23 Jul 68	ADTC	Niro	Study of Sporadic E (Chemical Release)	N. W. Rosenberg	Success
23 Jul 68	ADTC	Niro	Study of Sporadic E (Chemical Release)	N. W. Rosenberg	Success
23 Jul 68	ADTC	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Success
23 Jul 68	ADTC	Niro	Study of Sporadic E (Chemical Release)	N. W. Rosenberg	Success
23 Jul 68	ADTC	Niro	Study of Sporadic E (Chemical Release)	N. W. Rosenberg	Success
6 Aug 68	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Partial
8 Aug 68	Brazil	Niro	Meteoric Dust Collection	R. Skrivanek	Success
8 Aug 68	WTR	Injun V	Charged Particles and Electric Fields	R. Sagalyn	Success
11 Aug 68	Brazil	Niro	Meteoric Dust Collection	R. Skrivanek	Failure (P)
12 Aug 68	Brazil	Niro	Meteoric Dust Collection	R. Skrivanek	Success
15 Aug 68	Brazil	Niro	Meteoric Dust Collection	R. Skrivanek	Failure (P)
15 Aug 68	CHILL	Aerobee 150	Infrared Horizon Definition	R. Walker	Success
16 Aug 68	WTR	Atlas-Burner II	Ionospheric Entrapment of EM Radiation (ORBIS-CAL)	J. Mullen	Failure
19 Aug 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
20 Aug 68	CHILL	Nike Tomahawk	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
20 Aug 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
27 Aug 68	CHILL	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
27 Aug 68	CHILL	Nike Tomahawk	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
4 Sep 68	ADTC	Niro	Atmospheric Density (7″ Falling Sphere)	A. Faire	Success
4 Sep 68	ADTC	Niro	Atmospheric Density (7″ Falling Sphere)	A. Faire	Failure (P)
16 Sep 68	WSMR	Aerobee 170	Engineering Test	P. Gustafson	Success
26 Sep 68	WTR	OV2-5	Geomagnetic Storms/Ionospheric Scintillations/ Composition	B. Shuman J. Mullen M. Smiddy	Success
9 Nov 68	CHILL	Javelin	Magnetic Disturbances/Auroral Event Effects	R. Vancour	Success
9 Nov 68	CHILL	Niro	Magnetic Disturbances/Auroral Event Effects	R. Vancour	Failure (V)
19 Nov 68	CHILL	Black Brant	Polar Cap Absorption	J. Ulwick	Success
21 Nov 68	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success
9 Dec 68	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
9 Dec 68	ADTC	Niro	Atmospheric Turbulence (Chemical Trail)	N. Sissenwine	Success
10 Dec 68	Wallops Island	Niro	Ion Composition in D and E Regions (Mass Spectrometer and Langmuir Probe)	R. Narcisi J. Ulwick	Success
12 Dec 68	Wallops Island	Niro	Ion Composition in D and E Regions (Mass Spectrometer and Langmuir Probes)	R. Narcisi J. Ulwick	Success

Appendix B

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 - JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
6 Jan 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
7 Jan 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
12 Jan 69	ADTC	Niro	Study of F Region of Ionosphere (Chemical Release)	N. W. Rosenberg	Success
13 Jan 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
29 Jan 69	WTR	ISIS-A	Ion Concentrations and Composition	R. Narcisi R. Sagalyn	Success
31 Jan 69	Wallops Island	Niro	Atmospheric Density (Inflatable Sphere)	G. Faucher	Success
31 Jan 69	Wallops Island	Niro	Atmospheric Density (Inflatable Sphere)	G. Faucher	Success
31 Jan 69	Wallops Island	Niro	Ion Composition in D and E Regions (Mass Spectrometer)	R. Narcisi	Success
7 Mar 69	Brazil	Aerobee 150	Earth Infrared Profile Study	R. Walker	Success
18 Mar 69	WTR	OV1-17	Calibration of Meteor Trail Antenna	A. Barnes	Success
18 Mar 69	WTR	OV1-17A	Calibration of Entrapped Radio Signals in the Ionosphere	J. Mullen	Success
20 Mar 69	CHILL	Aerobee 150	Auroral Input-Output	J. Ulwick	Success
29 Mar 69	CHILL	Aerobee 150	Auroral Input-Output	J. Ulwick	Success
4 Apr 69	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	L. Heroux	Partial
4 Apr 69	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	L. Heroux	Partial
17 Apr 69	CHILL	Nike Tomahawk	Magnetic Field and Auroral Effects	R. Vancour	Success
17 Apr 69	CHILL	Niro	Magnetic Field and Auroral Effects	R. Vancour	Success
13 May 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
13 May 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
14 May 69	Kauai, Hawaii	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
15 May 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
15 May 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
15 May 69	CHILL	Javelin	Magnetic Disturbances/Auroral Event Effects	R. Hutchinson	Success
21 May 69	Kauai, Hawaii	Nike Tomahawk	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
21 May 69	Kauai, Hawaii	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
22 May 69	Kauai, Hawaii	Nike Tomahawk	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Partial
22 May 69	Kauai, Hawaii	Niro	Atmospheric Winds and Densities (Chemical Release)	D. Golomb	Success
23 May 69	ETR	OV5-6	Solar Radiation	K. Yates	Success
30 May 69	CHILL	Javelin	Magnetic Disturbances/Auroral Event Effects	R. Hutchinson	Success
5 Jun 69	WTR	OGO-F	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success
16 Jun 69	Brazil	Black Brant IV	VLF Penetration of the Ionosphere	R. Harvey	Partial
17 Jun 69	Wallops Island	Trailblazer	Plasma Sheath Effects on Radio Signals	W. Rotman	Success
24 Jun 69	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success

APPENDIX B

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 – JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
1 Jul 69	ADTC	Niro	Atmospheric Composition (Mass Spectrometer)	R. Narcisi	Failure (P)
6 Aug 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Partial
6 Aug 69	CHILL	Niro	Atmospheric Density (7" Falling Sphere/ Chemical Release)	A. Faire	Success
12 Aug 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Success
15 Aug 69	WSMR	Aerobee 150	UV Solar Radiation (Spectrophotometer)	H. Hinteregger	Success
6 Sep 69	Natal, Brazil	Black Brant	VLF Propagation	R. Harvey	Success
11 Oct 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Success
23 Oct 69	CHILL	Aerobee 150	Infrared Auroral Emission (Circular Variable Filter Spectrometer)	A. T. Stair	Success
2 Nov 69	CHILL	Black Brant	Polar Cap Absorption	J. Ulwick	Success
3 Nov 69	CHILL	Black Brant	Auroral Input-Output	J. Ulwick	Success
3 Nov 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Success
3 Nov 69	CHILL	Niro	Atmospheric Density (7" Falling Sphere/ Chemical Release)	A. Faire	Success
3 Nov 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer)	R. Narcisi	Success
3 Nov 69	CHILL	Niro	Atmospheric Density (7" Falling Sphere/ Chemical Release)	A. Faire	Success
3 Nov 69	CHILL	Black Brant	Polar Cap Absorption	J. Ulwick	Partial
3 Nov 69	CHILL	Black Brant	Polar Ionosphere	J. Ulwick	Partial
3 Nov 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Success
3 Nov 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Success
3 Nov 69	CHILL	Niro	Atmospheric Density (7" Falling Sphere/ Chemical Release)	A. Faire	Failure (V)
3 Nov 69	CHILL	Black Brant	Polar Cap Absorption	J. Ulwick	Failure (V)
3 Nov 69	CHILL	Niro	Atmospheric Density (7" Falling Sphere/ Chemical Release)	A. Faire	Success
4 Nov 69	CHILL	Niro	Ozone and OH Emission Measurements (Mass Spectrometer)	R. Narcisi	Success
4 Nov 69	CHILL	Black Brant	Polar Cap Absorption	J. Ulwick	Success
5 Nov 69	CHILL	Niro	Atmospheric Composition (Mass Spectrometer)	R. Narcisi	Failure (P)
7 Nov 69	CHILL	Niro	Ionospheric Composition (Mass Spectrometer and Langmuir Probes)	R. Narcisi	Failure (P)

AFCRL ROCKET AND SATELLITE PROGRAM: JULY 1967 – JUNE 1970

Date	Launch Site	Vehicle	Experiment	Scientist	Results
5 Dec 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Failure (P)
5 Dec 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
5 Dec 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
10 Dec 69	CHILL	Niro	Polar Ionospheric Disturbances	R. Sagalyn	Success
11 Dec 69	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
6 Feb 70	WSMR	Aerobee 150	Infrared Horizon Measurements (Radiometers)	R. Walker	Success
7 Mar 70	ADTC	Niro	Atmospheric Density (10" Falling Sphere)	A. Faire	Success
7 Mar 70	ADTC	Niro	Atmospheric Density (7" Falling Sphere)	A. Faire	Success
7 Mar 70	ADTC	Niro	Atmospheric Density, Molecular Oxygen, and Ozone Measurements (X-ray and Ultraviolet Photometers)	L. Weeks	Success
7 Mar 70	ADTC	Niro	Atmospheric Density (7" Falling Sphere)	A. Faire	Partial
7 Mar 70	Wallops Island	Niro	Atmospheric Composition (Mass Spectrometer)	C. Philbrick	Partial
7 Mar 70	Wallops Island	Niro	Atmospheric Composition (Mass Spectrometer)	C. Philbrick	Success
7 Mar 70	Wallops Island	Niro	Atmospheric Composition (Mass Spectrometer)	C. Philbrick	Success
7 Mar 70	ADTC	Niro	Atmospheric Density (7" Falling Sphere)	A. Faire	Success
7 Mar 70	ADTC	Niro	Atmospheric Density, Molecular Oxygen, and Ozone Measurements (X-Ray and Ultraviolet Photometers)	L. Weeks	Success
8 Mar 70	CHILL	Nike Tomahawk	Magnetic Disturbances/Auroral Event Effects	R. Vancour	Success
8 Mar 70	CHILL	Niro	Charged Particles and Electric Fields	R. Sagalyn	Success
13 Mar 70	CHILL	Aerobee 150	Vibrational Temperature of Atmospheric Nitrogen (Electron Beam Probe)	R. O'Neil	Success
25 Mar 70	CHILL	Niro	Charged Particles and Electric Fields	R. Sagalyn	Success
25 Mar 70	CHILL	Niro	Charged Particles and Electric Fields	R. Sagalyn	Success
4 Apr 70	ADTC	Black Brant	UV Solar Radiation (Spectrophotometer and Retarding Potential Analyzers)	H. Hinteregger	Failure (V)
12 Apr 70	ADTC	Niro	Atmospheric Density (10" Falling Sphere) Molecular Oxygen and Ozone Measurements (Ultraviolet Photometers)	A. Faire L. Weeks	Failure (P)
7 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
7 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
20 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
21 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
21 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success
22 May 70	ADTC	Niro	Ionospheric Winds (Chemical Release)	N. W. Rosenberg	Success

APPENDIX C

Air Force Cambridge Research Laboratories

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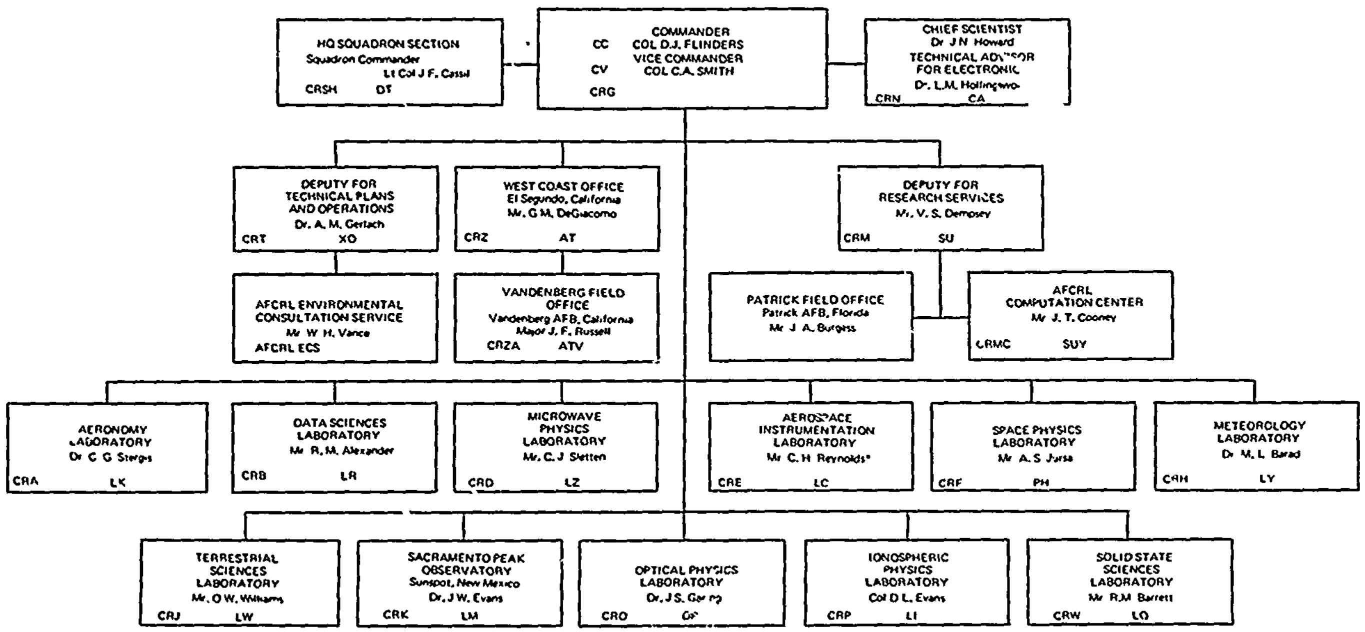

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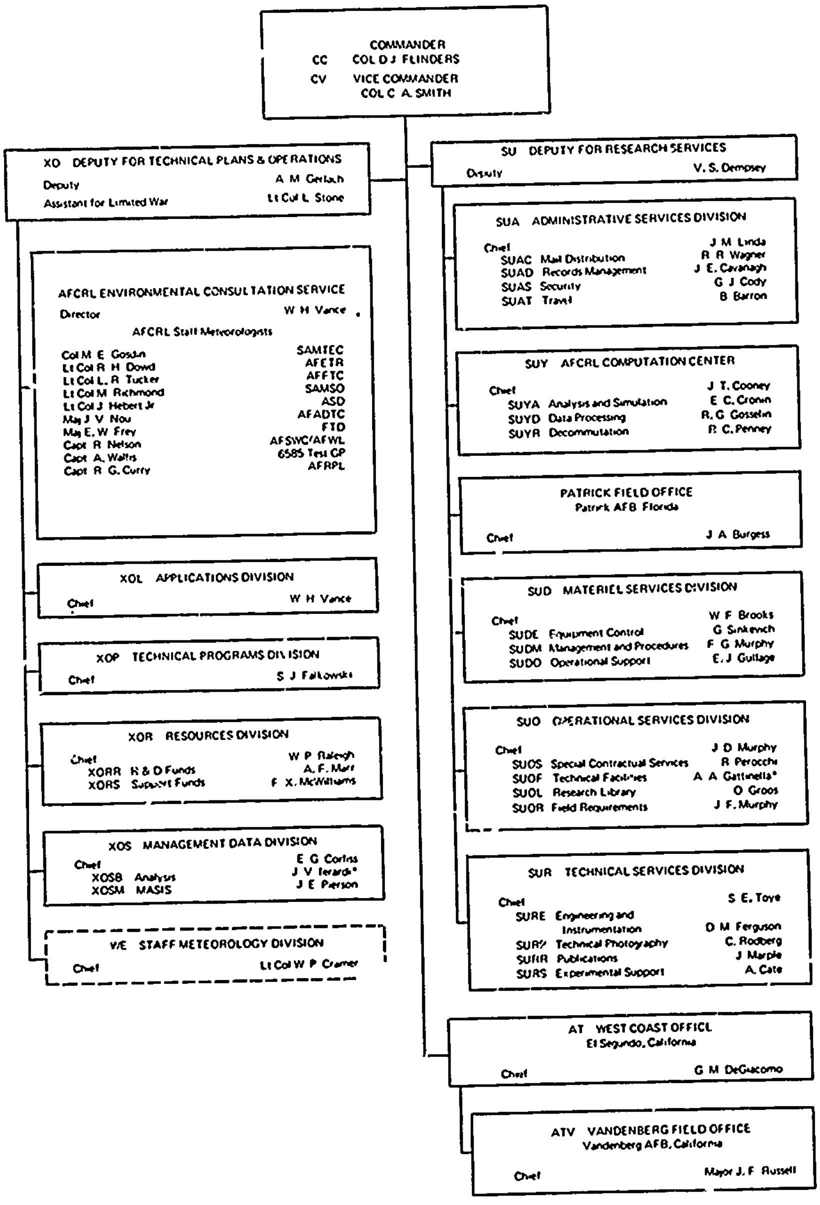

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LOD	Device Physics	R P Dolan
LOR	Radiation Effects	C D Turner

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13. ABSTRACT

This is the fifth in a series of reports on research at the Air Force Cambridge Research Laboratories. The report covers a three-year interval. This report was written primarily for Air Force and DOD managers of research development—and more specifically, for the managers in our Headquarters office, the Air Force Systems Command. But it is hoped that it will be of interest and value to a much broader audience. To encompass this broader audience and to make the content more meaningful, the report attempts to relate, by means of survey discussion, the programs to the larger scientific field of which they are a part. The work of each of the eleven laboratories is discussed separately in chapters with an overall introductory chapter on AFCRL management and logistic activities during the reporting period. ( )

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	ROLE	WT	ROLE	WT	ROLE	WT
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