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Radiation Intensity of the PAVE PAWS Radar System

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Engineering Panel on the PAVE PAWS Radar System

Assembly of Engineering

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This volume contains the results of a panel study of the assessment of certain aspects of the PAVE PAWS radar facility in regard to radiation emissions.

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Radiation Intensity of the PAVE PAWS Radar System

A Report by the
Engineering Panel on the PAVE PAWS
Radar System
of the
Assembly of Engineering
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

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NOTICE

The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

In May 1978, when the U.S. Air Force requested the National Research Council to assess certain aspects of its newest missile defense warning system then under construction at the Otis Air Force Base on Cape Cod, Massachusetts, the facility was the subject of intense public concern that exposure to its radiation emissions might be harmful to humans. The purpose of the radar facility, known as PAVE PAWS (PAVE being a code word for the Air Force unit in charge of the project and PAWS an acronym for Phased Array Warning System) is to detect and track ballistic missiles launched at sea as far as 3,000 nautical miles from U.S. shores. In order to discern ballistic missiles early in their trajectory, it operates at an angle as low as 3 degrees above the horizon. Its long range capability is achieved by a fairly high average power level of 145kW.

The Research Council's initial response was to establish two separate panels to examine the facility--one, the Engineering Panel on the PAVE PAWS Radar System, under the Assembly of Engineering, and the other, the Panel on the Extent of Radiation from the PAVE PAWS Radar System in the Assembly of Life Sciences. This is the report of the engineering panel. The report of the second panel, consisting of an analysis of the exposure levels and potential biological effects of PAVE PAWS, will be published separately.

From the beginning, the engineering panel was charged with reviewing the specifications and performance of the radar system with respect to its highest intensity of radio frequency radiation on Cape Cod. More to the point, the panel addressed three specific questions:

- o Can estimates based on the data obtained from tests and measurements of the PAVE PAWS microwave emissions provide valid upper limits to the radiation intensity to which the public is likely to be exposed?
- o In particular, does the analysis of the maximum radiation levels of PAVE PAWS by the Environmental Protection Agency (EPA) provide valid upper limits for the emissions to be encountered by the public?
- o Is there any significant probability that deviations from normal operating procedures will result in the estimated or measured limits of radiation to be exceeded?

The panel did not address questions of potential hazards, relative safety, and health effects of particular levels of microwave radiation. Nor did it attempt to evaluate the desirability or adequacy of existing radiation limits.

During the summer of 1978, the panel examined several documents setting out the description and function of the PAVE PAWS system, the design and performance specifications given to the primary contractor, the Raytheon Company, and the Environmental Impact Analysis prepared by the Environmental Protection Agency, which contains detailed estimates of maximum radiation levels to be expected where the public has access in the vicinity of the facility.

On September 7, 1978, the panel met at the Hanscom Air Force Base near Bedford, Massachusetts, to discuss the technical aspects of the system and the test measurements with representatives of the PAVE PAWS program office and Raytheon. Participants at this meeting are listed in the Appendix. The panel was impressed by the thoroughness of their presentations and the conciseness of their answers to questions. As it happened, the meeting had originally been scheduled for two days, but, because the participants were so well prepared and knowledgeable, it required only one day.

The introduction contains a background to the PAVE PAWS system and a brief chronology of events relating to it. This is followed by an overview summary of the principal findings of the panel's study. Section 3 is a technical description of the facility. Section 4 deals with the design of the phased array antenna, the antenna pattern, and the sensitivity of the pattern to malfunctions of components and degradations of the microwave beam. Section 5 concerns the pulse patterns of the radar and the intensities and time variations of the radiation field measured at ground sites near the radar. In Section 6 the panel reviews the measurements that have been or are still to be made of the radiation field. Section 7 addresses the configuration of computers that control the radar and the major features that protect against malfunctions and improper steering of a well-formed beam. Section 8 includes the effects of external conditions, such as weather, that might adversely affect the formation or control of the radiation pattern, and other conditions that might cause variations from the designated radiation patterns or intensities.

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1. INTRODUCTION

PAVE PAWS is the name the U.S. Air Force uses to designate an advanced fixed-base, phased-array radar system located at the Otis Air Force Base on Cape Cod, Massachusetts. PAVE is the code word for the Air Force unit in charge of the project, and PAWS stands for Phased Array Warning System. The primary purpose of the facility is to detect and track ballistic missiles launched from ships and submarines as far as 3,000 nautical miles from U.S. shores. As a secondary function, PAVE PAWS is designed to provide surveillance of earth satellites and to identify and track other objects in space for the Air Force Spacetrack System. The PAVE PAWS radar system is scheduled to go into operation in April 1979. An identical system at Beale Air Force Base on the California coast is to go into operation a year later.

As part of the nation's early warning network to detect the flight of ballistic missiles, these radar systems scan close to the horizon across the sector of potential approach. They possess the power and sensitivity to locate a booster rocket as it appears above the horizon after launching and to track the trajectory of its payloads upon separation from the booster. This information is transmitted to the North American Air Defense, the Strategic Air Command, the National Military Command Center, and the Alternate National Military Command Center.

While both radar systems are alike in design, the details of their sitings are different. This report concerns only the PAVE PAWS system as it was designed, built, and tested for its site at the Otis Air Force Base (Figure 1).

The PAVE PAWS radar project was initiated by the Joint Chiefs of Staff in November 1972. Its prime contractor, Raytheon Company, was named in April 1976. The project management for the Air Force Systems Command is the Electronic Systems Division (ESD), Hanscom Air Force Base, Bedford, Massachusetts.

In March 1976, the Air Force issued an environmental assessment, first prepared in August 1975 and subsequently revised, for the PAVE PAWS radar. For this assessment a power density or incident intensity of 10 milliwatts/cm^2 for 6 minutes was set as a guideline for the occupational exposure limit. This guideline is used by the U.S. Occupational Safety and Health Administration as the acceptable occupational exposure standard. In May 1976, the Illinois Institute of Technology

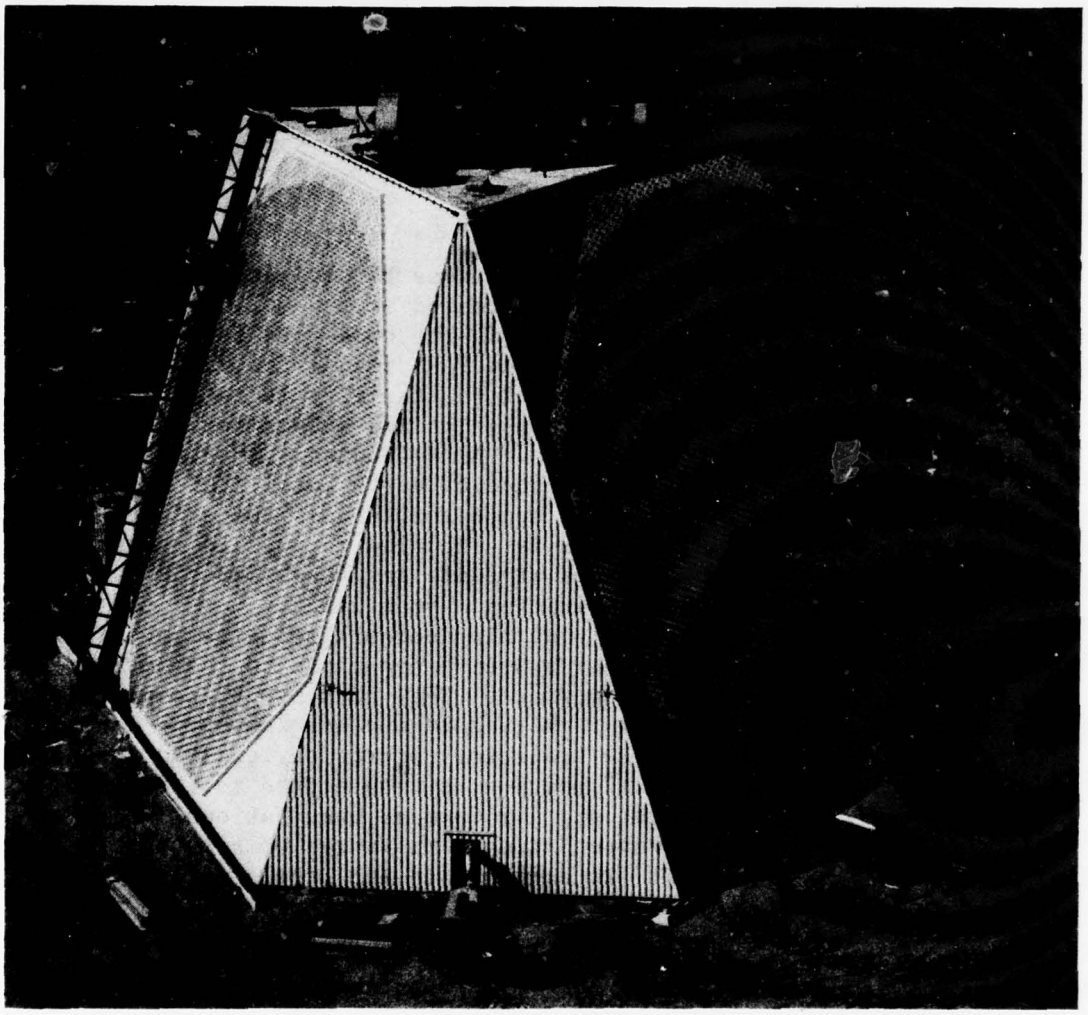


Figure 1
PAVE PAWS Radar
Courtesy of the United States Air Force

(IIT) Research Institute issued its report at the request of the Department of Defense's Electromagnetic Compatibility Analysis Center to determine the impact of the proposed radar system on the electromagnetic environment at and near Otis Air Force Base. The IIT Research Institute report was updated in July 1978.

Meantime, in December 1977, the Environmental Protection Agency released its Environmental Impact Analysis (Reference 1). Three months later, in March 1978, the Cape Cod Environmental Coalition, Inc., a citizens group, filed suit against several Air Force officials, alleging that the Air Force had violated the National Environmental Policy Act of 1969 by failing to submit an Environmental Impact Statement (EIS) for the PAVE PAWS project. In April 1978, the Air Force announced that it had engaged SRI International to prepare the EIS for PAVE PAWS.

To allay concerns by citizens about the possible adverse effects of radiation from the proposed PAVE PAWS installation on human health, Air Force survey teams measured the microwave levels at various specified locations on the cape during May, August, and October 1978. Then, in November 1978, the federal court action was suspended and the Air Force was allowed to continue its construction of the radar facility, while the Cape Cod Environmental Coalition was given the opportunity to participate in further environmental studies of the impact of PAVE PAWS radiation on the surrounding community. When the Air Force files its final EIS with the Environmental Protection Agency, the citizens' coalition will have 21 days to amend its legal complaint. Failing that, the court action will be dismissed.

2. OVERVIEW AND SUMMARY

Radar systems like PAVE PAWS, operating from a fixed antenna rather than one that is physically movable or scans automatically, typically radiate beams of energy at microwave frequencies in short pulses or bursts of peak power. The PAVE PAWS antenna consists of a circular array of 5,354 elements, of which only half, or 2,677, are to be active when the facility begins operation in April 1979, and of the active elements only 1,792 are powered. At some future date, which is not yet determined, the entire antenna may be placed in operation. The beam of radiation is focused and pointed in a specific direction by controlling the way the individual elements radiate. If the beam is to be directed to the left of center (or "boresight"), the signals radiated from the elements on the left side of the array are delayed relative to those emitted from the elements on the right, the period of the delay increasing progressively across the array from right to left.

PAVE PAWS has two antenna faces 120° apart covering from 347° (West of North) to 227° (47° West of South). When searching, the faces transmit in parallel the beams normally scanning by steps in a somewhat regular sequence across each 120° sector at 3° above the horizon. When it is tracking an object in space, the beam can search anywhere in the horizontal sector, from 3° to 85° above the horizon. The actual pattern of beam positions followed during any one scanning and tracking cycle depends on the particular search mode selected and on the position of the target under surveillance. In normal operation, when the PAVE PAWS beam is at 3° above the horizon, the beam is always 100 feet or more above ground level at the nearest point of public access, because the radar is on high ground at 325 feet above sea level.

The radar operates in the UHF (ultra high frequency) band at 420-450 MHz. No significant transmitted energy falls outside this band, which corresponds to wave lengths of from 71-67 centimeters. Each of the 1,792 transmitting elements of the array is connected to its own transmitter, and each element radiates about 320 watts of peak power during the one pulse. PAVE PAWS transmits a brief pulse or a short chain of pulses and then pauses while it awaits the returning echoes. The peak power of radar transmitted is about 580 kilowatts--derived by multiplying 320 watts by 1,792 elements. The actual time sequence of pulses depends, during an interval, on the functions performed and the number of targets

tracked. The duty cycle never exceeds 0.25. Therefore, the average transmitted power never exceeds 145 kilowatts (0.25 of 580 kilowatts), which is, in round numbers, about three times the average power transmitted by a typical large TV station and somewhat more than the average power of a typical high power FM station. The most powerful TV and FM stations, by comparison, radiate more power than the PAVE PAWS radar.

In December 1977, EPA investigators stated their calculations of power density levels for PAVE PAWS in their Environmental Impact Analysis. The EPA defines a high power source as one where the power density of the main beam is 100$\mu W/cm^2$ at a distance of 100 meters from the antenna. TV and FM broadcast transmitters fall into this range, as do radar systems and satellite communications earth stations. The measurements of power density levels by the Air Force in 1978, taken at various points up to 5 miles beyond the "exclusion" fence some 1,000 feet from the PAVE PAWS radar, have been reviewed by the National Bureau of Standards as to the validity of the techniques used as well as the ambient levels of electromagnetic radiation. The measurements show that at the fence the microwave power densities averaged in the range of 5$\mu W/cm^2$, with the levels decreasing at distances farther away from the radar. At the location where the public is most likely to be exposed--on Highway Route 6, some 3,450 feet from the radar--the measured intensity was 0.06$\mu W/cm^2$. The Air Force measurements of PAVE PAWS indicate that the power density levels do not exceed 0.1$\mu W/cm^2$ at points beyond about 1 mile from the radar.

After its examination of the PAVE PAWS design and technology and its review of the test measurements, the panel concludes, specifically, that *the EPA has calculated valid upper limits for the radiation fields at ground level near the PAVE PAWS radar.*

The panel also finds that:

o *The PAVE PAWS radar, though of advanced design, uses technology that is well known and has been tested in other radar systems already in operation. There is nothing in the design parameters that exceeds the capabilities of today's technology. In particular, the techniques used in the design and analysis of the antenna are well tried. Experience and measurement in other systems show that these techniques provide accurate estimates of antenna performance.*

o *In all features of the radar and system design that were examined, thorough attention has been given to safeguard against malfunctions. The safeguards are built into the system.*

o *It is in the basic nature of a phased-array antenna, such as the one used in the PAVE PAWS radar, that component or equipment failures are unlikely to cause radiation to be directed into public areas or in any undesignated direction in excess of the amounts estimated for normal operation. Independent monitoring devices and other protective features are designed into the system to detect malfunctions and, in the event, to shut the radar down.*

o *The PAVE PAWS radar is controlled by digital computers. The computer programs as now designed provide for multiple independent tests of antenna steering orders. Orders issued by the computers to direct radiation into improper directions, such as too close to the horizon or*

into the ground, are rejected. Indeed, if that were to happen, the events would be reported to operating personnel by way of status displays.

o The design and testing of the programs for the control computers of the PAVE PAWS radar conform to modern practice. The techniques are similar to, and to some degree based upon, those used in the design of a similar radar system--the Perimeter Acquisition Radar (PAR) in North Dakota (see Section 3). PAR has operated successfully and reliably over a four year period.

o The measurements being made by the contractor during installation and test of the PAVE PAWS radar, and independent measurements as planned by the Air Force, and now in process, can give a reliable verification of the estimates of performance to compare with design data.

o Measurements made to date are consistent with predictions from design data. They demonstrate that radiation intensities at ground level are below the bounds estimated in Reference 2. In particular, they are far below the level of 10 milliwatts per square cm that is the currently accepted U.S. occupational safety level for human exposure.

3. DESCRIPTION

Each face of the antenna is a metal plane 102 feet in diameter, from which a regular array of 5,354 antenna elements protrude (see Figures 2 and 3). Of these, 2,677 around the outer periphery are totally inactive, being provided now to allow for a possible increase in the size of the antenna and the power of the radar at some later date as yet undetermined. The 2,677 elements in the center of the array, a region 72 feet in diameter, constitute the antenna proper of the present system. Only 1,792 of these elements are actively transmitting. Each is connected to its own solid state transmitter and receiver module. The remaining 885 electrically active elements do not connect to power sources; they serve only to improve control of the shape of the beam.

The PAVE PAWS radar operates in the UHF band, using 24 different assigned frequencies in the range from 420-450MHz. Each of the 1,792 active radiators is powered by its own solid state transmitting module, and couples to its own receiver. The nominal power radiated by one of these single transmitting modules is 322 watts. Total radiated power during a pulse is then about 580kW (580,000 = 320 x 1,792).

The pattern of pulses transmitted is complex. It depends, at any particular time, on the function being performed and on the number and location of targets under track. More details are discussed in Section 5. Averaged over a few second's time, the duty cycle of transmissions from one face cannot exceed 0.25; in any 54 millisecond period, the duty cycle does not exceed 0.30. Average total transmitted power is then about 145kW (0.25 x 580). For a discussion of "peak power" see Section 5.

Table I summarizes major features of the PAVE PAWS radar, many of which will be referred to in later sections.

The PAVE PAWS radar resembles two other major radars now operating in the U.S. One in Concrete, North Dakota, was deployed as part of the SAFEGUARD Anti-Ballistic Missile (ABM) System from which it acquired the acronymic PAR (Perimeter Acquisition Radar). Upon the dismantling of the ABM system, the PAR was retained and is now operated by the Air Force as part of the early warning network of which PAVE PAWS is a part. The other is the FPS-85, located at Eglin Air Force Base in western Florida. This too is a phased array radar controlled by a digital computer. It is operated by the Air Force as part of the Space Track network.

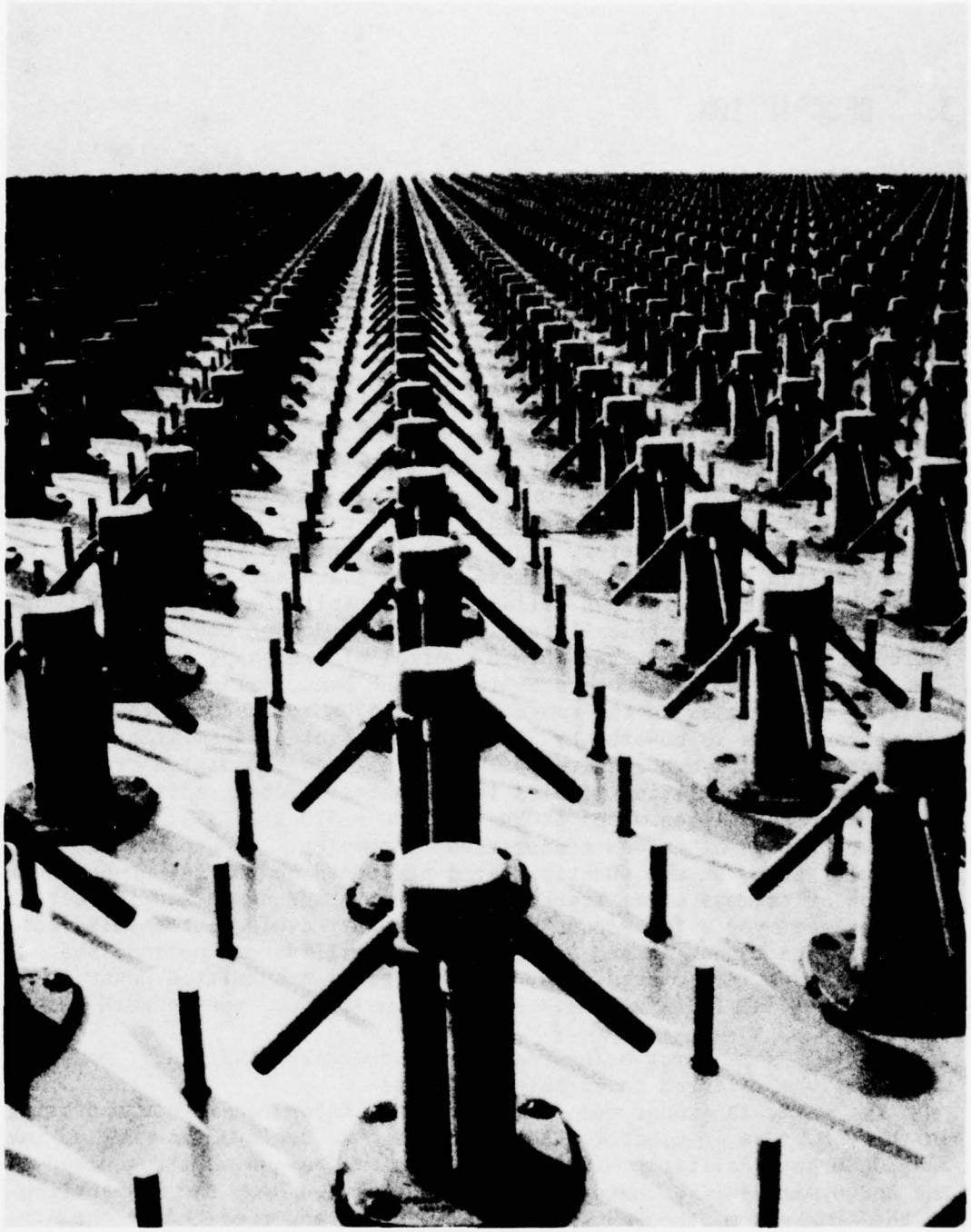


Figure 2

PAVE PAWS Radar
(One Face) Showing an Array of Antenna Elements
Courtesy of the United States Air Force

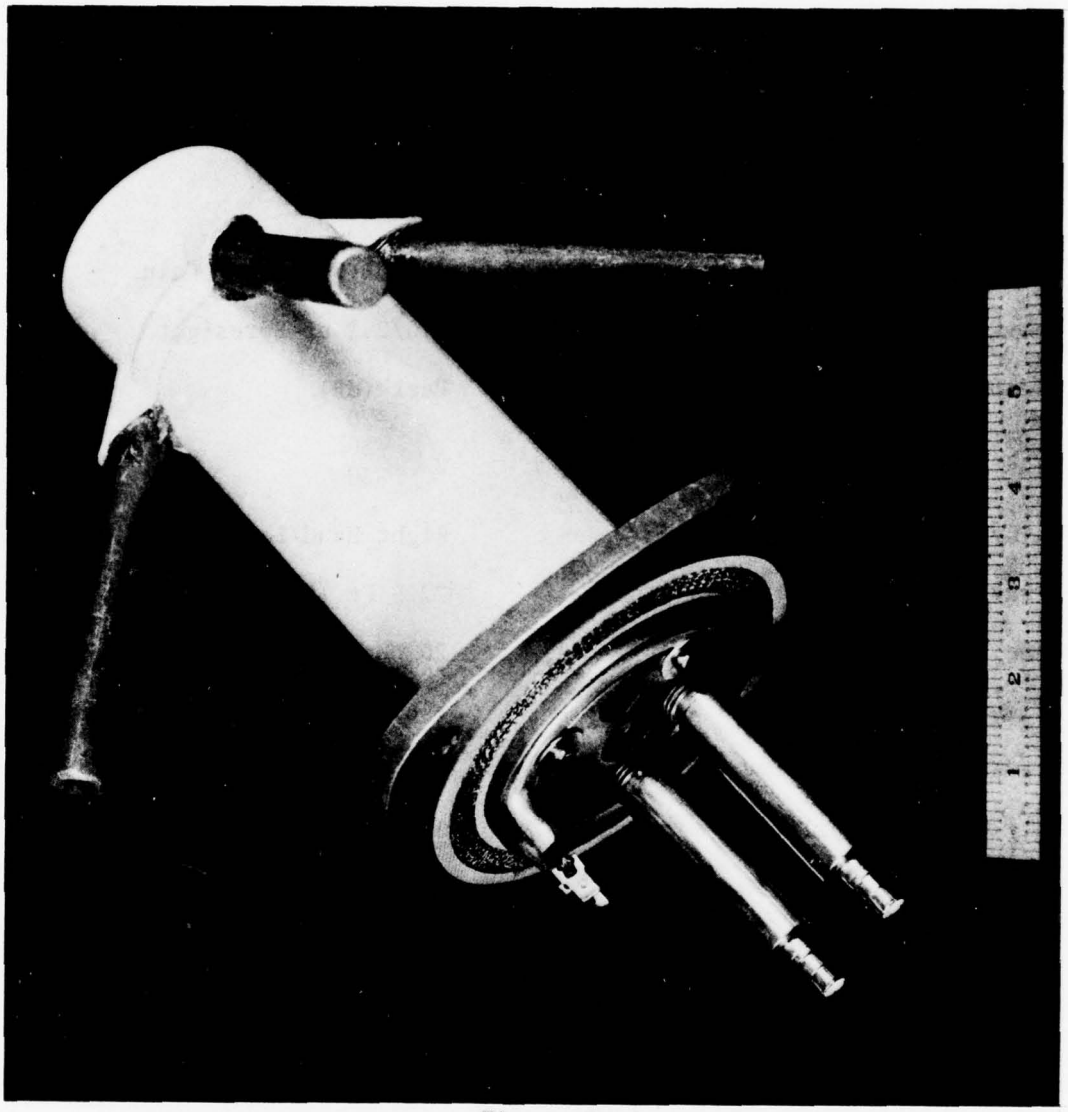


Figure 3
PAVE PAWS Radar Antenna Element
Courtesy of the United States Air Force

Table I

BASIC PARAMETERS - PAVE PAWS

Antenna Gain	38.6dB Directive Gain
Beamwidth, Deg (Transmit/Receive)	2.0/2.2 at Boresight
Sidelobes	Peak (dB)
Transmit 1st S.L.	-20
Transmit Other	-30
Receive	-30
Polarization (Transmit/Receive)	Right Hand/Left Hand Circular
Array Diameter	72.5 Ft (Utilized)
Face Tilt	20 Degrees
Azimuth	$\pm$ 60°, 240° with Two Faces
Elevation	3 - 85°
Duty Cycle Capability	0.25 Each Face
Waveforms	
Search	100KHz (0.3 to 8ms)
Track	1MHz (0.25 to 16ms)
Sensitivity	S/N = 17.7dB at Boresight R = 3000 NMI T = 16ms σ = 10m^2
MTBF	323 Hours
Inherent Availability	$\geq$ 0.9957 (Specification Requires $\geq$ 0.98)

The PAR transmits at 10MW (10^7 watts) peak radiated power with a maximum duty cycle of .05. The FPS-85 transmits at 26MW peak radiated power with a maximum duty cycle of .005. Both have transmitting antennas of the order of 100 feet in diameter, somewhat larger than PAVE PAWS. Properties of the transmitters are compared with PAVE PAWS in Table II.

The FPS-85 went into operation in 1965, and the PAR about a decade later. PAVE PAWS follows the PAR by five years. These radars represent three different generations of microwave technology and of computer technology in their control systems. There has also been an evolution during this period in techniques for computer programming and antenna design. The basic principles embodied in the PAVE PAWS system are those that have been tried and demonstrated in the predecessor systems. The design itself, based on these principles, has been supported by extensive calculations using the powerful computers that are today available to the designers.

The design itself exploits the simplicity and reliability of modern solid state microwave components and modern high speed control computers.

Table II

COMPARISON OF RADAR TRANSMITTERS

Radiated Power	PAVE PAWS	PAR	FPS-85
Peak	580kW	10MW	26MW
Average	145kW	500kW	130kW
Duty Cycle	0.25	0.05	0.005
Number of Active Transmitting Elements	1,792	6,144	4,660
Transmitting Beamwidth	2°	1.2°	1.4°

4. ANTENNA PATTERN

The powered elements of the antenna are all driven by transmitters identical in design. Taper of illumination across the aperture is achieved by powering only a fraction of the elements in the outer part of the array. The thinning ratio is 1:2, hence the presence of the 885 dummy radiators.

Given that each element of the antenna is excited with a signal of known phase and amplitude, the radiation pattern of the antenna can be calculated with great accuracy. The availability of simple approximate models allows for independent checks of the correctness of computations.

The functional demands of the PAVE PAWS mission require that the antenna, as it actually operates and not merely in some ideal state of perfect excitation, meet stringent conditions. The design then requires that tolerance limits be set on the amplitude and phase of each radiating element for each operating condition. It must be verified that when each element is within tolerance, the antenna still meets its requirements. Finally, controls must exist to hold the antenna elements within tolerances, and to detect departures from satisfactory operation.

Given the tolerance limits for, or statistical descriptions of, the amplitude and phase of the excitation at each radiating element, straightforward calculations can be made with great accuracy of the limits of departures of the antenna pattern from the ideal. As a necessary part of the design process, the radar contractor, Raytheon, has made such analyses. The information below is based on the contractor's analyses.

The panel did not, of course, repeat the many calculations involved. The panel's confidence in the results described here is based on the consistency of the quoted results (a) with simple models, (b) with the performance requirements of the PAVE PAWS system, and (c) with other systems, including the PAR and the FPS-85, with which some of the panel members have been directly involved.

The PAVE PAWS antenna radiates like any antenna of comparable aperture (in wavelengths) and taper. The main beam is nominally 2° wide at its half-power points. The first sidelobes are 20dB or more below the main lobe in power gain and are contained within a cone around the main beam of about 4° half angle (second nulls at about 4° off the main beam).

Secondary sidelobes are at least 30dB below the main lobe in power gain; they are distributed in a roughly random manner across the angular field around the main lobe, tapering in density but not in peak gain at angles remote from the main beam. This is the kind of pattern that results from a design that minimizes the maximum secondary lobes.

The ground level in the neighborhood of the PAVE PAWS site slopes away from the radar at 1° or more below the horizontal. Consequently, it is principally the secondary sidelobes that intersect the ground during normal operation. Much of the rest of this report deals with just two issues: the power in the secondary sidelobes and the possibility that, because of some departure from design conditions, a first-order sidelobe or the main beam may illuminate areas of public access.

Each of the 1,792 nominally identical transmitters in the radar is an amplifier provided with a switchable phase shifter. Steering is by what is known as "row and column" orders. The elements lie naturally in rows and columns on the antenna face. Although many row-column intersections do not contain active elements, each active element of the array is identified by the unique combination of row and column in which it appears. To steer the beam in a given direction a desired phase-shift is determined for each row. These progress in uniform steps from row to row. Similarly, a desired phase-shift is generated for each column progressing uniformly from column to column. A particular transmitting module simply adds the phase-shifts given by its row and column instructions to determine the phase-shift it then introduces into the signal applied to its input.

Were this process carried out with perfect precision and were the individual radiators themselves emitting spherically symmetrical waves, the resulting field would constitute a discrete approximation to a plane wave leaving the antenna face in a direction determined by the phase-shifts. The approximation replaces by a discrete set the plane continuum of spherical sourcelets that, by Huygens' Principle, generates a plane wave.

In the actual antenna further departures from the discrete approximation to Huygens' Principle result or can result from several sources:

- o The individual radiating elements are not isotrophic radiators.
- o Each phase shifter is quantized to steps of 22.5°.
- o There can be departures in each phase shifter from the desired 22.5° steps.
- o The transmitting modules are excited from a common source by way of cables. The delays along these separate distribution paths are held to uniformity only within some limit of tolerance.

All of these effects are controlled in one or more ways in the design, manufacture, and test of the radar. All of them can be analyzed and are accounted for in the contractor's analyses. Some basic features of the analysis or control are discussed below.

Element directivity: Each face of the antenna scans at most 60° off boresight in azimuth and elevation. The radiating pattern of an individual element is broad. The effect of the pattern of the element is to modify the whole antenna pattern as a function of angle off boresight; the modification is not large in comparison to the inevitable change in pattern with beam position that results from the fact that

the effective aperture of the antenna is already reduced by the cosine of the angle off boresight. All of these essentially geometrical effects are incorporated directly into the analyses.

Errors: The other effects listed above result from departures from ideal gain and phase in each radiator; they can properly be called errors. Indeed, consider the antenna pattern as being generated by two sets of radiators: (a) the ideal radiators that all produce fields of exactly the same amplitude, having respective phases exactly equal to the desired values, (b) parasitic radiators, located coincidently with each ideal radiator, that emit error signals. The error signal at each radiator is simply that signal which when added to the ideal produces the actual signal.

One aim of the design is to keep the error signals small. There are other considerations in the design process that also bear on the character of the error signals. One critical requirement of the radar is that the true direction of the main lobe be known--i.e., be exactly what is ordered by the computer. Another requirement is that echoes returned from the ground or sea because of sidelobes that lie below the horizon not interfere with the detection of targets. Errors in the phase-shifts that are systematic across the face of the antenna--or are systematic among a considerable fraction of the antenna elements--can deflect or broaden the beam or increase the sidelobe returns. Accordingly, errors must be kept small and must avoid systematic patterns.

Control is exercised in several ways:

o The design itself undertakes to randomize across the face of the antenna unavoidable departures of the actual phase-shift from that ideally ordered.

o Manufacturing tolerances are set on the cables and phase shifters as well as on amplifier gains.

o During operation, the antenna is systematically tested to verify that performance in gain and phase remains within specified tolerances.

The intent of the elements of control in combination is to make it possible to think of the antenna pattern as composed of the ideal pattern plus a sum of error signals from the various radiators that are not only individually small but also have no coherent or systematic pattern across the antenna aperture. Therefore, these error signals cannot focus into an undesired beam or sidelobe that is of high intensity. Thus it happens that in order to meet the primary criteria of antenna performance, the design process is such that it also limits the extent to which errors in individual elements can disturb the "ideal" pattern of sidelobes.

As to error control: row and column steering orders (phase-shifts) are presented to the individual transmitting element with a precision of six binary places (one part in 64). These result from calculations that start with the desired position of the beam expressed as sines of angles off boresight to 60 binary places. At four stages in the calculation, results are rounded to fewer places; at one of these roundings, a randomization of the least significant figure is introduced to avoid bias. At the antenna element, the row and column orders are added together and the result rounded to four binary places; the least significant figure then corresponds to 22.5^{o} of phase-shift.

Phase-shifts in the feed cables to the antenna elements are measured to eight binary places (approximately 1°). Cables are cut to a length specified to six binary places plus an increment (of maximum value about 4° in phase) that is deliberately controlled so as to appear spatially random across the face of the array.

Manufacturing tolerances are set on gain and phase of the individual transmitting modules and phase shifter with the intent that the root mean square (RMS) amplitude variation across the population of 1,792 elements be held to 0.114dB and the RMS phase variation (including rounding) to 16.4°. The panel is of the opinion that the processes as described can be expected to attain this level of statistical control over pointing errors.

Given error control to the degree described, the effects on the sidelobe patterns of the antenna can be given a precise statistical description. For example, the likelihood of a variation in a particular sidelobe from the nominal pattern by as much as 2dB is less than 5 percent.

Quite apart from the design calculations, measurements have been made to validate the design, and further measurements will be made during operation of the radar.

In one part of the contractor's test program the transmitting antenna pattern is probed by tracking satellites: with the receiver pattern fixed so that the satellite appears on the receiving main beam, two transmissions are made, one with the satellite on the main transmitting beam to calibrate the roundtrip loss, and a second with the transmitting beam directed in another direction. Comparing the returned signals from the two transmissions provides a sample of the sidelobe pattern in a particular steering configuration. Over the course of time, a map of sidelobe performance is thereby established. The contractor reports that, as measured to date, near sidelobes are at least 22dB below the main lobe. This observation is confirmed by plots of data shown to the panel.

An independent series of measurements, sampling the radiation field at points near ground level, is being conducted by the Air Force. Measurements are further discussed in Section 6.

In addition to errors of the kind just discussed, including small departures from nominal conditions, gross malfunctions must be considered such as failure of a module to transmit at all. When a module fails to transmit, the effect on the antenna pattern is to add coherently to the unperturbed pattern an error signal from the failed module equal in amplitude but opposite in phase to the ideal signal from that module. Since one module contributes only .06 percent of the power of the antenna, such an error signal can have but a trivial effect on the antenna pattern. Even if many modules fail, the effect on the main beam, where the power density is high, is small. The effect on sidelobes will also be small unless the failed modules lie in some systematic pattern across the face of the antenna, so that their error signals constitute a well-formed beam.

For a given number of failed elements, a worst-case configuration (not the only one) is that of uniform spacing along a line. Such a

line of radiators is an antenna having a conical main beam, (one concentrated near a central surface that is a cone). The axis of the cone is the line along which the failed radiators lie. The half-angle of the cone is the angle between this axis and a line, which is then a generator of the cone, that is parallel to the direction of the main beam of the antenna.

If a column of radiators were to fail, the axis of the cone points upward, and no generator of the cone lies at lower elevation than the main beam--hence the main lobe of the error pattern cannot strike the ground. If a row of modules fails, the axis of the cone is horizontal and the cone--i.e., the main lobe of the error pattern--always intersects the ground. This is an illustrative severe case.

The longest row in the PAVE PAWS antenna contains 32 elements. There are several such rows, none of them in fact contain as many as 32 powered elements. The maximum possible flux density at a given point from 32 radiators is 1,024 (= 32 x 32) times the flux density at that point created by one radiator. In the case of PAVE PAWS, at a point on the ground where such a maximum occurs, if that point is not illuminated by significant radiation from a secondary sidelobe of the unperturbed antenna, the flux density from the error pattern is 5dB below that of an unperturbed secondary sidelobe--i.e., 35dB below the main lobe. If the error lobe falls exactly at a point already illuminated by the maximum of a secondary sidelobe and if the error signal adds constructively to the unperturbed sidelobe at that point (constructive addition cannot be ruled out), the effect is to create a perturbed sidelobe about 4dB higher than the unperturbed one--i.e., a sidelobe 26dB below the main lobe.

Were a row of elements to transmit in reversed phase, the effective error signal would have twice the amplitude of that used in the calculation above. The main lobe of an error pattern from such a malfunction would be slightly more intense than a secondary sidelobe of the unperturbed antenna, and could, in the worst case, cause a perturbed secondary sidelobe 24.5dB below the main lobe. Failure of five adjacent rows to transmit would create an error lobe that is about 21dB below the main beam. This when added constructively to a secondary sidelobe of the unperturbed pattern could create a perturbed sidelobe 18.5dB below the main lobe.

These estimates are worst-case bounds, since it is unlikely that the main lobe of the error pattern where it intersects the ground will coincide both in position and in phase with the peak of an unperturbed secondary sidelobe. The estimates show, however, that the simultaneous failure of several rows of antenna elements or of their driving modules can have an effect on the secondary sidelobes of the PAVE PAWS antenna that is quantitatively much more severe than the effects of random small errors that were examined earlier.

Written into the specifications and designed into the PAVE PAWS system is a testing feature that continuously and automatically verifies the operation of the transmitting modules during operation of the radar and monitors the ability of the antenna to form proper beams. Some distance in the front of each antenna face mounted on a pole well

above ground is a monitoring receiver that measures the amplitude and phase of the signal received and reports the measurement to the control computer. Slightly more often than once per second this receiver is used to test features both of the transmitting and of the receiving operation.

Signals are distributed to the 1,792 powered elements of the PAVE PAWS antenna in such a way that these elements divide into 56 groups of 32 elements each. (Figure 4 shows how these groups lie on the antenna face.) Each group is simply a subarray forming a small phased-array itself. Each subarray is subject to the steering orders that are given to the whole antenna. The modules of the subarray share a common driver amplifier. Any subarray can be turned on or off independently of the others.

Once every 972 milliseconds (during one 54 millisecond period out of every 18) subarrays are steered one by one to the test antenna and their gain and phase measured. Each subarray is tested once every 30 seconds. Since a single transmitting module contributes 3 percent of the power of a subarray, a malfunction of even a few modules within a subarray is readily detected. Measurements are reported to the control computer. A major fault is reported if the gain of any subarray is not within 1dB of the design value. Individual transmitting modules can be tested by this same procedure, but that process is not done during the normal cycle of operation.

Figure 4 shows that the specific severe malfunction examined earlier, the simultaneous failure of one to several rows of modules, is a most unlikely event unless it results from the simultaneous turning off of about 12 subarrays. Whether or not subarrays as a whole fail, the malfunction of one to several rows of modules would appear as a malfunction in enough subarrays to be detected within a few seconds. In fact, almost any distribution of 30 to 100 malfunctioning modules that could create a reasonably well formed beam from error signals is one that would put enough malfunctions into some one subarray that the disturbance would be detected within 30 seconds.

If a subarray is turned off the resulting error signal is one generated by 32 elements. The arithmetic is therefore the same as that used above in estimating the effect of a malfunctioning row. However, a subarray is a compact antenna having not a conical beam but a broad main lobe oval in cross section and steered in the same direction as the main lobe of the unperturbed antenna. It is fringes of this broad lobe, or sidelobes from the subarray, that intersect the ground. Hence, the effect of turning off one to five subarrays is less severe than the bounds estimated earlier for the respective effect of one to five malfunctioning rows. In fact, measurements of sidelobes on the ground have been made during periods when several subarrays were not functioning. Within the capability of the measurement process, there was no difference detected from the sidelobes of the full antenna.

If a subarray were to be steered independently and its main lobe directed toward the ground, the effect could be the same as that estimated earlier for a malfunctioning row. The subarray alone illuminates the ground with 5dB less intensity than a secondary sidelobe of the

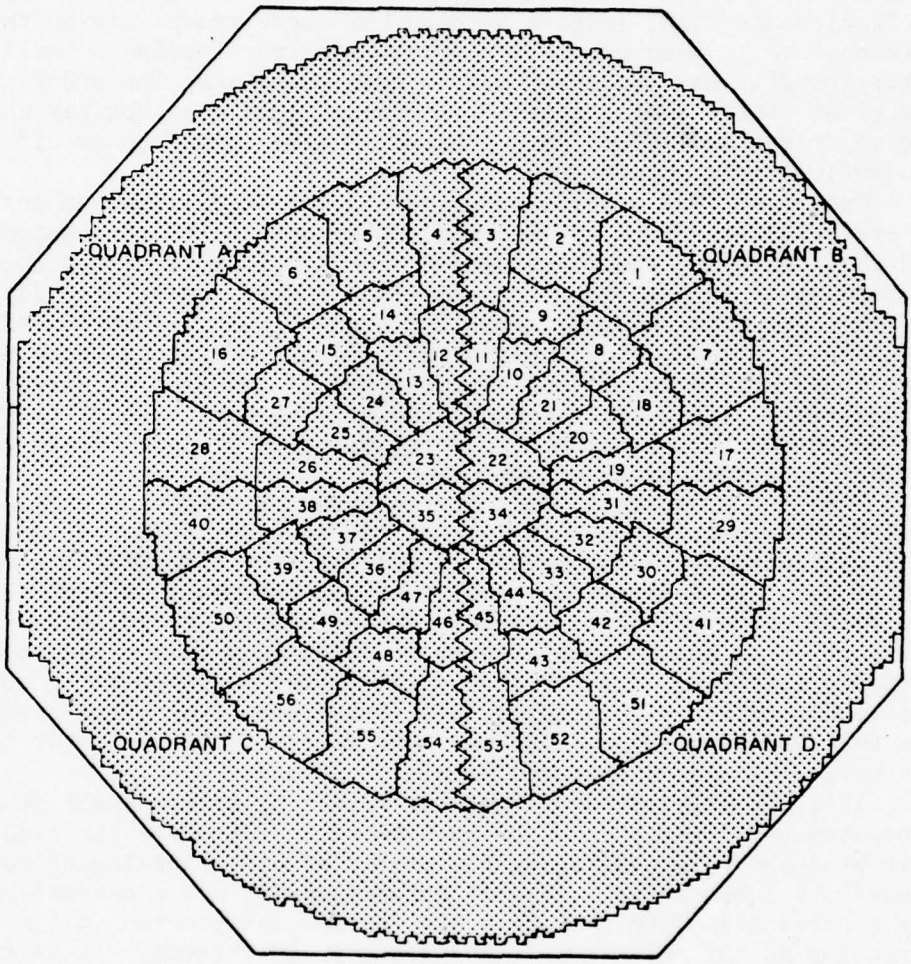


Figure 4
Subarray Positions
Courtesy of the United States Air Force

main antenna. Added constructively to a secondary sidelobe, this signal could create a perturbed sidelobe 4dB above the unperturbed one. To cause such faulty steering many malfunctions would have to occur, each in a very specific way. The event is most unlikely but in any case could not pass undetected for longer than 30 seconds.

An accumulation of water, ice, or snow on the antenna face can alter the gain and the phase of antenna elements across the antenna aperture both in a random and in a systematic way. Therefore, the effects of accumulated precipitation are amenable to analysis in the manner already illustrated. Analyses and measurements of these effects were made in connection with the design and installation of the PAR in North Dakota. These have been supplemented by measurements specific to PAVE PAWS.

Rainwater cannot accumulate deeply, and it takes a 10 inch accumulation of snow to have an electrical effect comparable to that of 1 inch of ice (or water). Therefore, in the climate of Cape Cod, an accumulation of ice is the condition most likely to be severe. Antenna elements are provided with heaters to prevent the accumulation of glaze in ordinary storms and to remove glaze after a severe storm. Past weather records indicated that even without ice removal, there will be only a few brief periods per decade in which enough ice can accumulate to affect the operation or result in shutdown. Degradation of performance by the presence of ice will be detected by the regular process of monitoring the subarrays.

Even if ice accumulation should occur, a uniform accumulation will not affect the sidelobe pattern. A systematically wedge-shaped accumulation that tapers by as much as 1 inch across the antenna face (an extreme condition) would not affect the sidelobe structure, but would deflect the whole pattern by not more than 1/20 degree. Such a deflection has no effect on the estimates of radiation intensity from the sidelobes that are discussed here. A sufficiently severe random component in the accumulation of ice could increase sidelobes. A variation in thickness by one-half inch distributed across the aperture in such a way as to have a severe effect could increase sidelobes by 2dB. An accumulation having random variations as severe as this is unlikely.

5. PULSE PATTERNS AND PEAK POWER

In operation the PAVE PAWS radar tracks targets, searches for new targets, and probes the ionosphere to explore for conditions, such as aurorae, that are likely to affect propagation or create excessive clutter. The type of pulse or pulse burst that is emitted and the spacing of the bursts in time depend upon the function (search, track, or probe) and upon the range to the targets being tracked or to the regions being searched or probed. The pattern of pulses is therefore complex and dynamic, varying with the tactical situation.

In addition to the variability in time of the pulse pattern itself there is further variability in the energy received at any fixed point on the ground, caused by the fact that each pulse is transmitted with the antenna pointing in a direction chosen for that pulse and at a frequency that is, typically, shifted from pulse to pulse. Therefore, a point on the ground sees radiation from a sidelobe pattern that changes with every transmission.

It is in the nature of high gain antennas that the sidelobe pattern is "spiky" in the sense that it is characterized by narrow lobes separated by deep nulls. Designed as the PAVE PAWS antenna is, with particular attention to minimizing the large lobes, a pattern may have a few tens of lobes with peaks within 5dB of the design maximum (i.e., for PAVE PAWS, between 30 and 35dB below the main lobe). Therefore, the energy received at a point on the ground from the PAVE PAWS radar will be characterized by a complex pattern of pulses further modulated from pulse to pulse by a gain factor that is sharply variable.

It is appropriate to consider (a) the maximum energy flux density observed during one pulse as viewed via one sidelobe, (b) the relation of this maximum flux density to average power density (since this bears on the problems of measurement), (c) the power spectrum (in frequency) of the envelope of the radiation seen by an observer, and (d) the likely recurrence of times of maximum fields.

During the transmission of a single pulse, the PAVE PAWS antenna radiates about 580kW (1,792 x 322 watts). The gain of the antenna is 38.6dB. This means that any point beyond about 400 meters from the antenna the energy flux density on the axis of the main beam is 38.6dB greater than would be the case if that 580kW were radiated isotropically. That is, on-axis flux density is 38.6dB above 4.6×10^4 ($= 5.8 \times 10^5 \times (4\pi)^{-1}$)

watts per steradian, or 3.3×10^8 watts/steradian. At slightly over one mile from the antenna (5,500 ft.) this creates a (peak) flux density in the main beam of 10 milliwatts per square cm.

The maximum gain of a secondary sidelobe of the PAVE PAWS antenna is at least 30dB below the gain of the main lobe and hence is not greater than 8.6dB (= 38.6 - 30) above an isotropic radiator. The radiation flux density during a pulse along the axis of a secondary sidelobe is therefore 8.6dB above 4.6×10^4 watts/steradian. This equates to a flux density of 3.3×10^5 watts/steradian. At one kilometer from the antenna, 3.3×10^5 watts/steradian creates a flux density of 33 microwatts/cm^2 (33μW/cm^2). This is a useful reference number; two of the points at which measurements have been made are located with unobstructed views of the radar at approximately this distance (Station 2, 3,900 feet, Station 1, 3,100 feet (see Section 6)) and only a few points of public access are less distant than this.

The figure 33μW/cm^2 is a reference based on the nominal level of -30dB for a maximum secondary sidelobe. Given that the antenna elements remain within design tolerances, the probability is less than 5% that the maximum flux density be as large as 46μW/cm^2 at one km (2dB above 33μW/cm^2). We will call this the "worst-case" reference flux density.

A reference flux represents the power during a pulse. It determines the gradient of the electric potential at the point at which the flux is measured by the simple relationship

$$\text{Potential gradient in volts/meter} = 0.1\,(377\,\phi)^{1/2}k,$$

where ϕ is the reference flux in μW/cm^2, 377 is the impedance of free space in ohms, and the factor 0.1 results from the conversion of μW/cm^2 to watts per meter^2. The factor k is $\sqrt{2}$ if by "field" one means the maximum amplitude of a sinusoidally varying field. Engineers usually use k = 1, nevertheless calling the result "peak field gradient." For consistency with other reports (Reference 3) we will use k = 1, calling the result "power-equivalent peak field."

Each pulse or short group of pulses emitted by the radar is followed by a listening period. (More details will follow in later discussion.) On the average the transmitter is operating at most one-quarter of the time (duty cycle - 0.25). At a maximum secondary sidelobe, then, the average energy flux density is one-quarter the maximum flux density.

The maximum duration of any pulse emitted is .016 seconds (16ms). The energy flux in joules/cm^2 from such a pulse is then equal to the flux density in watts/cm^2 times .016. Table III exhibits for comparison purposes the relevant quantities expressed for a point that is at a distance R in km from the antenna.

The reference levels in Table III represent conditions on the axis of a secondary sidelobe. At any point that receives energy only from secondary sidelobes, they describe upper bounds to the measurements that would be made of the indicated quantities.

When the main beam of the PAVE PAWS radar is directed to elevations higher than about 4.5°, no energy can reach the ground from first sidelobes, and the upper bounds in Table III apply to exposures or

Table III

ESTIMATES OF RADIATION AND FIELD INTENSITY ON THE AXIS OF A SECONDARY SIDELOBE
R > .5km

	Nominal	Worst-Case
Maximum flux density, watts/ steradian	3.3×10^5	4.6×10^5
Maximum flux density at distance R km, in $\mu W/cm^2$	$33\ R^{-2}$	$46\ R^{-2}$
Power-equivalent peak potential gradient at distance R km, in volts/m	$11\ R^{-1}$	$13\ R^{-1}$
Maximum energy density in one pulse, at R km, in joules/cm^2	$5.3 \times 10^{-7}R^{-2}$	$7.4 \times 10^{-7}R^{-2}$
Average power density, at R km, in $\mu W/cm^2$	$8.2\ R^{-2}$	$11\ R^{-2}$

measurements at points on the ground. With the main beam directed to its lowest elevation of 3^{o}, fringes of the first sidelobes illuminate the grounds. In this case, the entries in Table III are not necessarily upper bounds. To state absolute upper bounds for the most unfavorably situated points on the ground near the radar, to which R > .5km, multiply the power entries in Table III by 4 and the peak potential gradient by 2. The situation for R < .5km must be modeled in a different way and is generally more favorable than Table III suggests.

The EPA has calculated the fields in the vicinity of PAVE PAWS for the case in which the main beam is at 3^{o} elevation (Reference 1). The calculations use a refined model of the radiation pattern of the antenna and take into account the topography of the local area. The panel considers the calculations to be conservative,* in that they assume that a point not illuminated by the main beam or by a first sidelobe necessarily falls on the axis of a secondary sidelobe--i.e., is a point to which Table III applies. They are also conservative, in that they assume always a clear line of sight between the radar and the point at which exposure is calculated.

Exposures calculated in Reference 1 for points on the ground that are more than about 2km distant from the PAVE PAWS antenna are larger than those that would derive from Table III by substituting the proper value of R because of the effect of the first sidelobes. For the nearest points of public access, along the proposed extension of Route 25 and Route 6, the calculations of Reference 1 are in agreement with Table III.

The calculations by the EPA are conservative in all respects. Table III is offered for purposes of illustration and not as a substitute for Reference 1. It happens that Table III is conservative in the same way as Reference 1, at nearby points of public access.

The panel now turns to features of the radiation from PAVE PAWS other than simply power level. In the discussion, further light is shed on the conservatism in Reference 1 and in Table III in regard to average power levels.

The operation of the PAVE PAWS radar is timed to a basic cycle that is 54 milliseconds long. Thus, 17 consecutive cycles of 54 milliseconds each are devoted to search and track functions; the eighteenth is then devoted to radar tests.

A basic 54 millisecond cycle is called a "resource." A resource may consist of a period of about 16 milliseconds during which the transmitter is operating continuously or almost continuously, followed by 38 milliseconds of silence (transmitter off). Alternatively, a resource may be divided into shorter cycles, each of the same general form, consisting of a short transmission followed by a period of silence that is several times as long as the transmission. Each period of transmission has internal structure: pulses go out in rapid succession, typically in each of several directions and on different carrier frequencies.

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*By conservative the panel means from the point of view of concern about radiation exposure--that is, simplifications are used in making the calculations so that the estimate of exposure is likely to be greater than the actual exposure.

The pulses themselves are frequency modulated ("chirped") for spectrum spreading--i.e., to increase bandwidth and increase processing gain upon reception. Bandwidth in the search mode is 100kHz, in the track mode, 1MHz.

On either face of the radar, the maximum duty cycle during any resource is 16/54 = .30. The maximum possible duty cycle during any 18 consecutive resource intervals is then 17/18 of this, or 0.28. Actually the duty cycle over a period of one second or more is controlled by considerations other than pulse pattern (see Section 8) and is not greater than 0.25.

At a fixed point on the ground an observer samples each pulse through a filter defined by the sidelobe pattern. The gain of this filter depends upon the direction in which the main lobe is pointed and upon the carrier frequency used for that transmission of that pulse. Typically, these both change from pulse to pulse. The effect of this variable gain is twofold. First, it reduces the average power at the point of observation to something below the reference figures given in Table III, because these latter are based on the maximum gain of a secondary sidelobe, a gain of 8.6dB over isotropic. Second, it imposes an amplitude modulation of high peak-to-average ratio from pulse to pulse on the already complex pulse pattern. The two effects are discussed somewhat separately below.

It is possible in principle to calculate from design data the average power density received at some given point as the radar runs through a specified cycle of operations. One simply calculates the average gain that characterizes the field of sidelobes at specified sampling points and carrier frequencies. To identify such a calculation with an actual situation requires that a representative cycle of operations, or one that defines a practical maximum average gain, be specified. The model of a "worst-case" operation used in the EPA analysis and that implicit in Table III is one in which samples always fall at maximum secondary sidelobes.

Because actual measurements of radiation intensity are being made at representative points on the ground, all one needs from an analysis is reassurance that such measurements represent either the actual intensity or an upper bound to the intensit, of radiation intercepted at the point of measurement. The discussion below shows that the measurements can exhibit high peak-to-average ratios in time, and under some operating conditions a "spiky" fine structure in angular distribution. However, Table III still provides conservative estimates for nearby points of public access.

The most nearly regular and systematic operating mode of the radar is called enhanced search. In this mode, the main beam visits successively 120 different positions at 3^{o} above the horizon, seeking targets at maximum range. This scan is not interrupted for other functions and repeats approximately every 2.5 seconds. This is then a mode in which the greatest exposure is likely to occur at nearby points on the ground and is the mode exhibiting the most nearly repetitive pattern of pulses.

Most of the measurements to date have been made with the radar operating in a mode differing from enhanced search in two respects: (1) the normal pulse-to-pulse switching of carrier frequency is disabled

(so that one narrow-band measuring instrument suffices), and (2) scans at elevations from 3° to 10° above the horizon are measured to further explore the region near the main beam where sidelobes tend to concentrate.

To get a qualitative understanding of the exposure at one position on the ground during enhanced search, or as a measuring instrument might observe the modified enhanced search pattern, imagine that measuring points are set up at 120 locations around the radar uniformly spaced along the 120° of azimuth that is scanned during search. Each point is to be at 4° below the minimum scan elevation--i.e., at 1° below the horizontal. Such points are representative of the nearby terrain at points of public access. With the main beam fixed at one azimuth and 3° elevation, the 120 measuring devices will then sample a line of sidelobes in azimuth-elevation space. One such array of samples calculated by the contractor under the nominal design conditions of the antenna is shown in Figure 5.

By this curve perhaps 10 percent--i.e., 12--of the measuring points will be sampling sidelobe gains that are between 30dB and 35dB below the main lobe; another 5 percent on the "skirt" of a first sidelobe sample gains between -30dB and -25dB. Assume for the moment that these statistics of the curve, not the details, remain the same for other positions of the main beam. Then with the main beam at a different azimuth, some other 18 sampling points will experience similar sidelobe gains. Under these conditions, as the main beam steps through all 120 of its scan positions, a given measuring point can be expected to fall 10 percent of the time within 5dB of the peak of some secondary sidelobe and another 5 percent of the time on a fringe of a first sidelobe.

If one computes the total power received by a line of instruments spaced uniformly in angle from 0° to 60° along the horizontal axis of Figure 5, it is 36.6dB below the main lobe corresponding to 6.6dB below the nominal 30dB (below main lobe) used in computing the reference levels of Table III. Hence, if the statistics of the curve of Figure 5 are representative of the statistics of every sidelobe pattern in the search repertoire, the effect of sidelobe filtering can be expected to reduce the average power observed at one point during enhanced search by 6.6dB below that exhibited in the last line of Table III. This would reduce the nominal reference average power density at one km, to 1.8$\mu W/cm^2$. This is about 6dB greater power density at 1km than what is shown by the measurements to date. (See Section 6). From this comparison one is encouraged to believe that Table III, as it refers to average power, is highly conservative and that the model of a "spiky" sidelobe pattern provided by the single curve of Figure 5 is probably not grossly misrepresentative of the statistics of sidelobe gain seen at a fixed point on the ground as the main beam executes enhanced search. Other charts of sidelobe patterns support this latter conclusion.

The "spiky" nature of the sidelobe pattern as it scans past a fixed point has the effect that average power as measured over a one second interval varies by several dB, just as a high-gain pulse

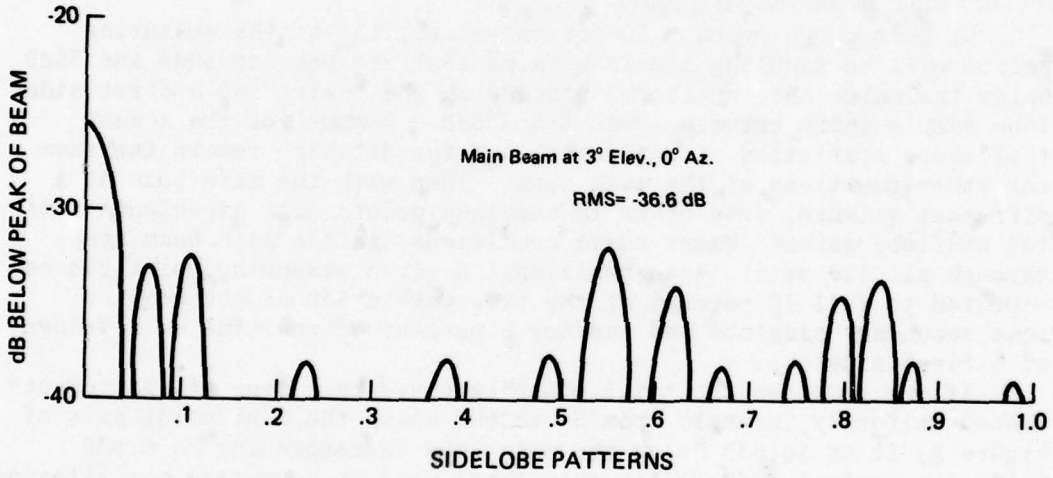


Figure 5
Calculated Radiation Intensity During Enhanced Search
Courtesy of the United States Air Force

is intercepted during the measuring interval. Accordingly, it has been the practice to quote measurements of average power based on averaging intervals of 10 or more seconds of duration. When measurements are made under standard operating conditions--i.e., with the antenna searching and tracking and carrier frequencies being shifted--much longer intervals will be needed to get representative data on either maximum power or average power.

Quite apart from the relation between peak values and average values, it is of interest to examine the modulation that appears at a fixed point on the ground on the envelope of the radio frequency carrier (a nominal 435MHz). In this discussion, the panel considers the carrier as modulated, first by the envelope of the pulse pattern, and then by the scanning of the sidelobes.

In the enhanced search mode, each resource that is occupied by a transmission consists of a period of about 16ms, during which either two pulses of 8ms each or three pulses of 5ms each are emitted. No other transmission takes place during the remaining 38ms of that resource. So, 17 consecutive transmissions are followed by one more during which the transmitter operates only at low power for antenna tests. There are 120 distinct beam positions across the 120° sector that is being scanned. During a period of about 2.5 seconds, each position is visited once. The pattern of visits tends to repeat during subsequent similar intervals, but repetition is not exact until about 25 seconds have elapsed.

In the pulse train of this enhanced search mode, there is clearly a repetitive element with a period of 54ms. The power spectrum of the envelope has a component at zero frequency, governed by the duty cycle. To a first approximation, it also has power concentrated at 18.5Hz ($.054^{-1}$Hz) and at the multiples thereof. The effect of periodic interruptions every .972 seconds (.972 = 18 x .054) introduces sidebands about these spectral lines, spaced every 1.03Hz ($.972^{-1}$Hz). Even after the spreading of energy caused by these sidebands, the single line at zero frequency contains nearly 30 percent of the total power. Less than 6 percent of the power falls at 18.5Hz and its nearby sidebands.

The simple and regular mode of enhanced search is not a likely one during normal operation. It is expected that, typically, only one out of two or one out of three consecutive resource intervals will be devoted to long range search. The intervening intervals of 54ms will be subdivided into shorter intervals, 27, 13.5, or 6.25ms long. This has the effect of reducing the spectral peak near 18.5Hz and of increasing the power around higher harmonics (37, 74, 148Hz) without reducing the concentration near zero Hz. Moreover, more sidebands are introduced about all of the spectral peaks because of the partially periodic recurrence of those resource intervals that are subdivided. These sidebands will also appear about the zero-frequency spectral peak.

Imposing on this envelope a further modulation induced by pulse-to-pulse sampling of the sidelobe pattern will produce a final spectrum

of modulation that is the convolution of the envelope spectrum, as just sketched, with the spectrum of the time series that represents the succession of sidelobe gains. This latter time series will be highly random in character if for no other reason than that the carrier frequency changes at random from pulse to pulse. The effect of this sampling is then to introduce a flat loss (estimated crudely above to be 6.6dB), and a further spreading of the lines of the envelope spectrum into sidebands near each line. The final power spectrum is dominated by power in the band from zero frequency to two or three Hz. The whole region from 10Hz to 25Hz has less power in it than in the band from 0 to 3Hz. Energy in the range 15Hz to 20Hz is less than 1 percent of the total energy of the signal--i.e., corresponding to a signal of average power at least 20dB lower than that shown in Table III.

The panel was shown a sample strip-chart record of power measurements made by the contractor (actually, from Station 2 as discussed in Section 6). Over a 40 second interval the record showed a fluctuating average power with a highly periodic and bi-modal structure. A basic fluctuation fairly regular in peak amplitude at about $0.4\mu W/cm^2$ showed a periodicity of two per second; superposed on this was a regular sequence of spikes regular in amplitude at about $1.4\mu W/cm^2$, having a period of four per 10 seconds. These records were taken with the radar scanning in a search pattern resembling the enhanced search discussed above but containing only 60 beam positions rather than 120. It was stated that this was a typical record. It is fully consistent with what the discussion above predicts for power measurements averaged over an interval of several times .05 seconds.

6. MEASUREMENTS

From the time in June 1978 that a few subarrays were operating on the south face of the PAVE PAWS antenna, measurements of radiation intensity have been made at points on the ground at distances from 1,600 feet to 2 miles from the antenna face. The contractor and government agencies have conducted test measurement programs. The PAVE PAWS Program Office has issued reports of the measurements made by government agencies. Reference 3 summarizes those obtained through August 1978. These, as well as measurements made by the contractor, were discussed with the panel on September 7, 1978.

Table IV summarizes the measurements of average power density reported in Reference 3 by the Air Force team. The report noted in Reference 5, subsequent to Reference 3, includes measurements at many more locations. In general the levels reported are very much lower than Table III would predict, presumably because few of the locations have a clear line of sight to the radar. There is only one measurement of maximum power in Reference 5 that exceeds (slightly) what Table III predicts. Table IV lists the four nearby locations where a clear line of sight exists.

The measurements in Table IV were made with the radar operating in the enhanced search mode at a fixed carrier frequency and at a duty cycle of 0.20. The Table also shows each measurement corrected, first by R^2 to an equivalent measurement at 1km, and, second, by a factor 1.25 (= .25/20) to a duty cycle of 0.25. The last column of Table IV therefore presents four long-term average power measurements for comparison with the bottom line of Table III. The comparison verifies that indeed the average power in Table III is conservative on the average by about 10dB. The model in Section 5 suggested 6.6dB.

On page 7 of Reference 3 there are caveats about the measurements in Table IV--that these in fact are for conditions under which one would expect higher levels than Table III projects for the measuring stations. Hence measurements in Reference 3 confirm the conservative values of Table III at nearby points on the ground. They also are consistent with the model of the spiky sidelobe pattern used in the qualitative discussion in Section 5. This also suggests that the model of the modulation of the envelope of radiation at a point on the ground, as developed in Section 5, is valid. The contractor's time

Table IV

MEASUREMENTS FROM REFERENCE 3 AND REDUCED TO 1km AND DUTY CYCLE 0.25

Station	Distance from radar (feet)	Azimuth from Boresight	Ave. power density $\mu W/cm^2$	Adjusted to one km and duty cycle 0.25 ($\mu W/cm^2$)
1	3100	12°	0.87	.98
2	3900	0°	0.38	.68
3	1600	9°	3.26	.98
4	1800	63°	1.71	.64
Average for four stations				.82

records tend to confirm this latter conclusion as do data in Reference 3 on the recurrence periods of peak measurements.

In reviewing the measurement program the panel concludes that the instrumentation used and the procedures followed conform to good engineering practice. In particular these conclusions apply to the instrumentation and procedures used by the Air Force team, which has done the bulk of the measurements reported to date. What has been reported to date and the measurements planned for the future should therefore give a valid picture of the intensities experienced at nearby points and at those points of public access where exposure will be greatest. As this picture now stands, the EPA analysis (Reference 1) appears to be conservative by at least several dB--a conservatism that is, moreover, supported by design data about the structure of the sidelobe patterns.

The four stations shown in Table IV exhibit average measurements that, reduced to a standard distance in the last column, vary among themselves over a range of nearly 2dB. Other measurements reported in Reference 3 and the contractor's measurements as reported to the panel cover a range wider than this. The variations are not surprising even in average power measurements. The presence or not of a clear line of sight is important. The possibility of sharp differences from one azimuth to another during enhanced search has already been suggested. Reference 3 does not claim a calibration of the measuring system to closer than ± 2dB for average power measurements. It is in the nature of the fields being measured that partially standing waves created by reflecting features in the local terrain can create local peaks and nulls. Even though the standard procedure is to seek a worst position (highest measured power) within the accessible area around each measuring station some variability is to be expected. The panel therefore does not consider that the variability among the measurements as reported in Reference 3 reflects in any negative way on their validity. On the contrary, much less variability could be a cause for concern. Neither does this variability cast doubt on the conservatism of Table III, within its limitations.

There is another source of variability mentioned in Section 5--namely, variability over time. There is an ambiguity that is more than merely semantic in the uses of the terms "peak power" and "peak field." A pulse from the PAVE PAWS radar can be as long as 16 milliseconds or as short as .25 milliseconds. In Section 5 the panel noted that it is possible that a single pulse may be sampled at maximum sidelobe gain while all other pulses that occur at times nearby are sampled through a filter having, relatively, many dB less gain. What is measured and reported as a "peak power," then, can depend in a dramatic way on the averaging time intrinsic to the instrument as well as on the statistical sampling procedure by which readings of "peak power" are defined and reported.

The panel recommends that measurements of power be made with an instrument of known averaging characteristics, preferably one with a time constant not longer than 0.2 seconds, and that rapid repeated samples be taken on a known and accurately defined sampling cycle that is

not accidentally synchronous with a subharmonic of .054 sec^{-1} nor with any cycle rates intrinsic to the search patterns being measured. Such measurements taken over a period of several times 10 seconds would allow a statistical analysis of "peak power" measurements capable of a more refined check against Reference 1 and Table III than has been made here.

Given the instrumentation as reported in Reference 3, it seems likely that data of the kind just suggested already exist in the time records. If so, the panel suggests that these data be given some statistical analysis. Of interest, as suggested by the considerations of Section 5, would be recurrence times or recurrence rates of power peaks above threshold and of the average power delivered in peaks above threshold measured at several different threshold levels.

7. COMPUTERS, STEERING, AND BEAM POINTING

Preceding sections discuss the radiation intensity at nearby points on the ground that can result from normal operation of the PAVE PAWS radar and the effects on that intensity that might result from possible degradations in antenna performance. Key to the discussion was the assumption that at ground level only sidelobe energy is received. This section evaluates those features of the antenna's control system that assure that the main beam is never directed below 3° elevation and therefore that points of public access are not exposed to energy other than that from sidelobes.

Primary control of the pulse-by-pulse operation of the PAVE PAWS radar resides in a CYBER-174 computer. The basic functions performed are to schedule radar pulses, to process data returned from the received echoes, to detect, track, and classify targets, to determine launch and impact points, to operate displays and alarms and to maintain checks on status and operability of the radar and computer. There are two CYBER-174 computers on site. One operates on-line, the other is available as a spare should the on-line computer require maintenance.

The radar is under detailed control of its own radar controller, a MODCOMP IV general-purpose computer. The basic functions performed are: to receive beam-steering and pulse schedules from the CYBER-174, to convert these into steering commands and commands to the receiver-exciter, to do or to control signal processing on radar returns, to report processed returns to the CYBER-174, and to conduct and report on performance monitoring tests. A spare MODCOMP IV will take over automatically if the on-line unit goes out of service.

Steering directions for each pulse to be transmitted are generated in the CYBER-174. Directions for a search pulse along the 3° elevation line are simply read from a table that describes all 120 possible search positions. Other pulses--those scheduled for tracking targets, for example--are steered to directions that may be computed from current track files or satellite catalogs, etc. Steering directions are computed as $\sin \alpha$, $\sin \beta$, each expressed to 60 binary places, where α is the angle of rotation about the column direction, and β the angle of rotation about the row direction, that would be required to bring the beam from its desired position into coincidence with the vector normal to the array face (boresight). By a direct geometrical calculation, the

pair sin α, sin β is tested in the CYBER-174 to verify (a) that the beam elevation lies at least 3^{o} above horizontal, (b) that the beam azimuth is within 61^{o} of the azimuth of boresight, and (c) that the beam is within 65^{o} of the array normal. If a steering direction fails any one of these tests, the pulse for which it was generated is not scheduled, and no instruction goes out to the radar controller. This same geometrical test indicates when a target in track will have to be transferred from the coverage of one face to that of the other.

A steering order that passes the coverage test in the CYBER-174 is rounded to 16 binary places and issued to the radar controller.

The radar controller computes the amourts by which, from row to row, and from column to column, the phase is to be incremented to create the desired beam direction. The row increment (RWI) and column increment (CLI), each to 16 binary places, are then transferred to a separate beam steering unit--a special purpose digital computer. This computer verifies that the increments RWI and CLI describe a permissible beam position. This is done by consulting a table stored in a permanently wired ("burned in") read-only memory. The beam steering unit rejects an illegal command and reports a fault. If the command is legal, the beam steering unit computes, for each row or column, a desired phase shift. For the n^{th} row (or column) the desired shift is n x (RWI) (or n x (CLI)), plus a correction to improve the randomization of phase errors after rounding. Row and column commands to six binary places are summed in each transmitting module, the sum is rounded to four places to command the four quantized increments of phase shift in that module. A spare beam steering unit takes over automatically if the on-line unit becomes inoperative.

In the programs of the CYBER-174 and the radar controller and in the hardware of both of these computers, as well as in the beam steering unit, there are self-testing and error-sensing features of many kinds. In particular, programs in the radar controller subject the beam steering unit to tests during each resource interval that is reserved for tests (one in eighteen). Among the functions tested is the response to steering commands, both those that are out of coverage limits, as well as those that are legal. Failure to recognize an illegal command as being illegal is reported as a radar fault, and the faulty beam steering unit is taken out of service. Other incorrect responses are treated similarly. During the course of a few minutes, both legal and illegal commands lying near the boundary of coverage and exploring that boundary, are tested. These tests of the beam steering unit also detect malfunctions that could distort the beam severely, therefore protecting the integrity of the beam quite independently of the periodic subarray tests described in Section 4.

In this section the panel has so far discussed features of the pointing and control of the transmitting beam that ensure that areas outside of the desired zone of coverage are not illuminated. There are also protections against letting the beam dwell too long in one position ("spotlighting") even when that position lies within the zone of coverage. The operation of these protective features has the effect of warning against, or of preventing, a condition in which some

nearby point on the ground is exposed on every pulse to a worst-case sidelobe. Even such a condition would, in general, create exposures no greater than those shown in the last line of Table III.

When under control of the CYBER-174, the radar controller will not permit seventeen consecutive pulses to go out in the same direction. If sixteen have already been transmitted in a given direction, the seventeenth is inhibited. The event is reported as a minor radar fault and is entered in the running status report.

Instructions can be entered manually into the radar controller, directing the beam to "spotlight" in a chosen direction. Such manual steering is used for test purposes and for special search operations. Beam steering orders from this manual source are tested in the radar controller for compliance with scan limits. The scan limits used for a manually ordered spotlighted beam reject any beam directed below 6° elevation. These steering commands are again tested (just as are all others) in the beam steering unit (i.e., against the 3° horizon limit).

The CYBER-174 and the radar controller are general purpose digital computers totally slave to the programs written into them. The writing of these programs to achieve the designer's intent and the testing of them are critical steps in the process of creating a functioning radar system out of an assemblage of hardware.

The beam steering unit is also a digital computer. Its program is in large measure embodied in its wiring diagram or hardware configuration. This fact does not diminish the criticality of careful design and test. The functions of the beam steering unit are, however, repetitive and comparatively simple. In particular, proper design and operation can be verified by a small battery of simple tests. Those performed automatically during every eighteenth resource interval suffice to verify operability.

Tactical software residing in the CYBER-174 and the radar control software in the radar controller are independent of each other and are written by different organizations. The processes of writing and testing are governed by military specifications. Both suites of software are built using methods and controls designed to assure that only software of a known, tested, and approved configuration is used at site.

These development methods are as good as any available at the present time. They do not, of course, totally preclude the possibility of erroneous operation at the site. As indicated by the discussion above, the software and hardware are so configured that the possibility of an event such as the pointing of a beam below 3° in elevation is virtually excluded. All beam steering orders emanating from the tactical software are subject to two separate checks against the scan limits in two distinct computers by distinct processes. One check resides in software, the other in a hard-wired table of numbers. Unless these checks are satisfied, transmission is prevented. Suitable alarms and displays are provided to indicate out-of-limits commands, and the hardware verification circuits in the beam-steering unit are tested every few seconds to verify correct functioning of these interlock circuits themselves. Thus, when the radar is operational, at least two nearly

simultaneous failures would have to occur before the beam elevation could go below 3°. Also, in maintenance testing, two nearly simultaneous failures, accompanied by an incorrect manual action, would have to occur. In either case, one of the failures would have to be a hardware failure, and the other would have to be a software error in a different part of the system. With this arrangement, there is essentially no likelihood of such an event happening by chance or inadvertence, and it is difficult to see how it could be caused intentionally by any one individual, no matter how highly skilled. It appears that the radar beam could be pointed below 3° only by concerted specific, carefully planned software and hardware modifications made by at least two people working in concert. Such an action would constitute a partial redesign of PAVE PAWS.

Testing of the software for PAVE PAWS during the process of development includes testing of the computer systems against a radar simulator that can simulate, from the point of view of the computer, an actual tactical environment. The tests used include traffic loads (number of targets) up to 150 percent of the design load. Simulation programs are also provided in the software used on site, to be used for training, and for systems test. Experience in other systems has shown that such simulations are highly effective, not only in ferreting out possible errors in software (i.e., departures from design intent) but also in verifying that the design responds properly to those problems and off-design conditions that a real environment can give rise to.

8.0 CONDITIONS AFFECTING PATTERNS AND INTENSITIES

Section 4 was concerned with the effects that snow or ice accumulated on the PAVE PAWS antenna could have on the integrity of the beam pattern. The conclusion was that the limits of Table III would not be exceeded.

Fog or precipitation in the atmosphere can intercept radiation and absorb or scatter it. The phenomena are well known, have been carefully measured in other connections, and are readily subject to theoretical analysis. At the frequency of the PAVE PAWS radar, the effect of scattering by precipitation is very small; its presence would not change the estimates in Table III.

Weather conditions also create some refraction in the atmosphere especially near ground level. This causes a ducting phenomenon that can lead to detection by the radar of ground objects at longer range than usual. However, at the short ranges involved in this report, the effect is merely one of causing some downward bending of the rays with a curvature in the daytime of the order of three-quarters the curvature of the earth and somewhat more at night. The downward curvature can amount to several times the curvature of the earth on so-called "radiation nights" when there is no high cloud and ground fog may form. This effect is equivalent to raising the terrain at a distance of one kilometer from the radar by less than one meter, that is, by less than the height of a person. The effect is therefore unimportant to any estimates of radiation intensities at ground level nearby.

The panel's conclusions refer to the design of the PAVE PAWS radar as given in the contractual specifications and as described to the panel by way of the information discussed and distributed at its meeting on September 7, 1978. Some features of that design, e.g., the 3^{o} horizon limit, that are emphasized in this report reside largely in software. The question arises: Can such features be altered? The answer is, of course, Yes.

A more appropriate question is: Is there any incentive for altering the design of the radar in such a way as to invalidate the estimates in Table III? The answer is at least a qualified Yes. For example, the PAVE PAWS building and antenna are now designed for the addition of more active elements to the antenna, with the consequent increase of radiated power and antenna aperture. Reference 1 analyzes this higher powered version of the radar. The general effect of increased power on such

estimates as appear in Table III and in Section 4 is to increase them, but not to the extent that the radar power increases, because an increase in power is offset by the fact that with a larger aperture antenna, sidelobes can be narrower and be lower in intensity relative to the main beam.

The incentives for increasing power and aperture are direct. The performance of the radar in its several missions would be improved. The change is a major one and would be costly. No defined program now exists for its accomplishment. Should such a change be made, the matter of radiation exposure in public areas would require attention comparable to that given the same matter in the present design.

The panel notes that there is a possible incentive for changing the 3° horizon limits that prevail in the present PAVE PAWS design. Without trying to evaluate the exact degree of difficulty involved, the panel concludes that this change is easier and less costly to accomplish than would be an increase in power.

An incentive for lowering the search horizon is that this could bring about the earlier detection of a hostile target. There is also an operational disincentive in that, at lower angles to the horizon, atmospheric effects tend to create more false targets, thus masking real ones. For other reasons also, lowering the search angle does not necessarily guarantee an earlier detection of a valid target. The balance between incentives and penalties is not sharp or clearcut. Most long range search systems tend to limit the lowest scan angle to one that keeps the first sidelobes above the horizontal. For the PAVE PAWS antenna, this would put the main beam at or above 2° from the horizontal.

There is little incentive for dropping the main beam by 1° (or even 2°), from its present 3°. The greatest improvement in detection time that can result occurs when the target sought is at long range so that its apparent angular velocity in elevation is the least. Typical trajectories viewed at ranges of 2,000 to 3,000 miles have angular velocities in elevation of the order of one milliradian (.06°) per second. Depressing the beam by 1° then advances initial detection by 16 seconds. Compared to the travel time of a ballistic target from detection to impact--more than 1,000 seconds--advancing detection by 16 seconds can hardly be considered a powerful incentive. A target, once detected, must be kept under track for sufficient time for it to be classified as threatening and an impact prediction made. Detecting a target at 2° above the horizon rather than at 3° will not advance significantly and perhaps not advance at all the time at which tracking is completed to adequately determine a trajectory. The panel therefore finds no strong incentive to lower the horizon limits below those of the present design.

One other point relative to Table III needs comment for completeness. The maximum power used for Table III was based on a nominal output of 322 watts per module, and average power on a duty cycle of 0.25. The long term duty cycle of 0.25 results from constraints in the tactical software that prevent scheduling of too many pulses. Quite apart from these software constraints, temperature monitors, voltage monitors, and overload protectors throughout the system will cut off

power supplies within a few seconds if the power demand on one face is as great as that represented by a duty cycle of 0.30. For these reasons, there is no possibility of a condition in which either power during a pulse or average power could materially exceed the 580kW and 146kW, respectively, which are the basis of Table III.

While the panel was concerned essentially with the peak field intensity of the PAVE PAWS radar measured at ground sites where humans may be exposed, it turned during its final deliberations to the subject of passing aircraft. The panel observes that aircraft may fly, perhaps inadvertently, through the main beam of PAVE PAWS. Restrictions have been issued and widely distributed to caution aircraft from flying within one-half mile of the PAVE PAWS antenna. Beyond this boundary, the radiation flux in the main beam does not exceed the current U.S. occupational standard of $10mW/cm^2$ (average).

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APPENDIX

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