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AIRCRAFT-BORNE MEASUREMENT OF INFRARED SOURCES AND BACKGROUNDS

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Instruments for infrared measurements of natural and man produced infrared sources are described and measurements were planned, performed, and analyzed. The measured or analyzed data included the following: Measurements of aircraft emissions and reflections in fixed spectral bands between 2.5 and 7.5 μm; analyses of near infrared auroral and airglow emissions in the 1.7 μm and 2.8 μm region; and quantitative measurements and

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analyses of the spatial emissions and backgrounds in the 2 to 15μm region. The measurements were taken with the radiometric instruments described and by spectrometers, and spatial mappers which were operated on AFGL's NKC-135 aircraft. The instruments were periodically inspected, maintained and kept in a state of readiness. Studies and recommendations were made indicating that the reliability of many future measurements could be improved using cryogenically cooled radiometers and interferometer-spectrometers.

Item 18 (Cont'd)

Nuclear Agency under Subtask S99QZXHI004, Work Unit 11, entitled: Infrared Phenomenology and Optical Code Development.

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Several employees of the Electro-Dynamics Laboratories (EDL) were instrumental in the completion of the contractual efforts. Supervision of the efforts was performed by Ronald J. Huppi and Doran J. Baker. Engineering and field measurement support were provided by Thomas Hudson, Dr. John H. Schummers, Brian Walker and Ronald J. Huppi. Data reduction and analysis efforts were accomplished by Ronald J. Huppi, John H. Schummers, Brian Walker and Charles Eastman. In addition, the complete EDL team was available for consultation providing great depth for solving the required problems.

The author would also like to recognize the direction given by Brian P. Sandford and Dr. A.T. Stair of AFGL. Their guidance and interest in the efforts were appreciated.

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INTRODUCTION

Under this contract Utah State University (USU) has planned and performed spectral infrared measurements of natural and manmade background and target sources. The measurements were taken with radiometers and interferometer-spectrometers from an Air Force NKC-135 aircraft. The infrared instruments were maintained, improved, and operated in the field by USU employees.

Much of the measured data has been reduced and analyzed. Reports have been written which incorporate the measured data. Also, a report describing the advantages and the limitations of using cryogenic Fourier-transform interferometers was written to provide guide lines for planning future measurements.

The major contractual efforts performed for the contract are itemized below:

1. Modifications and maintenance of the Dual-Channel NIR radiometer system were made.
2. Modifications and inspections of the Type III interferometer system were periodically made.
3. Reductions and analyses of infrared auroral measurements in the 1.70 μm and 2.9 μm regions were made and reported.
4. Infrared measurements of aircraft emissions and reflections from 2.5 μm to 7.5 μm were performed with the NIR radiometer system.
5. Support was given to collect and analyze spatial infrared data.
6. Scientific reports and open literature reports were written and published.

The work performed on the tasks listed above are summarized in this report. The completion of the items fulfill the contractual requirements.

MODIFICATIONS AND MAINTENANCE OF THE DUAL CHANNEL NIR SYSTEM

Pictorially, the original dual channel NIR radiometer is shown in Figure 1. Modified versions of this radiometer were used in this contract. The modified instruments have additional infrared channels. A four channel configuration is shown in Figure 2, and a three channel configuration incorporating a Probeye* infrared viewing device is shown in Figure 3. The three channel configuration is actually made from the four channel unit through the use of a reversible modification. The modification was designed and constructed under the contract to improve the capabilities of the instrument for the specific measurements of interest.

To accomplish the planned contractual measurements, either a three channel or a four channel radiometer was placed on a trackable platform in the aircraft as shown in Figure 4. The instrument views a target or background through a 12-inch diameter germanium window mounted to the aircraft shell. Either the three or the four channel configuration can be hand tracked on an infrared target through the use of the Probeye infrared viewer which converts an infrared image to a visible image. The three channel configuration is sometimes desired over the four channel configuration since it has less tracking limitations when mounted on the existing aircraft platform.

Each channel of the radiometers has independent optics and an independent detector, but the multi-channel instruments use a common optical chopper and a common filter wheel to minimize the physical size of the unit. The optical layout of each channel is represented in Figure 5. The basic lens system consists of a 2-inch diameter, f/2.5 objective lens followed

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*The Probeye infrared viewer is a commercially available unit manufactured by Hughes Aircraft Company.

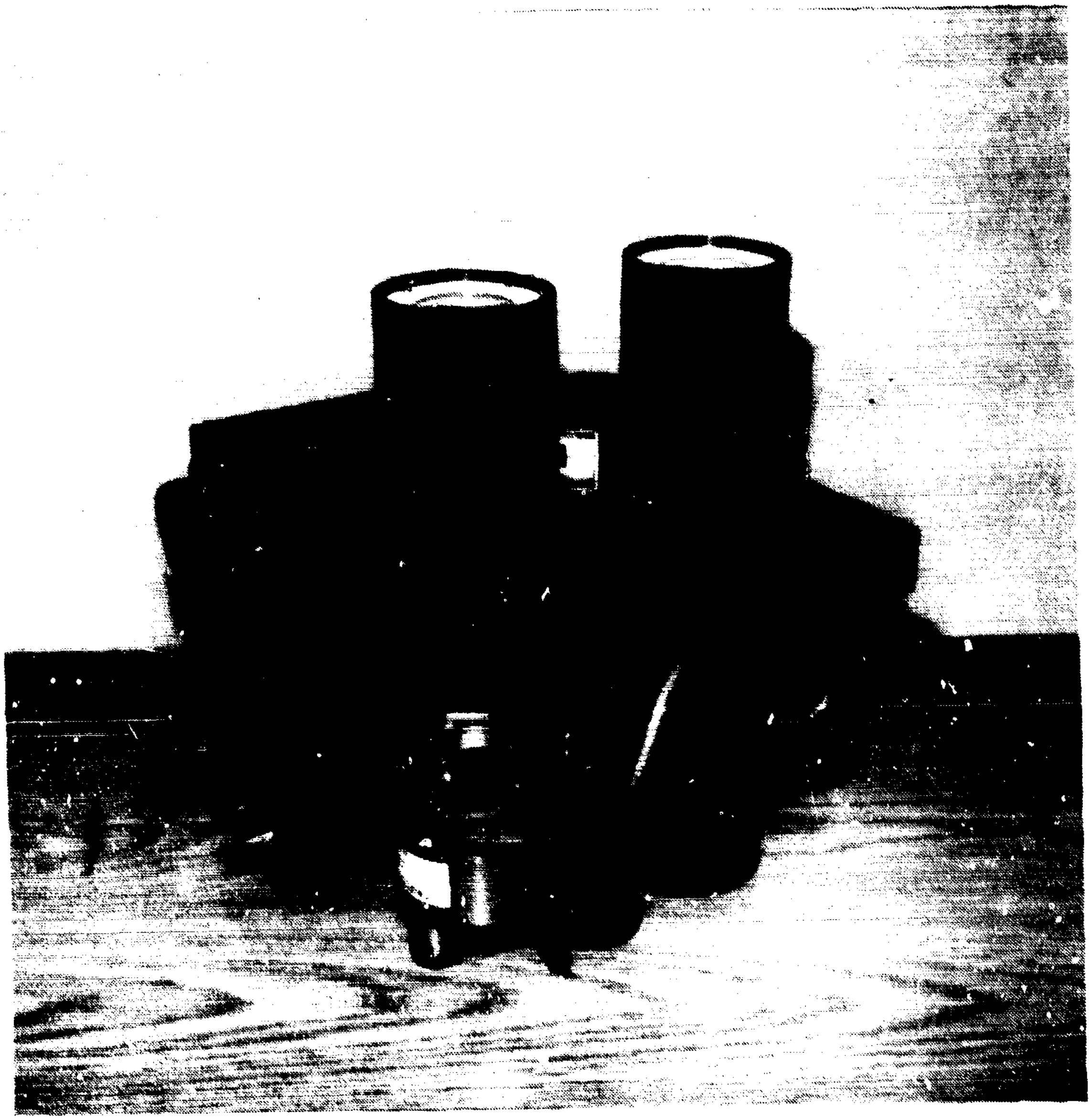

Figure 1. Dual channel NIR radiometer.

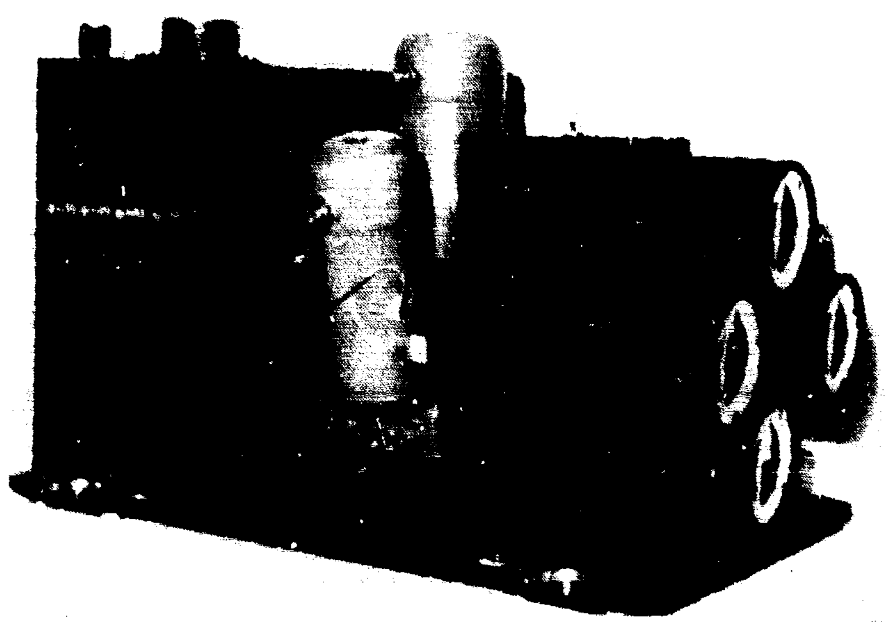

Figure 2. Four channel NIR radiometer.

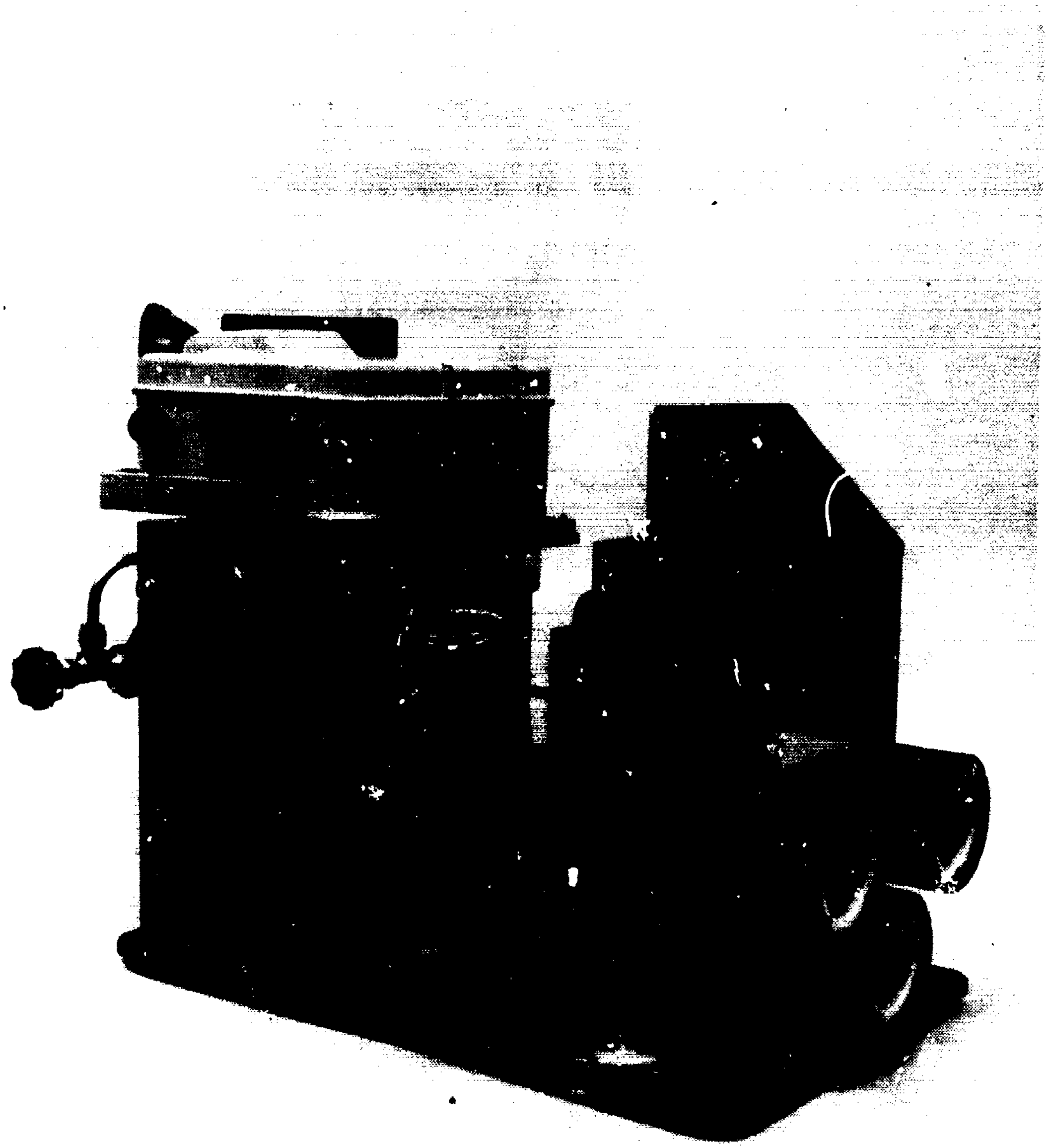

Figure 3. Three channel NIR radiometer with infrared image viewer.

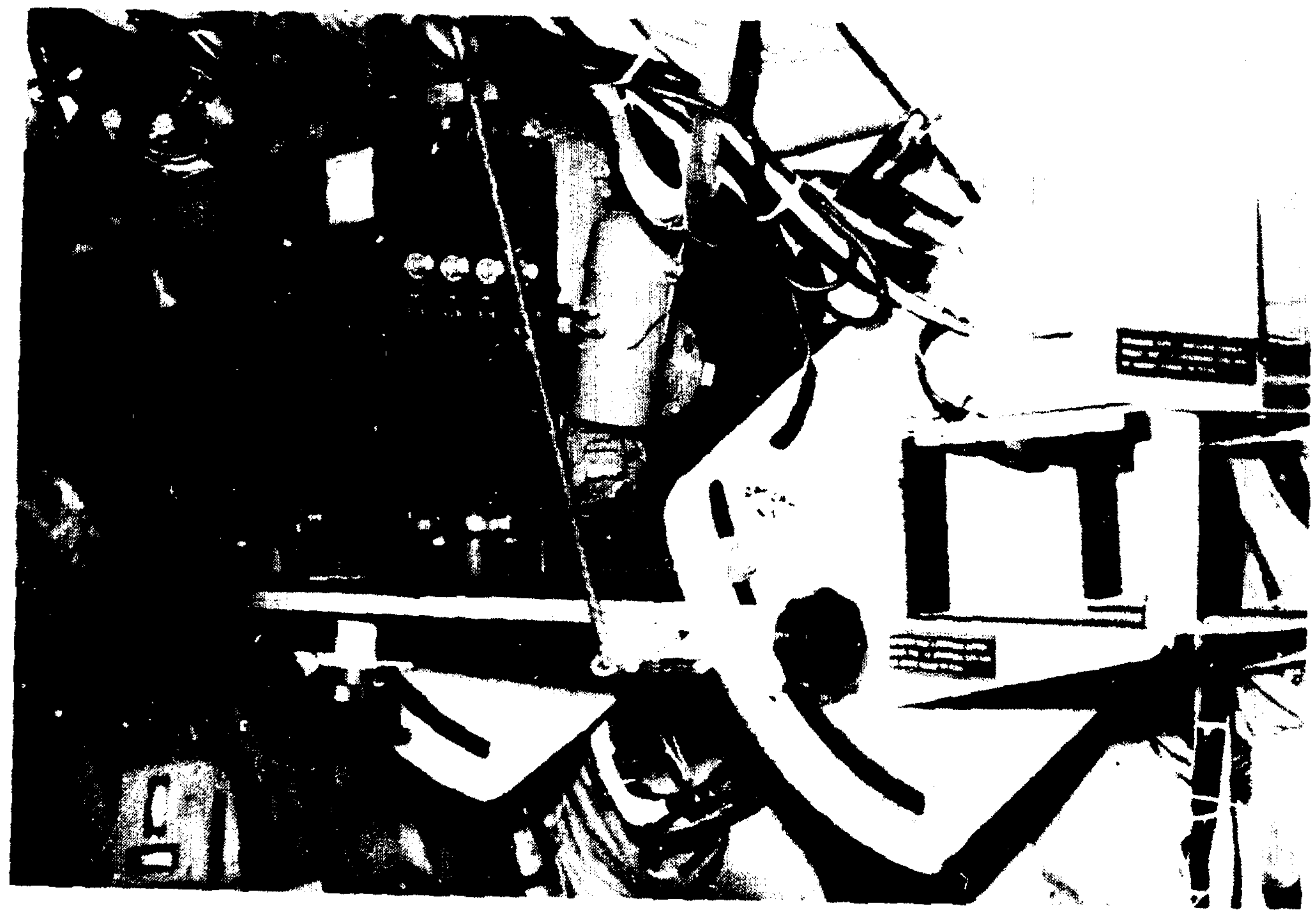

Figure 4. Multi-channel radiometer mounted on trackable aircraft-borne platform.

by a 1-inch diameter f/.7 field lens. The objective lens images point at infinity on the aperture plane which defines the field of view of the radiometer. Since the objective lens is relatively slow, its imaging properties can be made extremely good to guarantee a sharply defined field of view. However, the field lens does not require these same sharp imaging qualities, since its function is to collect the optical signal passing through the aperture and condense it onto a detector. As a result, the field lens can be made relatively fast which minimizes the required detector size and maintains a low equivalent f number for the optical system.

As shown in Figure 5, the radiometer design incorporates an optical chopper to modulate the signal. The chopper is located within .025 inches of the aperture plane. The standard chopper modulates the complete aperture on a fifty percent duty cycle basis; however, coded or reticle type choppers were typically used to define the aperture.

The reticle configuration is extremely useful for target emission measurements at wavelengths as long as 7 μm. The reticle system is designed to balance out the instrument thermal emissions and also bright uniform backgrounds. However, small infrared targets are not balanced out, and they are detectable with the radiometer.

A typical reticle chopper and aperture arrangement is shown in Figure 6. These parts replace the chopper and aperture shown in the optical layout presented in Figure 5. The chopper is constructed such that an equal and a constant amount of the aperture area is blocked and open at all times while the chopper is rotating. As a result, large uniform radiation sources which fill the field aperture opening are unmodulated when they reach the detector. Emissions reaching the detector from the chopper blade and instrument are also unmodulated, since they are also uniform and fill a constant area of the aperture at all times. However, a source will be completely modulated upon reaching the detector if its image size in the

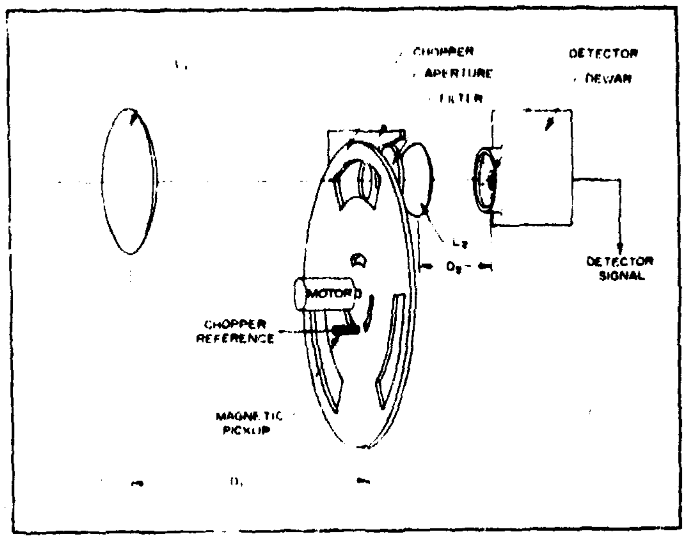

Figure 5. Optical layout of each radiometer channel.

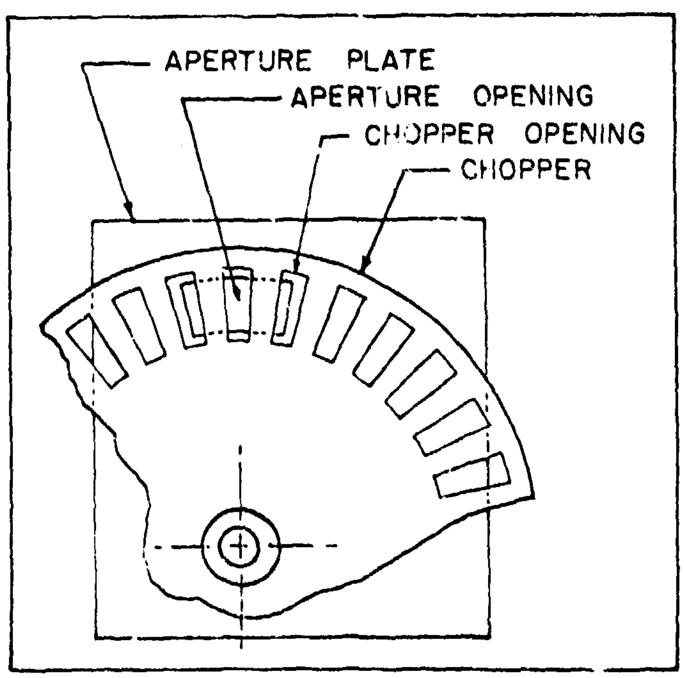

Figure 6. Typical reticle chopper and aperture plate.

focal plane of the objective lens is smaller than the size of the opening formed by one chopper blade opening and the aperture opening. These modulated signals are the only ones that are detectable with the radiometer, since the detector signals are synchronously demodulated with a vector phase-lock amplifier which extracts only modulated signals that are referenced to the chopper. These characteristics made the instrument very useful for the measurement of infrared targets such as airplanes and rockets.

The FOV of the radiometer channels can be tailored to the measurements needs by changing the reticle and aperture. Different reticle and aperture sizes were designed and used during the contract. Typically the instantaneous FOV of two channels of the radiometer were designed to be 2^{o} vertical by 4^{o} horizontal while the remaining one or two channels were designed to be 4^{o} vertical by 2^{o} horizontal. On occasion, a different reticle was used to change all the FOV's to $.5^{o}$ by $.5^{o}$.

The advantages of operating the radiometer with a reticle type chopper are many. However, the radiometer operating in the reticle mode has some practical limitations. In addition to the usual limitations of the detector's sensitivity and the qualities of the optical components, there are practical limitations as to what extent the reticle scheme can suppress or balance out the thermal emissions of the instrument and the extended bright backgrounds. If a reticle is carefully constructed and optically balanced, one can obtain as much as four orders of background suppression. With this suppression, the uncooled instrument is capable of measuring sources having spectral radiances as small as 10^{-8} watts/cm^2sr μm in the 4 to 5 μm range. At shorter wavelengths even lower intensity sources can be measured, while at longer wavelengths the instrument is more limited because of the increased instrument thermal emissions.

The NIR radiometer system has proven to be a valuable and reliable tool for extensive measurement programs. It was maintained and kept in a state of readiness for the entire contractual period. No major failures occurred as a result of the continual and comprehensive inspections, calibrations, and maintenance procedures which were followed. All electrical, optical and mechanical parts were inspected after each flight or monthly. Any marginal parts were immediately replaced or repaired. Calibrations were periodically performed to provide accurate absolute measurements of the various emission sources of interest. The procedures described by *Sandford et al.*, [1976] were used to perform these calibrations. The calibrations were primarily done in the laboratory, but a limited amount of secondary calibrations were done while airborne to give assurance that the instrumental characteristics were stable.

MAINTENANCE, CALIBRATION, AND MODIFICATION OF THE TYPE III INTERFEROMETER-RADIOMETER SYSTEM

The layout of the Type III interferometer-radiometer system is shown in Figure 7. As described by *Huppi* [1974], the interferometers or radiometers operate at ambient temperatures inside the aircraft while the chopper acts as a cold reference and provides a method for distinguishing between the source emissions and the thermal emissions of the aircraft and instrument structures. Three instruments can be operated simultaneously behind the three windows in the chopper assembly which mounts to the aircraft surface as shown in Figure 8.

The complete system including the chopper assembly, interferometers, and radiometers was periodically inspected, maintained, and kept in a state of readiness. Since AFGL elected not to fly the system during the contract period, no major replacement parts were needed; and only simple parts such as preamplifier battery packs were replaced.

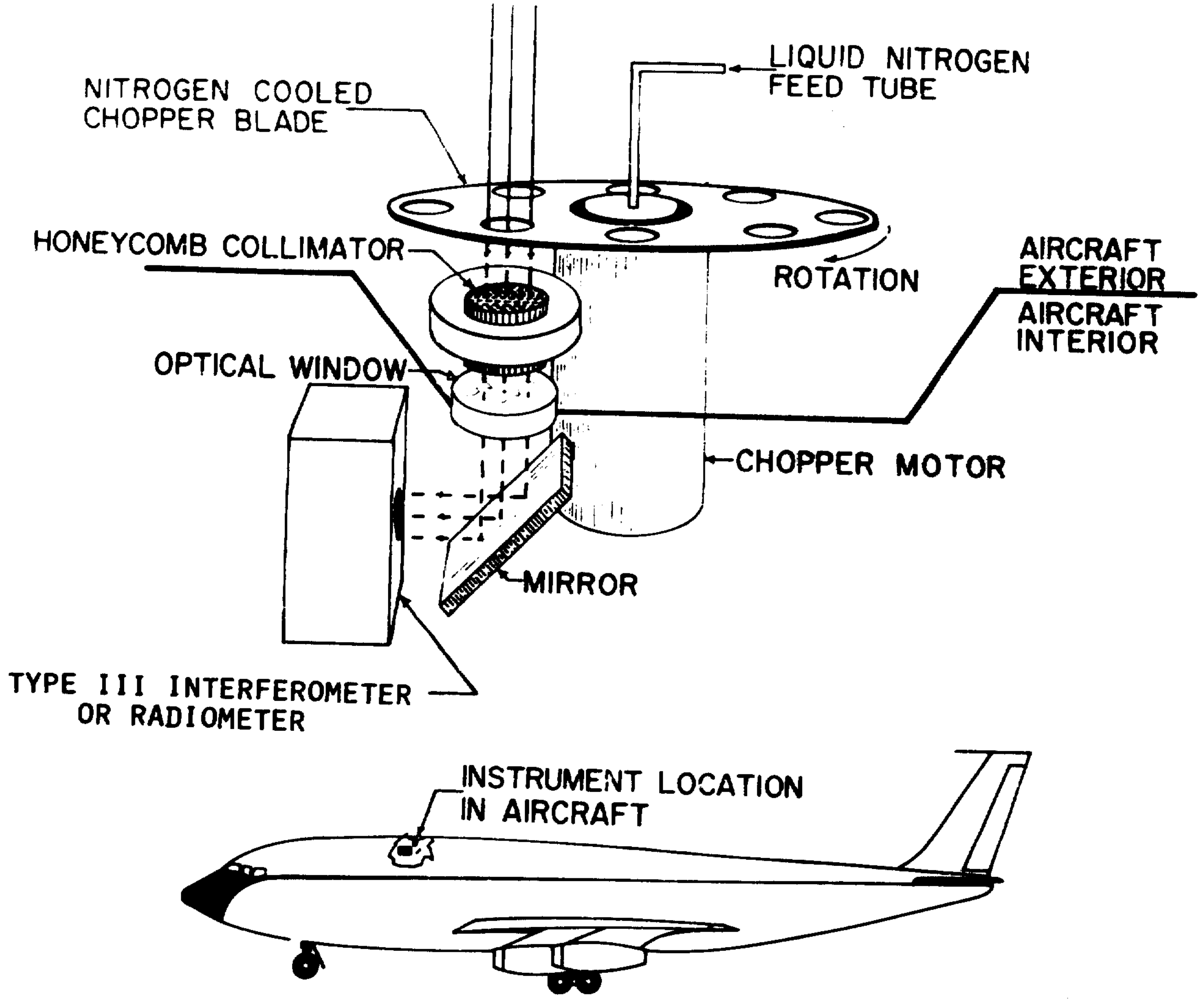

Figure 7. Liquid nitrogen cooled chopper and warm interferometer system.

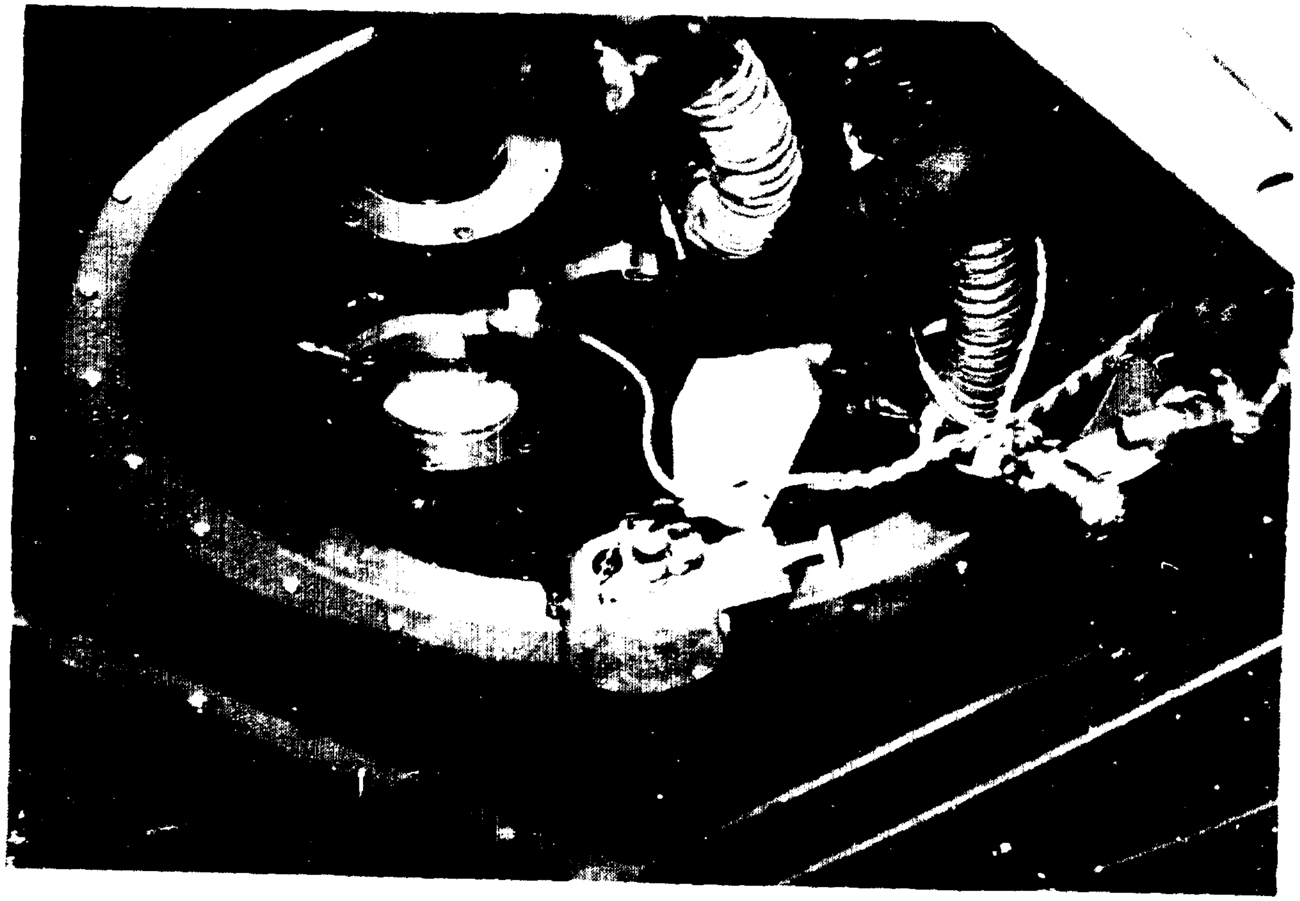

Figure 8. Cryogenically cooled chopper assembly mounted in the AFGL KC-135 aircraft.

The radiometer and interferometer components were calibrated in the laboratory using conventional techniques similar to those described by *Sandford et al.* [1976]. Typically, the calibrations were done using both a point source and an extended source to guarantee the accuracy of the procedures.

In addition to the calibrations of the radiometers and interferometers, the Type III system has an added calibration problem, since the instruments are operated behind the cold optical chopper and collimator system as shown in Figure 7. The attenuation of this chopper system must be determined if absolute values are to be placed on data measured through the system. The calibration is complicated by the fact that the attenuation of the collimator portion varies as a function of angle; and therefore, the throughput will vary when used with instruments having different fields of view. The best way to calibrate the attenuation effect of the collimator is to perform a measurement using an extended source, the chopper system, and the actual radiometer or interferometer which is to be used. This process was performed for a radiometer for three fields of view settings. The calibration set up is shown in Figure 9. As shown, a point source is chopped and sent into an integrating sphere. The sphere converts the point source to an extended source which is then measurable with the radiometer through the chopper system. During this process, the chopper blade is left in the open position. Then the chopper system is removed and the measurement is repeated. The ratio between the first and second measurement gives the integrated attenuation of the collimator and aperture for the specific field of view characteristics of the radiometer. Table 1 summarizes the attenuation of the chopper system for the three fields of view which were measured with a type III radiometer whose entrance aperture is partially vignetted by the chopper aperture. These values give a rough overview of typical attenuations that can be expected for a practical radiometer or interferometer for various fields of view. To

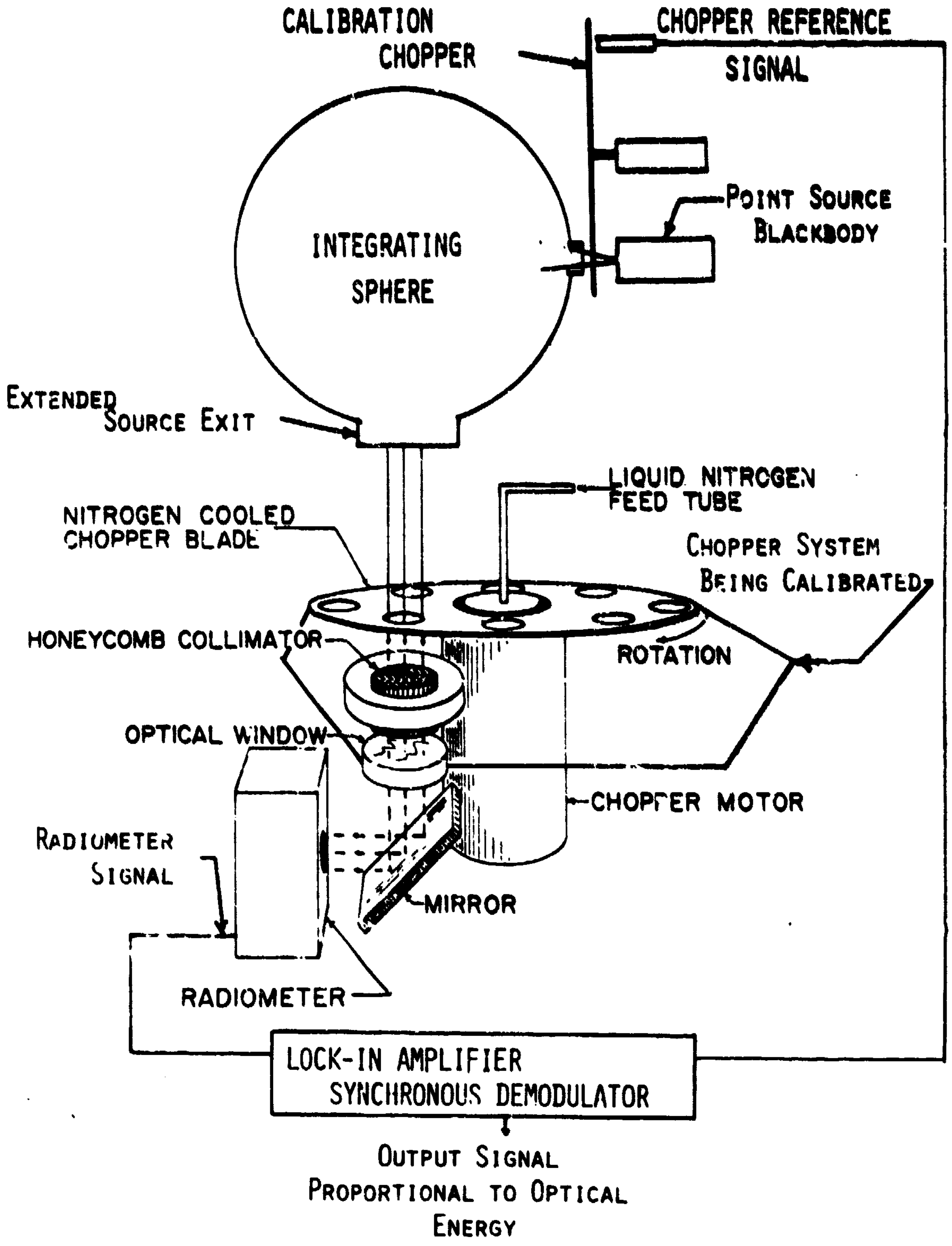

Figure 9. Calibration set up for the liquid nitrogen cooled chopper-collimator.

TABLE 1. OPTICAL TRANSMISSIONS OF THE LIQUID N_2 CHOPPER SYSTEM WITH Ca_2Fl AND GE-106 WINDOWS FOR VARIOUS FIELDS OF VIEW OF RADIOMETERS.

Field of View (Degrees)	Window Type	Measurement Wavelength (μm)	Window & Collimator Transmittance Unchopped (Percent)
10	Ca_2Fl	2.9	23.5
10	GE-106	2.9	19.1
5	Ca_2Fl	2.9	31.0
5	GE-106	2.9	28.7
2	Ca_2Fl	2.9	34.5
2	GE-106	2.9	31.0

complete the calibration of the chopper system, the above results must be multiplied by the chopping efficiency of the rotating chopper. This efficiency can be readily calculated from the geometry of the system. The actual chopper blade modulates the incoming radiation in an almost sinusoidal fashion and has an efficiency of about 40%. This is only slightly less than an optimum square wave chopper which has an efficiency of 50%.

The complexity of the calibration of the Type III chopper-collimator system and the sensitivity limitations of the warm instrument used with the system are undesirable features. This has led to investigations of the advantages and limitations of interferometer and radiometer systems which incorporate cryogenic cooling techniques to cool the instrument's optics, structures, and detectors. Scientific Report No. 2 by *Huppi and Steed* [1981] outlines the advantages, the limitations, and some typical characteristics of cryogenically cooled Fourier transform spectrometers. The report indicates that cooling an FT-IR interferometer-spectrometer can substantially improve its sensitivity, reduce or eliminate its unwanted background signals from self-emissions, and stabilize its optical alignment. As a result of the investigations it is suggested that the type III interferometer-radiometer system be modified or replaced by cryogenically cooled instruments.

Using recently developed and proven technology, cryogenically cooled interferometers and radiometers could readily be designed and constructed to operate in the aircraft. A cryogenically cooled radiometer system which has been developed and tested by USU for aircraft use is shown in Figure 10. The radiometer is made to operate in the AFGL KC-135 aircraft behind a cryogenically cooled window and baffle system which was initially developed by John Rex of AFGL and is shown in Figure 11. The window and baffle are mounted in the eyeball arrangement shown in Figure 12 which allows the optical axis to be rotated 25^{o} in any direction from the normal position.

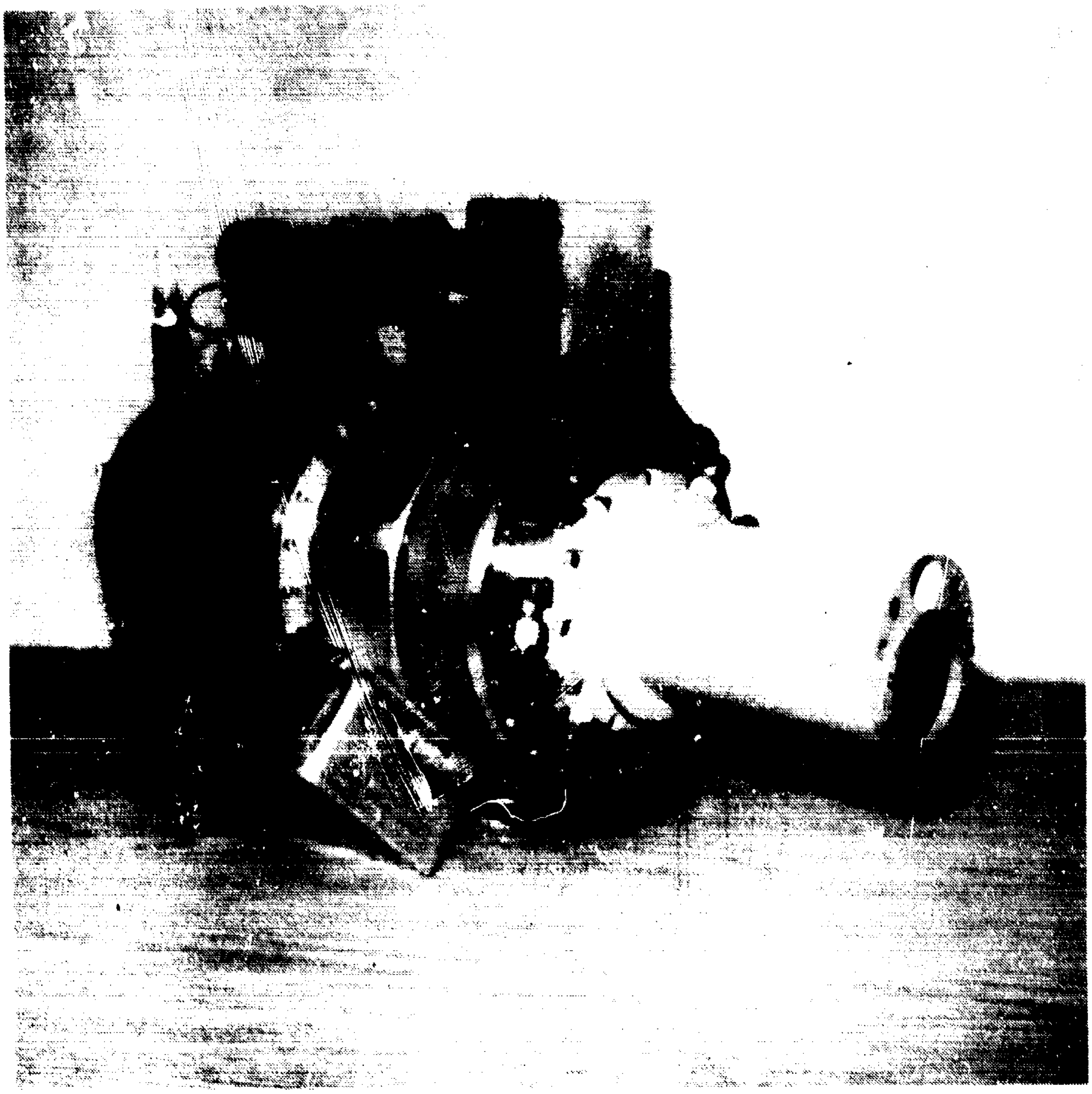

Figure 10. Cryogenically cooled radiometer developed for aircraft use.

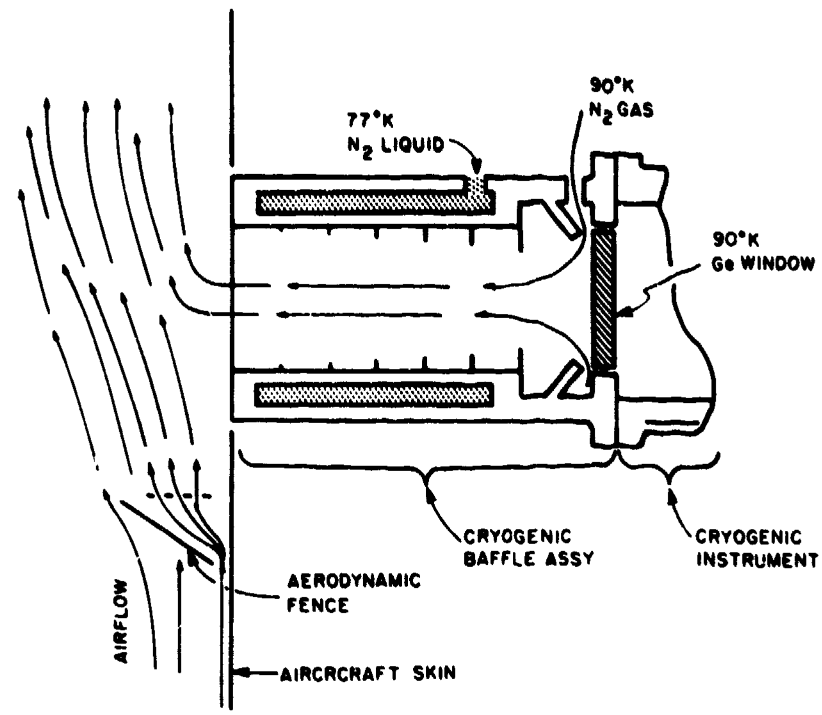

Figure 11. Aircraft-bo:ne cryogenically cooled window and taffle system.

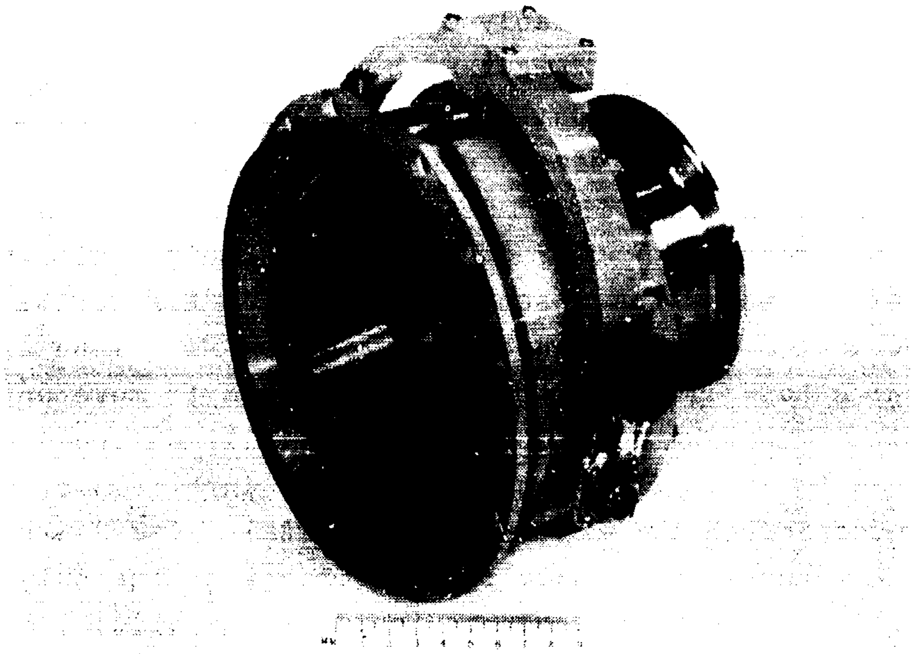

Figure 12. Trackable eyeball mount.

A photograph of the radiometer and mounting configuration is shown in Figure 13. The basic infrared optical system is shown in Figure 14. The detector, the lens system and the radiometer structures are all cooled to 77°K by conduction from a LN_2 cold finger. The entrance window and the baffle are also cooled with LN_2, and they are defrosted with gaseous N_2 which boils off of LN_2. Actual temperature measurements on the window and baffle system during a flight indicate that temperatures between 77°K and 87°K can be maintained, and no frosting occurs. This completely cold radiometer and window system operates very reliably over long periods of time, and it can be tracked on a target with a visible sighting scope. Thus, it would appear that it is an ideal system for measurements of the type performed for TEAL RUBY and other similar programs.

A pictorial view of a cryogenically cooled interferometer-spectrometer and dewar assembly is shown in Figure 15. The interferometer uses a standard flat mirror Michelson arrangement which has a flex-pivot drive mechanism to move one mirror. The drive mechanism is of the type initially designed by John Rex of AFGL. Cryogenic operation of the interferometer has been accomplished by *Kemp and Huppi* [1980]. The dewar system, shown in Figure 15, is made to interface with the cold window and baffle system described previously. Vibration isolation for the interferometer is accomplished external to the dewar through the use of Berry mounts and a large flexible bellows. The bellows and mounts respectively isolate the main part of the dewar from the eyeball assembly and the aircraft structures. Additional vibration isolation of the interferometer is obtained inside the dewar through the use of a flex-pivot mounting arrangement. The interface of the interferometer dewar to the eyeball arrangement enable the complete unit to be tracked or aimed at sources. Thus, if the Type III interferometer system were replaced with one of these cryogenically

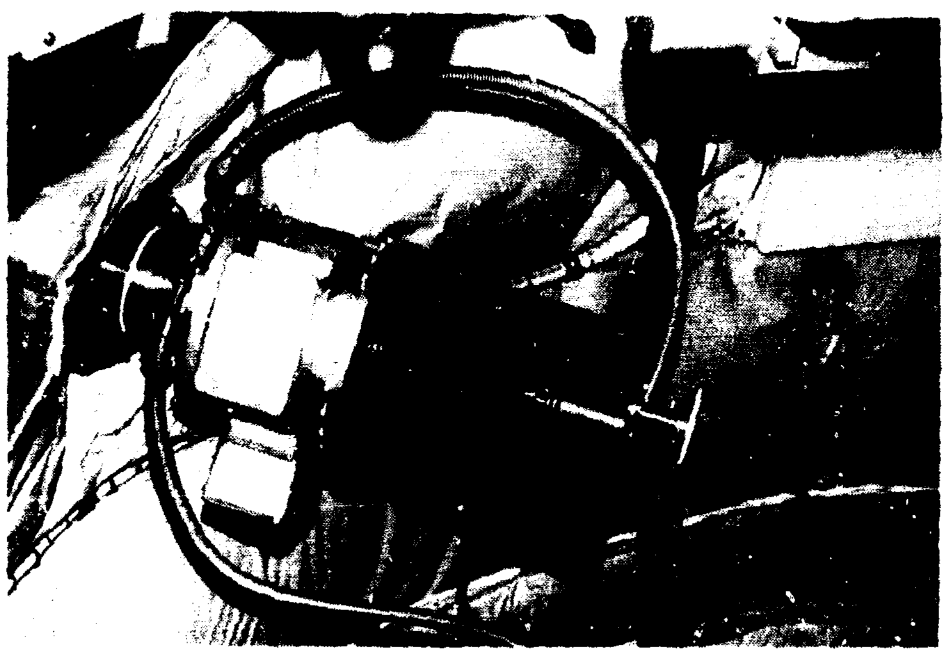

Figure 13. Cryogenically cooled radiometer mounted in the aircraft.

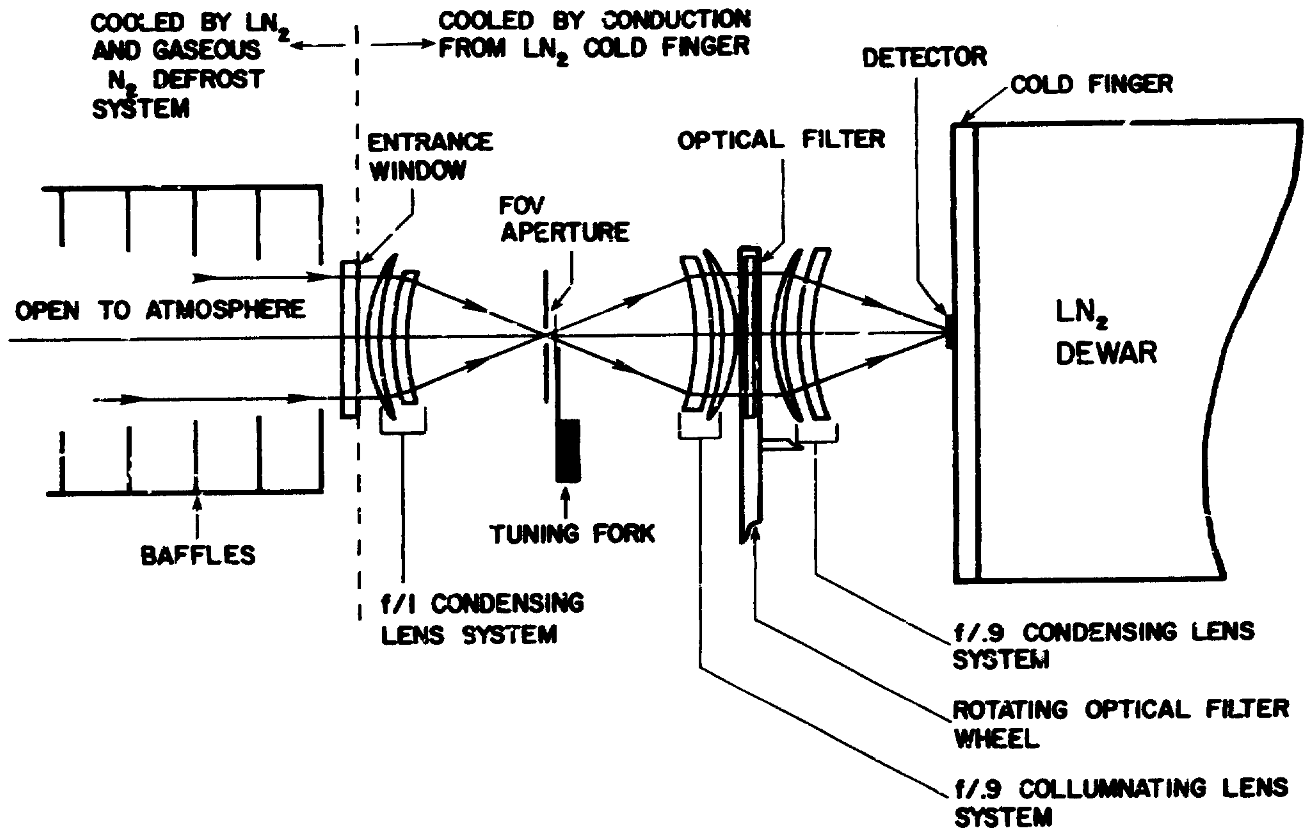

Figure 14. Optical layout of a cryogenic radiometer for aircraft use.

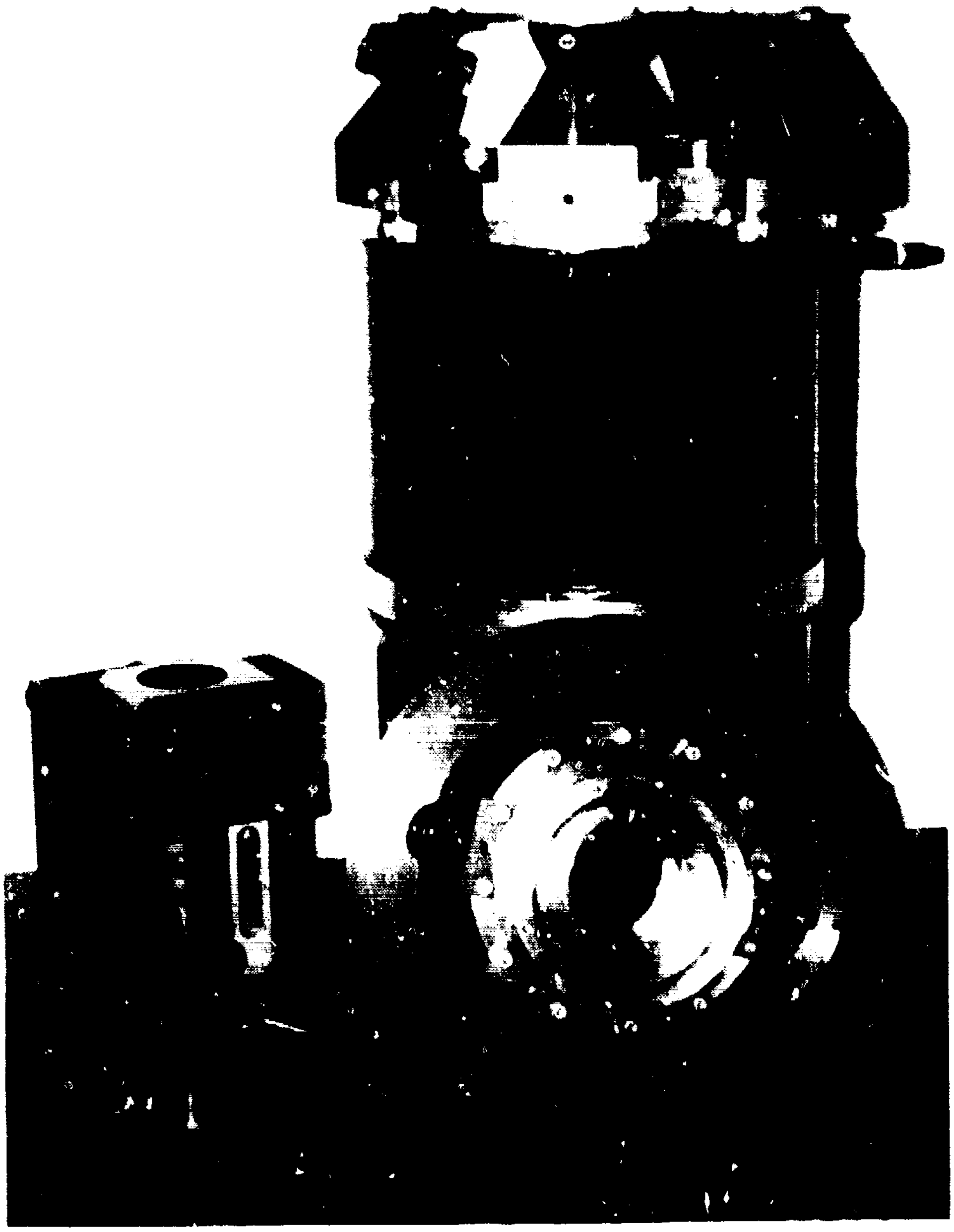

Figure 15. Cryogenically cooled interferometer-spectrometer and dewar assembly for aircraft use.

cooled units it could be used for measuring target emissions as well as atmospheric aurorae and airglow emissions.

REDUCTION AND ANALYSIS OF 1.7 μm AND 2.9 μm AURORAL MEASUREMENTS

Significant infrared emission enhancements in a spectral band centered at 2.94 μm (2.84-3.04 μm) have been measured from the AFGL KC-135 aircraft with the Type III radiometer system while viewing an aurorally enhanced atmosphere. The measurements were made as part of the 1976 DNA/AFGL ICECAP program by *Huppi and Reed* [1977]. The 2.94 μm enhancements are spatially and temporally correlated with aurorally induced enhancements of the N_2^+ first negative band at 3914A. The measured 2.94 μm enhancements are superimposed on a slowly varying background emission which even exists at times when the atmosphere is not excited by aurora. *Huppi and Reed* [1977] postulate that this background is mainly chemiluminescence from hydroxyl (OH) fundamental airglow chemistry. However, this OH chemiluminescence is not a feasible source of the measured 2.94 μm enhancements, since corresponding enhancements are not seen in the OH overtone (5,3) and (6,4) bands as monitored by a coaligned 1.7 μm (1.66 - 1.74 μm) radiometer. A more feasible source of the enhancements, postulated by *Stair et al.*, [1975], is chemiluminescence generated by nitric oxide (NO) first overtone ($\Delta V = 2$) chemistry.

As part of this contract, investigations of the 2.94 μm background and the enhancement emissions were performed and reported by *Schummers and Huppi* [1979] in Scientific Report No. 1. Consideration was first given to the source producing the slowly varying background. Calculations were performed showing that OH fundamental emissions can completely account for the measured background levels. Assuming that the OH fundamental emission intensities are directly and temporally correlated with the OH overtone emissions as monitored at

1.7 μm, an experimental method for separating or removing the postulated OH background from the auroral enhancements was applied to the 2.9 μm data. The experimental results, based on the actual measurements, verified that the calculated OH predictions are feasible. Once the background was subtracted from the data, magnitude and temporal comparisons were made between the enhancements occurring at 2.94 μm and 3914A. Figure 16 and Figure 17 show samples of the measured data and some of the comparisons. The comparisons indicate that the auroral enhancements at 3914A and 2.94 μm are closely correlated. Assuming that the 2.94 μm enhancements are chemiluminescence from NO chemistry and using the 3914A emissions as a monitor of the total auroral energy, the percentage of the total auroral energy which was emitted as NO photons (photo-energy efficiency) was calculated for seven measurement periods. The results are tabulated in Table 2. As shown in the table, the photo-energy efficiency varies significantly from one auroral event to another. Presently, it is postulated that these variations are due to altitude dependencies of the reaction relative to variations in auroral penetration.

INFRARED MEASUREMENTS OF AIRCRAFT EMISSIONS AND REFLECTIONS

Infrared emissions generated or reflected from various aircrafts during flight were monitored with the NIR radiometer system operating in a three or four channel configuration from the AFGL NKC-135 flying laboratory. Up to twelve selectable spectral bands in the 2.5 to 7.5 μm range were monitored on each aircraft, as defined by *Sandford et al.* [1976]. Time histories of the irradiances of the aircraft sources were measured for various power increases, power decreases, fixed power settings and aircraft maneuvers. Absolute irradiance numbers were obtained for the various power conditions. Specific radiometric measurements and supporting comparisons with the data from the AFGL interferometer-spectrometer and

TABLE 2. PHOTOENERGY EFFICIENCIES OF AURORALLY EXCITED OVERTONE NO EMISSIONS

Date	Time	Ratio $\frac{2.9\ \mu m\ \text{Radiance (kR)}}{3914A\ \text{Radiance (kR)}}$[a]	Ratio $\frac{\text{Photons (NO)}}{\text{Photons (3914A)}}$[b]	% of Auroral Electron Energy Radiated as NO Overtone Photons
7 March 1976	1000-1030	3.0	7.5	0.54
7 March 1976	1120-1150	3.0	7.5	0.54
26 March 1976	1010-1040	5.2	13.0	0.93
26 March 1976	1120-1150	4.3	10.8	0.77
26 March 1976	0905-0935	4.3	10.8	0.77
8 March 1976	0730-0800	3.3	8.3	.59
3 March 1976	0500-0530	2.3	5.8	.41

[a]The measured 2.9 μm enhancement occurring within the spectral bandpass of the instrument which includes only a portion of the complete NO band.

[b]The total photons emitted from the complete NO overtone band which is determined by scaling the measured 2.9 μm radiance by an appropriate factor based on a synthetic NO model.

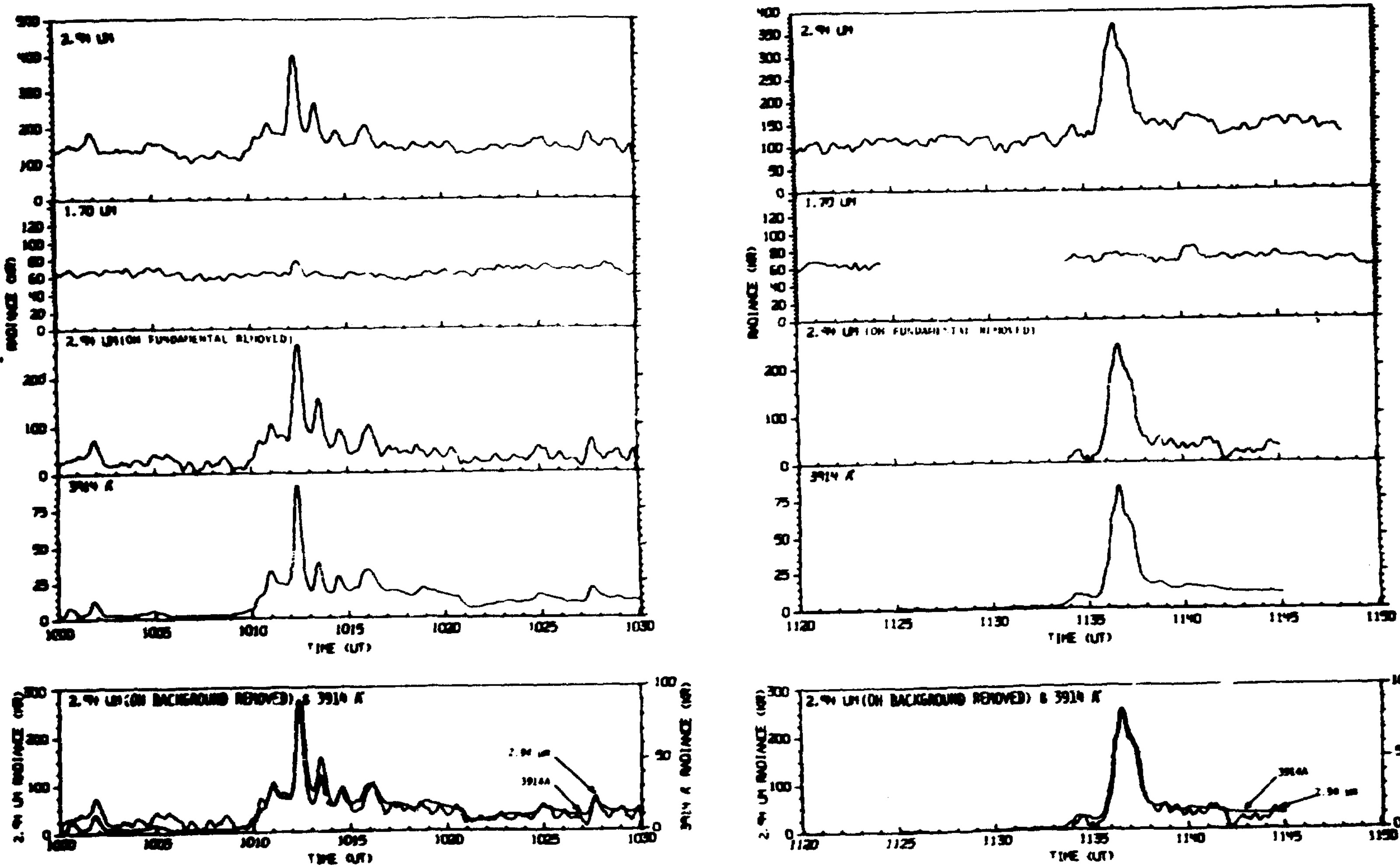

Figure 16. Comparison of 2.9 μm enhancements and 3914A N_2^+ emissions for data measured 7 March 1976.

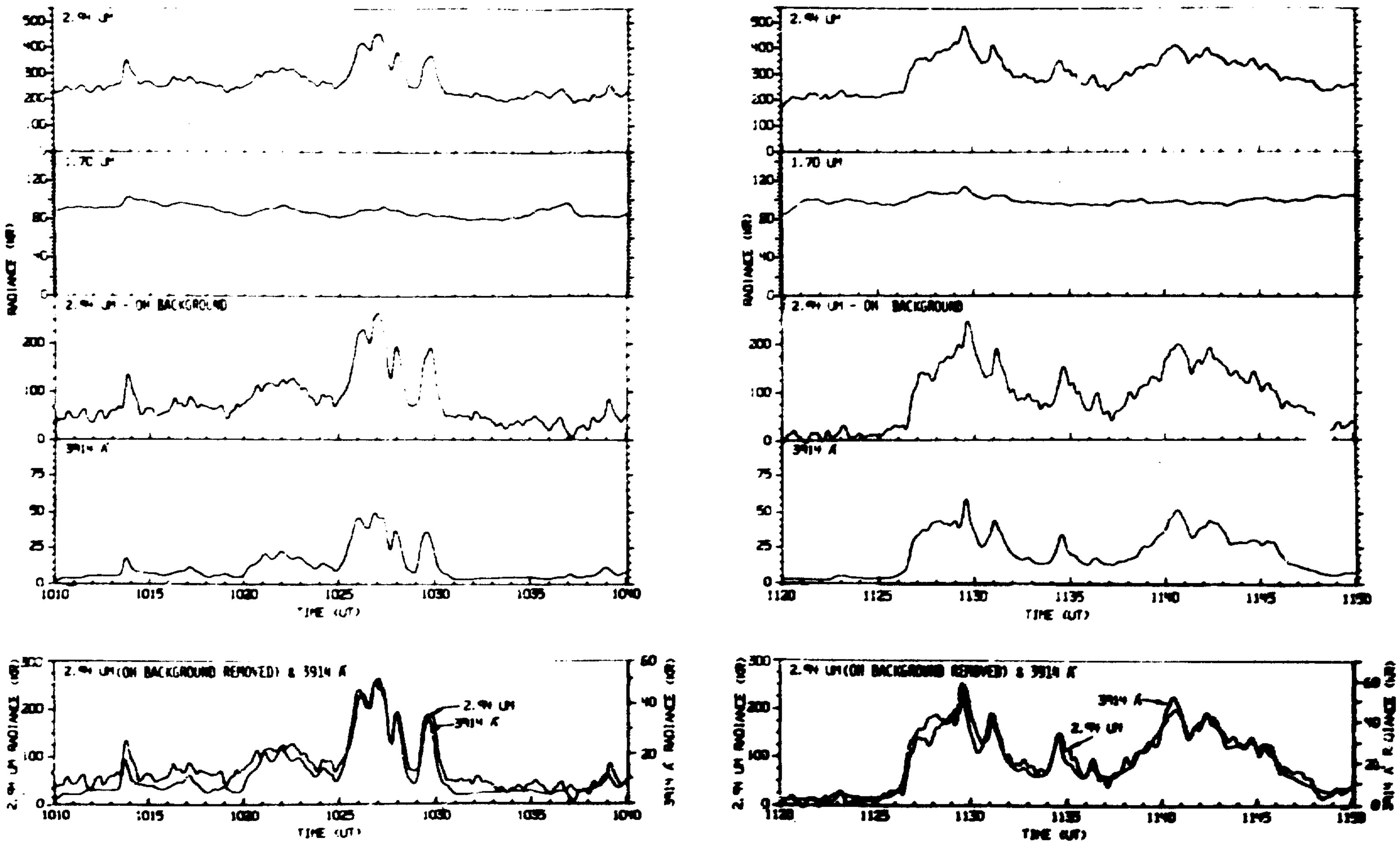

Figure 17. Comparison of 2.9 μm enhancements and 3914A N_2^+ emissions for data measured 26 March 1976.

the thermal spatial scanners have been presented in a series of AFGL reports co-authored with Brian Sandford and his associates. The radiometric data and the results of the comparisons are reported as direct contributions to the appropriate chapters of the reports.

The comparisons between the radiometric data and the interferometric data were accomplished by integrating the measured interferometric spectra over the spectral passbands of the radiometer. As presented in the AFGL reports, the radiometer measurements and interferometer measurements are in good agreement.

SPATIAL INFRARED MEASUREMENTS

A large amount of spatial infrared measurements were taken of backgrounds and airborne vehicles with the AFGL Norelco spatial mapper system. The measurements were made from the AFGL NKC-135 aircraft. USU supported the measurements by supplying personnel to track the instruments and to operate the control consoles during many data gathering missions.

A significant amount of data reduction and analysis were performed on the collected data using a Hewlett-Packard Model 21MX computer-analyzer system. The reduction and analysis procedures which were developed and followed enable the data to be presented in various calibrated formats. The basic procedures involved in the analysis of the data are described in the following paragraphs.

The first step is to assess the data. It is necessary to determine what scene was being viewed as a function of time and which bandpass filters were used during the data collecting runs. This is done by monitoring various housekeeping functions and the voice information on the recorded data tapes. Using this information, the time intervals of interest can be defined. The computer can then be commanded to digitize several infrared pictures and store them on a digital disc memory. Once a large number of pictures have been digitized, they are displayed on the pictorial display device. By careful examination of each digitized picture, individual pictures can be selected for further processing, or in cases where the scene is stationary for several frames, the pictures can be averaged for better signal to noise levels and then further processed.

The next step is to eliminate or minimize any distortions introduced by the measurement system. The most important distortions introduced into the data are caused by the ac coupling of each detector in the instrument before the detectors are multiplexed together to form the analog video signal. This ac coupling is used to reduce the large amount of low frequency noise produced by the detectors, but it also eliminates the low frequency structure in the pictures. In the most general situation, the low frequencies cannot be re-inserted into the data; but under many circumstances, the appropriate low frequency signals can be assumed known, and higher frequencies boosted to compensate for the attenuation by the instrument. Other types of distortions can also exist due to the ac coupling. Since each detector is ac coupled independently the average level can shift due to differences in the scene from detector to detector, but if all detectors can be forced to agree in that region and thereby reduce the offsets in average level between detectors. If large noise spikes occur in certain spots, the picture can be filtered in small regions to eliminate or reduce the noise.

The remaining procedures to be applied to the data involved calibration and display. Once the response of each detector is known for each bandpass filter that was used, calibration of the data frame is reasonably straight forward. One difficulty arises when the filter passband is not flat and the spectral energy distribution of the source across the band is not uniform. The reduction programs were written to allow a spectral calibration to be used with an input spectral energy distribution, but in many cases the detailed spectral characteristics of the calibration and the incoming energy are not accurately known. In these cases, appropriate assumptions have to be made. One of the most difficult problems encountered was to obtain calibrations of the detectors that were repeatable and stable with time. Many erroneous calibrations were performed due to high background levels that were not subtracted out, measurement procedures that were inadequate, or calibration signals that were not the necessary size and shape. These problems have been sorted out and accurate calibrations can now be made.

The last step of reducing the data concerns storage and display of the corrected and calibrated pictures. Storage is important since many pictures are analyzed and comparisons between many pictures are desired. The storage problem was solved by giving each file a name that described its type, i.e., data or calibration, the bandpass filter used, and the time of measurement, and then storing it on the disc file storage area. Each picture can then be recovered, further processed or displayed at any time. An adequate display of the final results is a critical part of the analysis as well, since a proper type of display is necessary to pass the information on to the user. Calibrated pictorial displays, contour plots and perspective plots are some of the display methods currently used.

The analyzed spatial data has been reported in co-authored reports published by the Air Force Geophysics Laboratory.

SCIENTIFIC AND OPEN LITERATURE REPORTS

The data measurements, the data reduction, and the instrumentation work performed for this contract led or contributed to several reports. The reports are published as AFGL scientific reports or as open literature reports. Quarterly status reports were also written but were not formally published.

The following is a listing of the reports published by Utah State University.

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