AD-A058 266 AIL DEER PARK N Y F/G 17/5

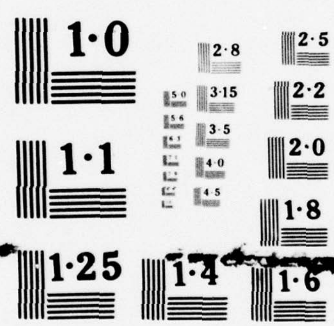
2.8 MICRON INFRARED HETERODYNE RADIOMETER.(U)

JAN 78 D YUSTEIN, J WOLCZOK, R LANGE F29601-76-C-0045

UNCLASSIFIED AFWL-TR-77-66 NL

1 OF 1
ADA
058266

END
DATE
FILMED
11-78
DDC



NATIONAL BUREAU OF STANDARDS

AFWL-TR-77-66

DDC

AFWL-TR-
77-66

LEVEL II

ADE200130

ADA058266

2.8 MICRON INFRARED HETERODYNE RADIOMETER

AIL, Div. of Cutler-Hammer
Deer Park, Long Island, NY 11729

January 1978

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

This final report was prepared by the AIL, a division of Cutler-Hammer, Deer Park, Long Island, New York, under Contract F29601-76-C-0045, Job Order 33260916 with the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico. Capt Terrence F. Deaton (ALO) was the Laboratory Project Officer-in-Charge.

When US Government drawings, specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Office of Information (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Terrence F. Deaton

TERRENCE F. DEATON
Capt, USAF
Project Officer

FOR THE COMMANDER

James D. Dillow

JAMES D. DILLOW
Lt Col, USAF
Chief, Advanced Beam Control Branch

Armand D. Maio

ARMAND D. MAIO
Lt Col, USAF
Chief, Advanced Laser Technology Division

DO NOT RETURN THIS COPY. RETAIN OR DESTROY.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFWL-TR-77-66	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): 2.8 MICRON INFRARED HETERODYNE RADIOMETER	5. TYPE OF REPORT & PERIOD COVERED: Final Report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): D. Yustein, R. Lange, J. Wolczok	8. CONTRACT OR GRANT NUMBER(s): F29601-76-C-0045
9. PERFORMING ORGANIZATION NAME AND ADDRESS: AIL, a Division of Cutler-Hammer, Deer Park, Long Island, New York 11729	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62601F 3326
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Weapons Laboratory (ALO), Kirtland Air Force Base, New Mexico 87117	12. REPORT DATE: January 1978
	13. NUMBER OF PAGES: 28
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Infared
Heterodyne Radiometry
Optical Mixing
Solar Radiometry

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

A gain modulated, Dicke switched Infrared Heterodyne Radiometer (IHR) has been designed, developed, and tested which is capable of measuring the atmospheric absorption characteristics within a 200 MHz bandwidth about selected hyrdogen fluoride (HF) laser transistions between 2.7 and 3.1 micrometers.

The IHR has been installed in a KC-135 test aircraft. Provisions for remote control and remote calibration were incorporated into the radiometer.

DD FORM 1473, 1 JAN 73 — EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) times 10 to the -19th power

The heterodyne receiver sensitivity (NEP) of the IHR is 1.3 $\times 10^{-19}$ W/Hz and the calculated temperature resolution $\left(\Delta T_S/T_S\right)$ is given for a variety of source temperatures and total transmittances (α).

alpha

delta T sub S / T sub S

TABLE OF CONTENTS

SECTION I

INTRODUCTION

The objective of this program was the design, development and construction of a gain modulated, Dicke switched Infrared Heterodyne Radiometer (IHR) which is suitable for the measurement of the atmospheric absorption characteristics at the hydrogen fluoride (HF) laser wavelengths.

The vertical path atmospheric transmission at selected CO_2 laser transitions have been reported for ground-based (ref. 1 to 3) and airborne (ref. 4) infrared heterodyne radiometers. Ground-based IHR measurements at HF and DF laser transitions have also been reported (ref. 5). An IHR has been developed and tested which is designed for use as an airborne platform and is capable of measuring received solar radiation within a 200 MHz bandwidth about selected HF laser transitions.

The solar flux will be measured at several laser wavelengths between 2.7 and 3.1 microns using the IHR. These data will then be used to derive the absorption coefficients at various altitudes in the atmosphere for each of these laser wavelengths. During the development of the IHR, consideration was also given to the feasibility of airborne operation with the DF and the CO lasers at 3.8 and 5.0 μm, respectively.

The IHR optical package (figure 1) has been designed for remote operation because of the limited instrument accessibility

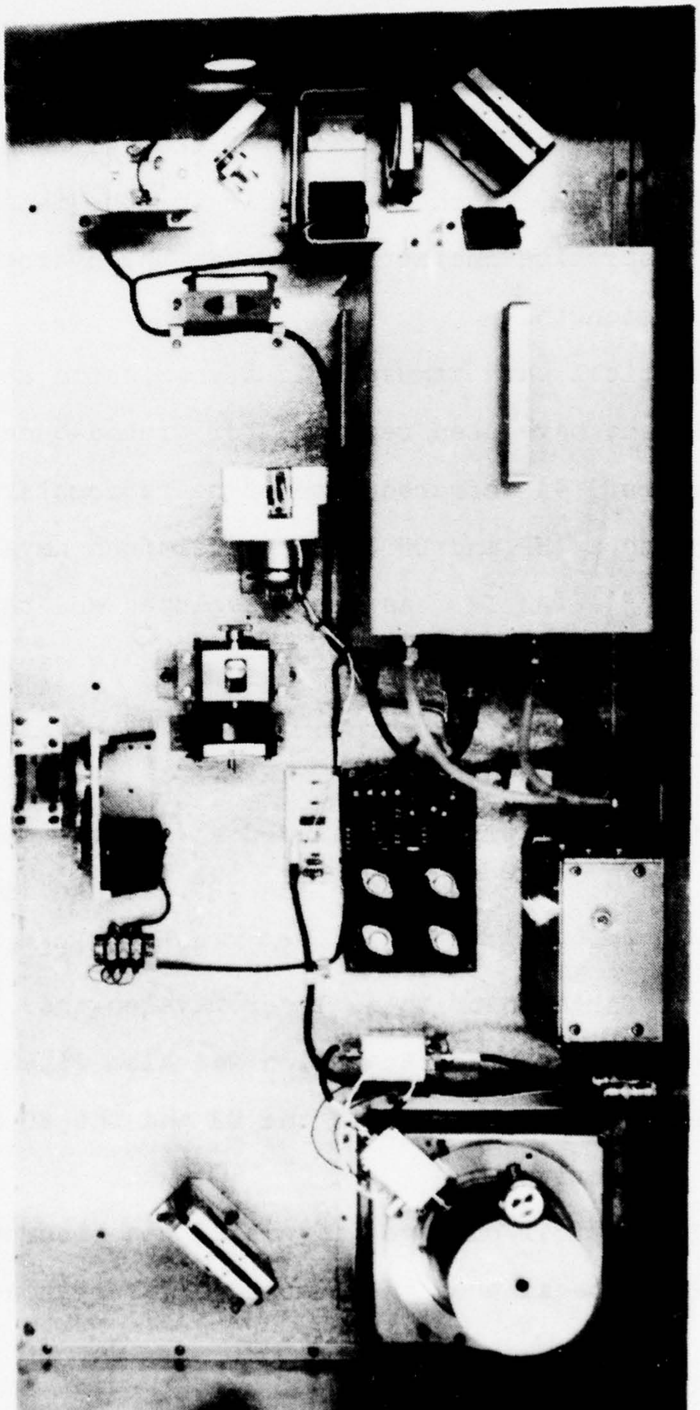


Figure 1. Top View of the 2.8 Micron Infrared Heterodyne Receiver Unit.

which is available when the instrument is mounted in a KC-135 military aircraft. A ruggedized cryogenic dewar, an RFI interconnection network, a remotely controlled calibration network and a processing radiometer with an analog/digital output has been incorporated into the IHR.

SECTION II

INFRARED HETERODYNE RADIOMETERS

General: A Dicke-switched IHR using IF gain modulation was designed, developed and fabricated. The IHR package includes: (1) a photovoltaic InSb infrared mixer element, (2) a diffraction limited infrared collection system, (3) an infrared Dicke switch, (4) a calibration subsystem which uses a 1900 K blackbody source, and (5) a radiometric processing back-end.

Using the IHR, high resolution infrared radiometric measurements can be carried out that are unachievable using conventional direct detection techniques. The predetection electronic (IF) bandwidth of 100 MHz establishes the instantaneous infrared bandwidth of the IHR (6.7×10^{-3} cm^{-1}) and still finer spectral resolution is achievable by using narrower IF filters.* The IHR spectral resolution is two to three orders of magnitude finer than is presently obtainable with conventional spectroscopic techniques and permits evaluation of fine grain structure of thermal emission-absorption spectra. In addition, infrared vibration-rotation signature lines which overlap the laser local oscillator transition can be remotely examined.

The basic arrangement of the IHR instrument, shown in figure 2, includes optics for the collection of solar radiation, a Dicke switch, optical elements for relaying the infrared radiation to a photomixer,

*The IHR specificity will be ultimately limited by the frequency stability of the laser LO.

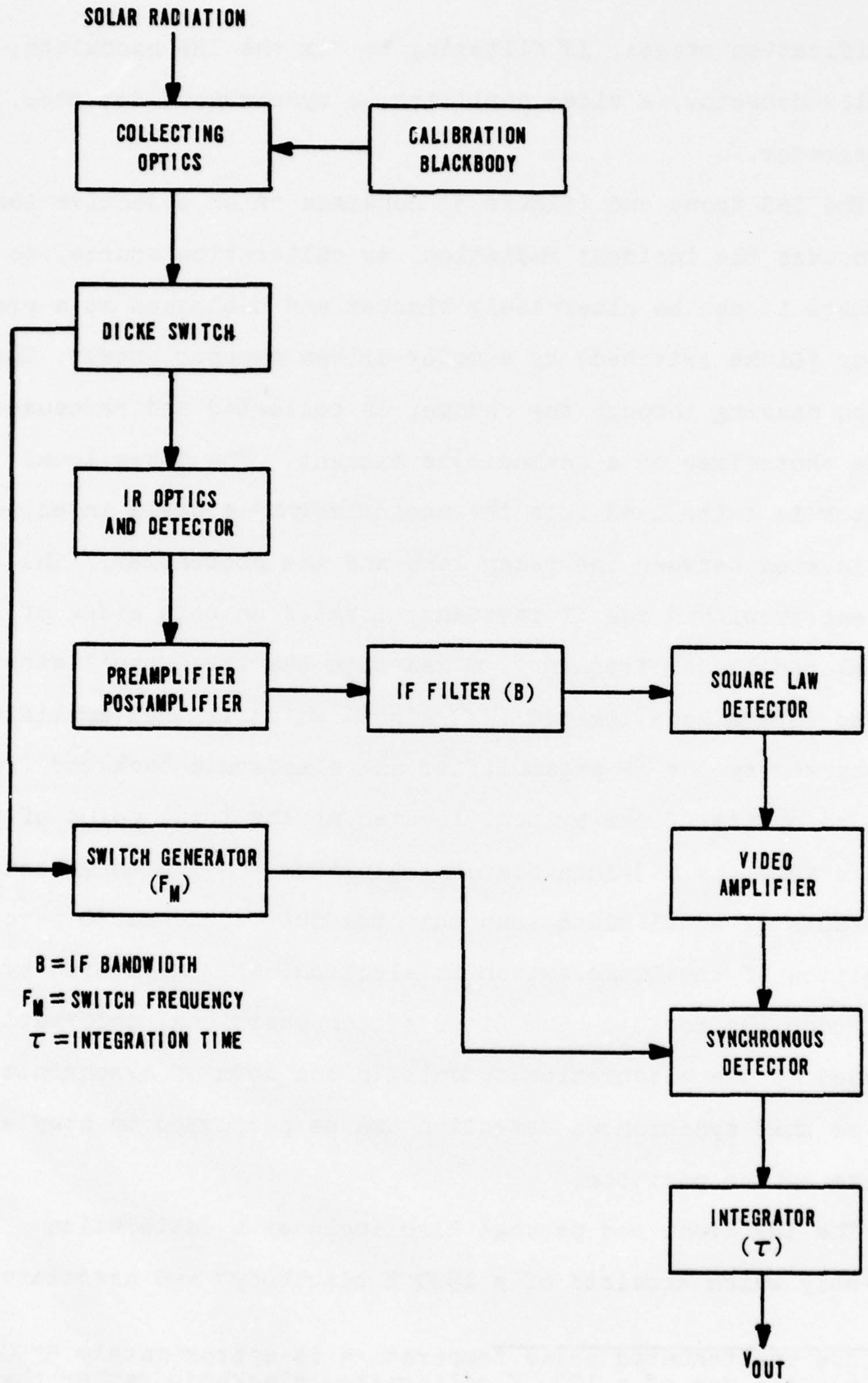


Figure 2. Block Diagram of Infrared Heterodyne Radiometer

IF amplification stages, IF filtering to fix the IHR bandwidth, a square law detector, a video amplifier, a synchronous detector, and integrator.

The IHR front end (figure 3) consists of an objective lens which focuses the incident radiation, or calibration source, to a plane where it can be alternately blocked and unblocked at a preset frequency (Dicke switched) by a motor driven chopper wheel. The radiation passing through the chopper is collected and refocused onto the photomixer by a second lens element. The laser local oscillator is introduced into the photomixer by a small injection mirror located between the relay lens and the photomixer. The source energy within the IF passband, located on both sides of the local oscillator frequency, mixes with the local oscillator energy to form a band limited (IF) signal which is then amplified and processed by the IF preamplifier and electronic back-end (ref. 1).

The optical Dicke switch, located at the focal point of the objective lens, is a 3-inch diameter aluminum wheel with 20 equally spaced slots of equal width such that the duty cycle is 50 percent. The position of the Dicke switch is electronically monitored by an optical coupling device. The Dicke switch positional information is relayed to the electronics console in the form of synchronizing pulses so that synchronous detection can be performed in step with the Dicke switch position.

The IHR front end package also includes a calibration subassembly which consists of a 1900 K blackbody* and associated

*Since the unattenuated solar temperature is approximately 5750K (ref. 6), the use of a 1900 K calibration blackbody rather than a lower temperature source will permit improved IHR resolution.

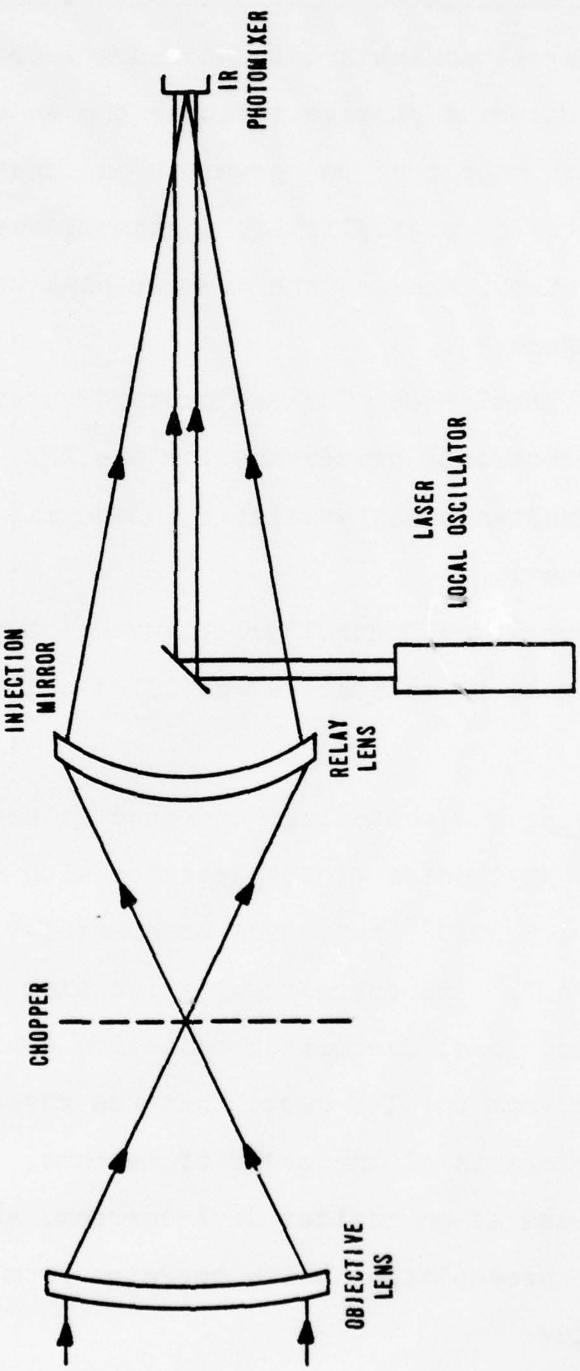


Figure 3. Simplified Schematic of IHR Optical Train

optics. The configuration of the radiometer allows the operator to replace the collimiated input beam with a matched beam from the 1900 K blackbody as an ambient temperature source.

The electronics package includes the Heterodyne Radiometer Controller which supplies: (a) power to all the motorized components, (b) ±15 volts to the preamplifier, postamplifier and synchronous detection circuitry, and (c) the reverse bias voltage for the photomixer (figure 4).

The Universal Model 777 Radiometer Processor (figure 5) provides the electronic processing for the IHR. The processor outputs are simultaneously available in decimal (LED), binary, and analog formats.

The Temperature Controller (figure 6) supplies the power and control signal to maintain a specified calibration blackbody temperature.

<u>InSb Photomixer</u>: The photomixer employed in the IHR is a photovoltaic Indium Antimonide (InSb) detector with an active area of approximately 1.5×10^{-4} cm^2. The measured I-V characteristic is shown in figure 7. The current variation with voltage is shown with and without local oscillator radiation applied to the diode. It is observed from the I-V curve that the reverse shunt resistance for InSb detectors is of the order of megohms. This feature results in (a) low values of photomixer dark current, and (b) the requirement for an IF preamplifier which operates from a relatively large source impedance.

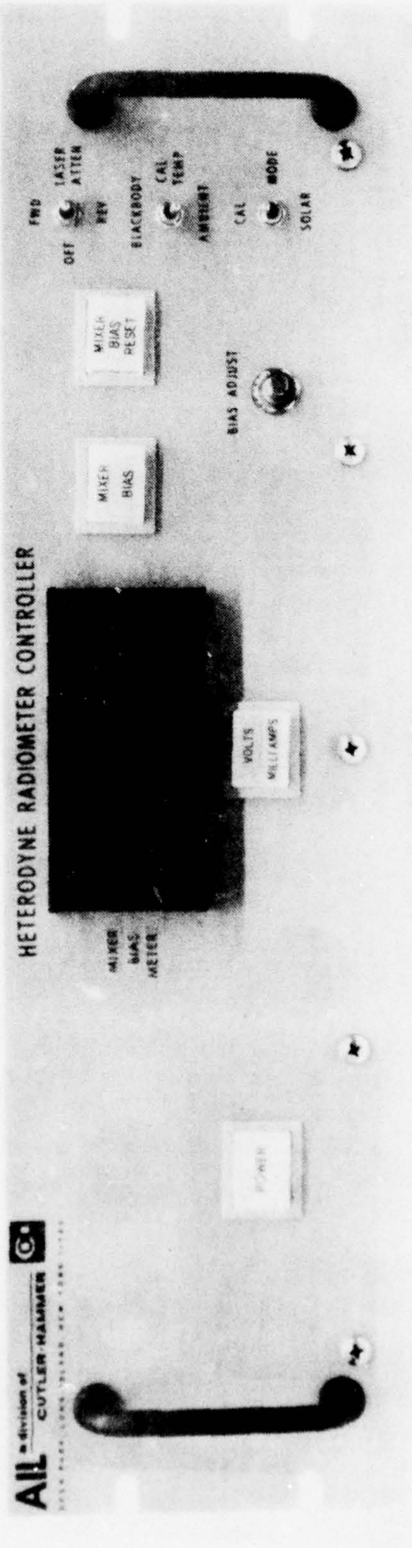


Figure 4. Heterodyne Radiometer Controller Unit

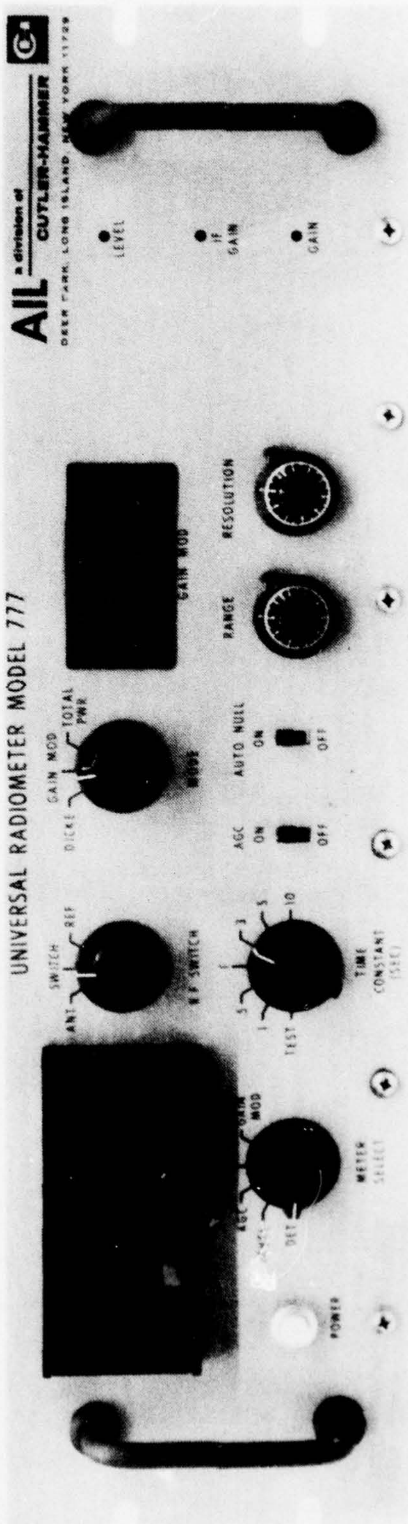


Figure 5. AIL Universal Radiometer Unit

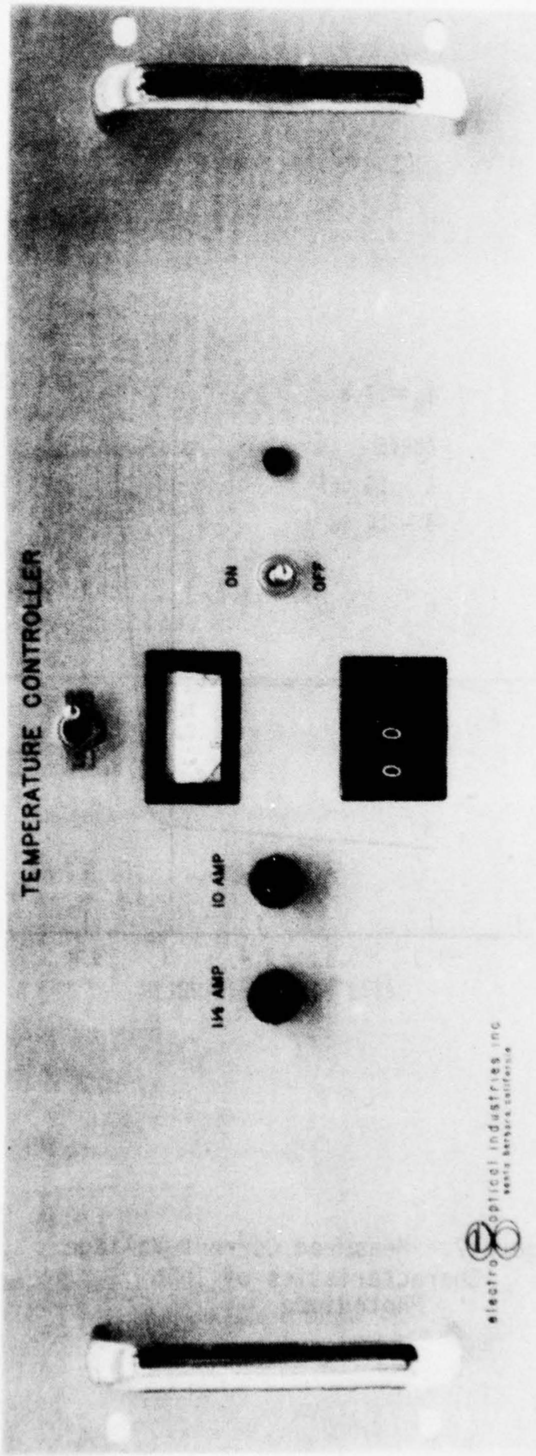


Figure 6. Temperature Controller Unit

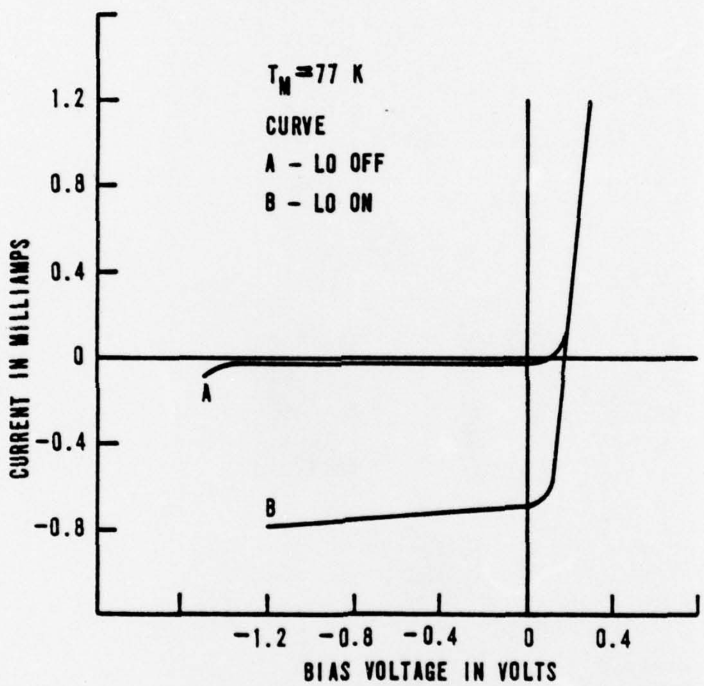


Figure 7. Measured Current-Voltage Characteristics of InSb Photodiode

Frequency response measurements were carried out for the InSb photomixer, preamplifier and postamplifier combination. The measurement results are represented by a plot of the normalized heterodyne receiver response as a function of the IF frequency and is shown in figure 8 (ref. 7). It can be seen that the response of the system is down by 3 dB from its peak at a frequency of 50 MHz, for a reverse bias voltage of 600 mV, and increases to 60 MHz when the reverse bias is increased to 800 mW.

The above measurements were performed for the case of the photomixer operating at 77 K.

<u>IHR Performance Characteristics</u>: The IHR exhibits the following system characteristics:

Wavelength	2.7 to 3.3 μm
Receiver Type	Gain modulated, Dicke-switched heterodyne receiver
Receiver Field of View	2 mrad
Detector Sensitivity, NEP	$< 2 \times 10^{-19}$ W/Hz
Dicke Switch Rate	500 to 2000 Hz, selectable
IF Bandwidth	50 or 100 MHz, selectable
Integration Time	0.1, 0.5, 1, 3, or 10 seconds, selectable
Reference Temperature	Ambient temperature
Calibration Temperature	1000 to 1900 K, or ambient temperature
Blackbody Calibration Accuracy	± 1 percent

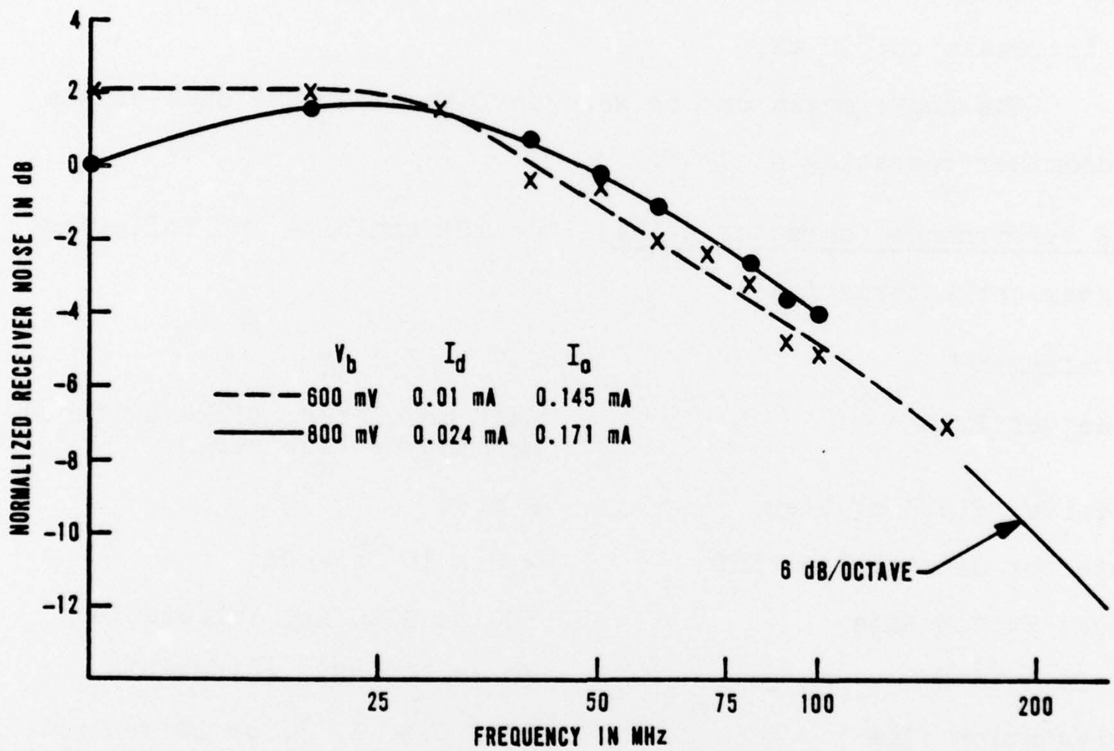


Figure 8. Measured Response of InSb Photomixer and IF Amplifier Units

Blackbody Calibration Stability (long term) $\pm$ 0.25 percent

Blackbody Calibration Stability (short term) $\pm$ 0.05 percent

IHR Temperature Resolution Accuracy: The IHR temperature resolution ΔT_s is defined as the maximum change in source temperature for which no change in output signal-to-noise ratio is observable. The temperature resolution of the IHR is given (ref. 1) by:

$$\Delta T_s = \frac{k^2 T_s^{\,2}}{h^2 \nu^2} \cdot \left[\frac{\exp(h\nu/kT_s) - 1}{\alpha \exp(h\nu/kT_s)}\right]^2 \cdot \frac{K}{\sqrt{B\tau}} \left[\frac{}{k\left[\exp(h\nu/kT_s) - 1\right]} + \int_{f_1}^{f_2} \frac{NEP(f)df}{kB}\right] \quad (1)$$

where:

α = transmittance of the media and optics between thermal source and infrared photomixer

K = sensitivity constant = 2 for Dicke-type receiver

T_s = source temperature

B = predetection bandwidth

τ = postdetection integration time for a pure integrator

ν = infrared frequency

NEP = sensitivity of heterodyne receiver

k = Boltzmann's constant

h = Planck's constant

f = IF frequency

The receiver sensitivity (NEP) for a heterodyne receiver having a photovoltaic photomixer is given (ref. 7) by:

$$NEP \int_{f_1}^{f_2} NEP(f)df \qquad (2)$$

where:

$$NEP(f) = \frac{h\nu}{\eta}\left\{1 + 2K \frac{(T_m + T'_{IF})}{q\, I_o} G_D \left[1 + (f/f_c)^2\right]\right\}$$

and: η = photomixer quantum efficiency

T_m = photomixer temperature

T'_{IF}= effective input noise temperature of the IF amplifier

G_D= reverse shunt conductance of the photomixer

I_o= LO induced photocurrent

f_c= 3-dB cutoff frequency of the photomixer

The temperature resolution of the IHR is affected by optic losses, spherical aberration, coma, astigmatism, lens emissivity, lens temperature, amplitude fluctuations which occur faster than the Dicke switch rate, and the obscuration due to the LO injection mirror.

The calculated temperature resolution accuracy, $\Delta T_s/T_s$, of a gain modulated Dicke-switched IHR is given in figure 9 for $\lambda = 3$ µm, $B\tau = 5 \times 10^9$, and a heterodyne receiver NEP of 1.3×10^{-19} W/Hz with the transmittance, α, as a parameter. For a source temperature of 2000 K and a total transmittance of $\alpha = 10$ percent, the calculated temperature resolution accuracy is $\Delta T_s/T_s = 6 \times 10^{-2}$, while for $\alpha = 100$ percent the resolution accuracy improves to $\Delta T_s/T_s = 6 \times 10^{-3}$. For the solar viewing case ($T_s \approx 5750$ K) and $\alpha \approx 0.25$, the calculated temperature resolution accuracy is $\Delta T_s/T_s = 9 \times 10^{-5}$.

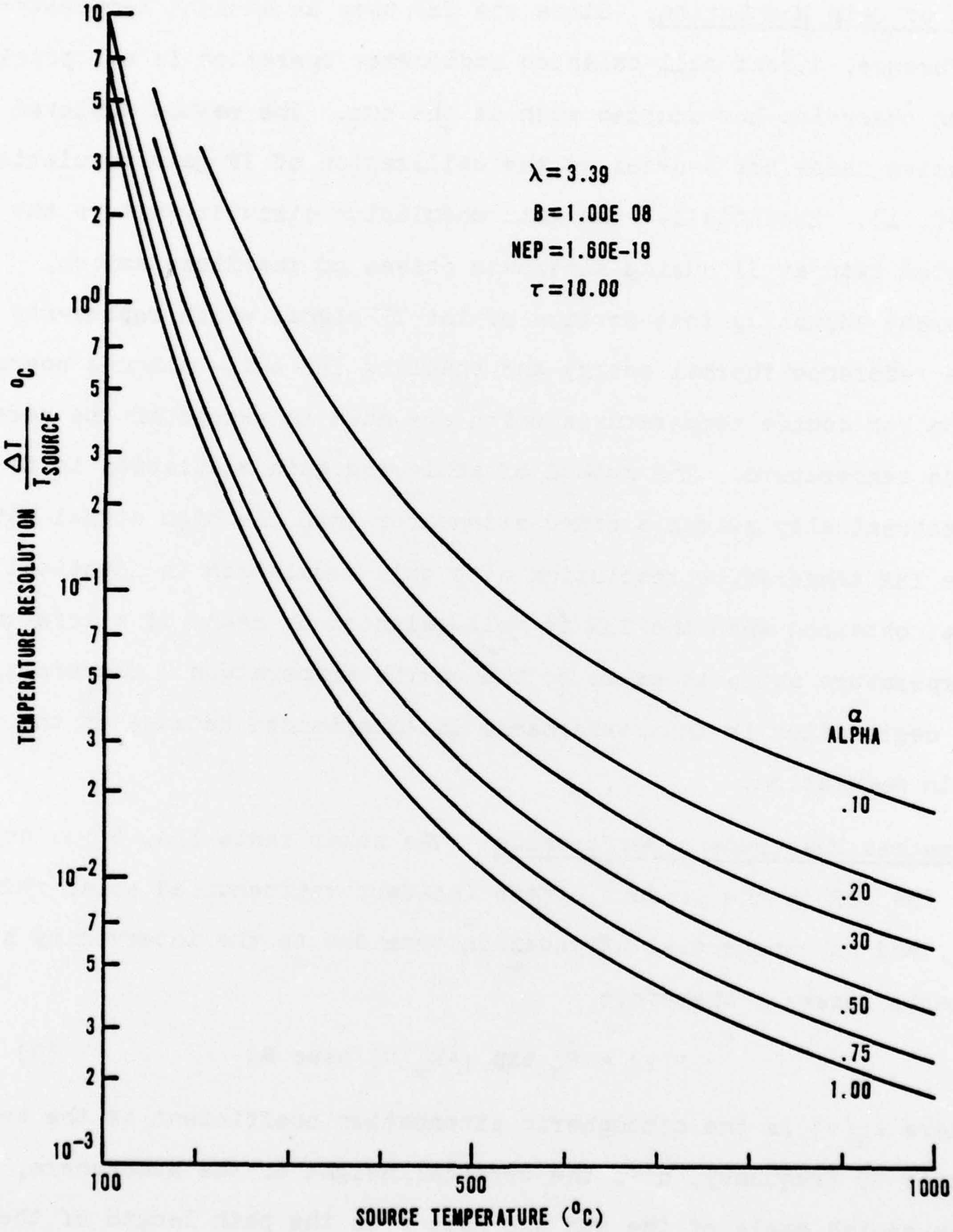


Figure 9. IHR Temperature Resolution

Use of Gain Modulation: Since the IHR uses an ambient temperature reference, direct null-balanced radiometer operation is not possible when observing hot sources such as the sun. The method employed to resolve these hot sources is the utilization of IF gain modulation (ref. 1). Essentially, the gain modulation circuitry alters the system gain at IF during alternate phases of the Dicke switch, thereby adjusting that portion of the IF signal which represents the reference thermal energy and enabling IHR null-balanced operation for source temperatures which are much in excess of the reference temperature. The method of achieving gain modulation is to electronically switch a fixed attenuator into the high signal path. The IHR temperature resolution with gain modulation is identical to that obtained when the IHR is null-balanced by means of a reference temperature which is equal to the source temperature. Therefore, no degradation in IHR performance is experienced because of the gain modulation.

Expected Measurement Performance: The sol_r radiation, $P(\nu)$, collected at the IHR is the product of the incident unattenuated solar radiation, P_o, and an exponential attenuation term due to the intervening atmospheric losses. Therefore

$$P(\nu) = P_o \exp\left(-k_\alpha(\nu)\, h \sec \Theta\right) \qquad (3)$$

where $k_\alpha(\nu)$ is the atmospheric attenuation coefficient at the selected laser LO frequency, h is the vertical height of the atmosphere, Θ is the zenith angle of the sun and h sec Θ is the path length of the sunlight through the atmosphere. The IHR output voltage is proportional to the collected source energy. The slope of the logarithm of $P(\nu)$ plotted against sec Θ is $-k_\alpha(\nu)$ h and exp $(-k_\alpha(\nu)\ h)$ is the total vertical path transmission, α (ref. 1 and 2).

The vertical path atmospheric transmission can be determined by tracking the sun as it traverses the daytime sky from a ground-based or airborne IHR. The measurements can be carried out at different laser local oscillator frequencies, and/or different altitudes.

When observing an extended thermal source of temperature (T_s) which fills the IHR field-of-view, the postdetection signal-to-noise ratio is given (ref. 1) by:

$$SNR = \frac{\eta' \ \alpha \ (B\tau)^{1/2}}{e^{h\nu/kT_s} -1} \qquad (4)$$

where B is the IF bandwidth, τ is the postdetection integration time of an ideal integrator, and k is Boltzmann's constant.

Using equation (3),

$$\alpha = \gamma \frac{S}{N} \qquad (5)$$

where γ is a constant for a fixed set of measurement parameters. Differentiating α with respect to S

$$d\alpha = \frac{\gamma}{N} dS \qquad (6)$$

The minimum detectable signal change occurs when dS = N, therefore the accuracy of the measurement of atmospheric transmission is given by:

$$\frac{d\alpha}{\alpha} = \frac{1}{SNR} \tag{7}$$

For a typical solar observation, $T_s \approx 5000$ K, B = 100 MHz, τ = 10 sec, and η' = 0.2, a total atmospheric transmission of α = 0.5 from 30 km to sea level during midlatitude summer at λ = 3, the calculated SNR of a ground-based IHR observing the solar disk at zenith it calculated (equation 4) to be

$$SNR \approx 2000 \tag{8}$$

The expected accuracy of equation (8) of the measurement is:

$$\frac{d\alpha}{\alpha} = \frac{N}{S} \cong 5 \times 10^{-4} \cong 0.05 \text{ percent}$$

Calculations have been carried out to determine the expected transmission values at various altitudes for a number of HF laser lines. The calculations for midlatitude winter model (with no aerosol present) are given in Table 1 (ref. 8). The atmospheric transmissions are given for 3 HF lines; the 2.854 μm transition which is the most strongly absorbed in the atmosphere, the 2.957 μm transition which is the least absorbed in the atmosphere, and the 2.870 μm transition which exhibits an intermediate value of atmospheric absorption. The transmission values have been calculated for the optical path between the edge of the atmosphere and the selected aircraft altitude with the solar viewing angle at a variable parameter.

Calculations were also carried out to determine the obtainable IHR power resolution. The resolution is a function of: (1) the effective system quantum efficiency (η'), and (2) the effective source

Table 1.

Atmospheric Transmission of HF Laser
Midlatitude Winter - No Aerosol
(Θ = Sun's Angle from Zenith)

Altitude (km)	Transmission $\theta = 80^\circ$	Transmission $\theta = 70^\circ$	Transmission $\theta = 60^\circ$	Transmission $\theta = 50^\circ$	Laser Line (μm)
10	.9225	.9599	.9724	.9785	
9	.8886	.9418	.9598	.9686	2.854 (max abs)
8	.8128	.9001	.9305	.9455	
7	.6478	.8022	.8600	.8893	
6	.3466	.5839	.6921	.7511	
10	.9996	.9998	.9999	.9999	
9	.9993	.9996	.9998	.9998	2.957 (min abs)
8	.9986	.9993	.9995	.9996	
7	.9965	.9982	.9988	.9991	
6	.9907	.9952	.9967	.9975	
10	.9552	.9770	.9842	.9877	
9	.9348	.9664	.9769	.9820	
8	.8984	.9471	.9635	.9717	2.870
7	.8241	.9064	.9350	.9491	
6	.6791	.8216	.8742	.9007	

(calibration) blackbody temperature, and (3) the $B\tau$ product. The smallest calculated change in irradiance which can be measured for a given input radiance is given in Table 2. The system quantum efficiency depends on both the quantum efficiency of the infrared photomixer and the degradation introduced by the front end optical configuration. The PV:InSb photomixer used in the IHR has an effective quantum efficiency of approximately 75 percent. The IHR system loss factor of approximately 3 dB is due to both optic and mixing inefficiency. This yields a system quantum efficiency of 37 percent. As seen from Table 1, the use of a 1900 K blackbody calibration source will yield a resolution between 3 and 4 parts per 1000 as compared to 10 to 13 parts per 1000 for a 1300 K source temperature (this resolution is based on the instrument rms noise).

In comparing the IHR resolution capability with the expected values of transmission (Table 1) it can be seen that most of the HF laser lines can be accurately investigated in the altitude region of interest with the exception of the weakest line at 2.957 and 2.964 microns if a 1900 K blackbody is employed. The measurements of the weaker lines appear to be limited to altitudes below 7 kilometers.

Table 2

Calculated IHR System Resolution

System Quantum Efficiency	IHR System Resolution: Blackbody Temp = 1300 K	IHR System Resolution: Blackbody Temp = 1900 K
0.1	0.038	0.011
0.2	0.019	0.0055
0.3	0.013	0.0037
0.4	0.0098	0.0028
0.5	0.0078	0.0022

A 1900 K blackbody calibration source is employed in the IHR to provide improved accuracy and to insure that a calibration reference is available above (T_c = 1900 K) and below (T_c = 290 K) the apparent solar temperature at the IHR.

Conclusions: An infrared heterodyne radiometer has been designed, developed and fabricated for high performance operational capabilities from an airborne platform. The extremely narrow bandwidth (0.0033 cm^{-1}) IHR developed on this contract is an unusual combination of optical, infrared and radio frequency technology.

The instrument has a number of key features which make it particularly advantageous for aircraft applications. These are:

1. Compact packaging of components
2. Ruggedized optical and mechanical mounting
3. High frequency chopping rate (up to 2000 Hz) which reduces the effects of external noise sources
4. Electromagnetic interference suppression filtering
5. Remote control for switching from signal to calibration mode
6. Remote control - selectable calibration source (300 or 1900 K)
7. Variable attenuation mechanism for control of LO power

During the design and development of the equipment package, consideration was also given to the system modification requirements for operation at other wavelengths. Although the IHR is presently being used for solar and atmospheric transmission measurements, there are a number of other potential applications for this unique instrument. The infrared spectrum is rich in spectral absorption (emission) phenomena which are signatures of a multitude of elements and compounds. The narrow bandwidth IHR offers the potential of spectral overlap with selected signature lines to permit the remote detection and monitoring of various atmospheric constituents.

REFERENCES

1. B.J. Peyton, et al, "An Infrared Heterodyne Radiometer for High-Resolution Measurements of Solar Radiation and Atmospheric Transmission," IEEE J. Quantum Elec., QE-11, Aug. 1975.
2. S.R. King, D.T. Hodges, T.S. Hartwick and D.H. Baker, "High Resolution Atmospheric-Transmission Measurement Using a Laser Heterodyne Radiometer," Appl. Opt., Vol. 112, p 1106, June 1973.
3. J. Gay, A. Journet, B. Christophe and M. Robert, "Heterodyne Detection of Blackbody Radiation, Appl. Phys. Letters, Vol. 22, No. 9, p 448, May 1973.
4. B.J. Peyton, et al, "Infrared Heterodyne Spectrometer Measurements of Atmospheric Ozone Using the CV 990 Airborne Platform," submitted for publication in NASA SP Publication.
5. F.I. Shemabukuro, et al, "Atmospheric Transmission Measurements at HF and DF Laser Wavelengths," Appl. Opt., Vol. 15, No. 5, pp 1115-1117, May 1976.
6. F.H. Murcray, D.G. Murcray, and W.J. Williams, "The Spectral Radiance of the Sun from 4 μm to 5 μm," Appl. Optics, Vol, 3, No. 12, pp 1373-1377, Dec. 1964.
7. B.J. Peyton, et al, "High Sensitivity Receiver for Infrared Laser Communication," IEEE J. Quantum Elec., QE-8, pp 252-263, Feb. 1972.
8. R.A. McClatchey and J.E. Selby, "Atmospheric Attenuation of HF and DF Laser Radiation," Air Force Cambridge Research Lab. Report No. AFCRL-72-0312, May 1972.