Far-Infrared Photometer System for Airborne Infrared Astronomy

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Laboratory photometric and spectral calibrations were performed for a gallium-doped germanium (Ge:Ga) and epitaxial gallium arsenide (GaAs) photo-conductive detector optimized at 100 and 285 μm respectively. They were flown in a photometer system aboard a NASA Lear jet for far-infrared astronomical observations, and a comparison of the sensitivities of the airborne flight measurements was made relative to the laboratory measurements.

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CONTENTS

FAR-INFRARED PHOTOMETER SYSTEM FOR AIRBORNE INFRARED ASTRONOMY

INTRODUCTION

The operation of a far-infrared astronomical telescope in the stratosphere at an altitude of 14 km was first achieved by Low [1] onboard a NASA Lear jet using a simple photometer system with a gallium-doped-germanium bolometer [2] operating at 2.2 K. Photoconductive detectors had already been developed and used in liquid helium cooled, rocket-borne telescopes [3, 4] for far-infrared background measurements and for galactic astronomy, but the means of comparing the sensitivity of these photoconductive detectors with a bolometer was lacking. To make such a comparison possible, a photometer was developed which was capable of using either gallium-doped germanium [5] (Ge:Ga) or epitaxial gallium-arsenide (GaAs) photoconductive [6] detectors for engineering flights onboard the NASA Lear jet. The results of the sensitivity comparisons of airborne measurements relative to laboratory measurements and conclusions derived from these results are presented in this report.

LABORATORY MEASUREMENTS

Photometer System

The photometer consisted of a stainless steel dewar used to contain the liquid helium. The detector, load resistor, filters, and a series of baffles to reduce background were mounted on a copper plate as shown in Fig. 1 and were cooled by conduction to 4.2 K. Two dewars were used, one for Ge:Ga and the other for GaAs. An optical schematic of the detector-baffle system is shown in Fig. 2. A 2 mm aperture was used in front of the detector to define a 4-arc-min field of view. The material properties of the detectors and the filters used to specify the spectral band are shown in Table 1.

Blackbody Calibrations

The DC voltage characteristics of the detectors at 4.2 K with all the filters and apertures in place are shown in Figs. 3 and 4. The load resistor, which was connected in series with the detector, was selected to match the impedance of the detector as measured from the current-voltage curves.

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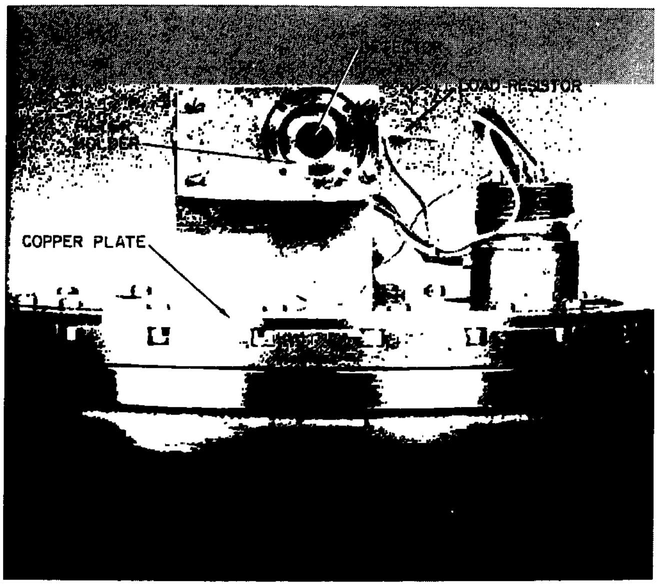

Fig. 1 — Detector assembly

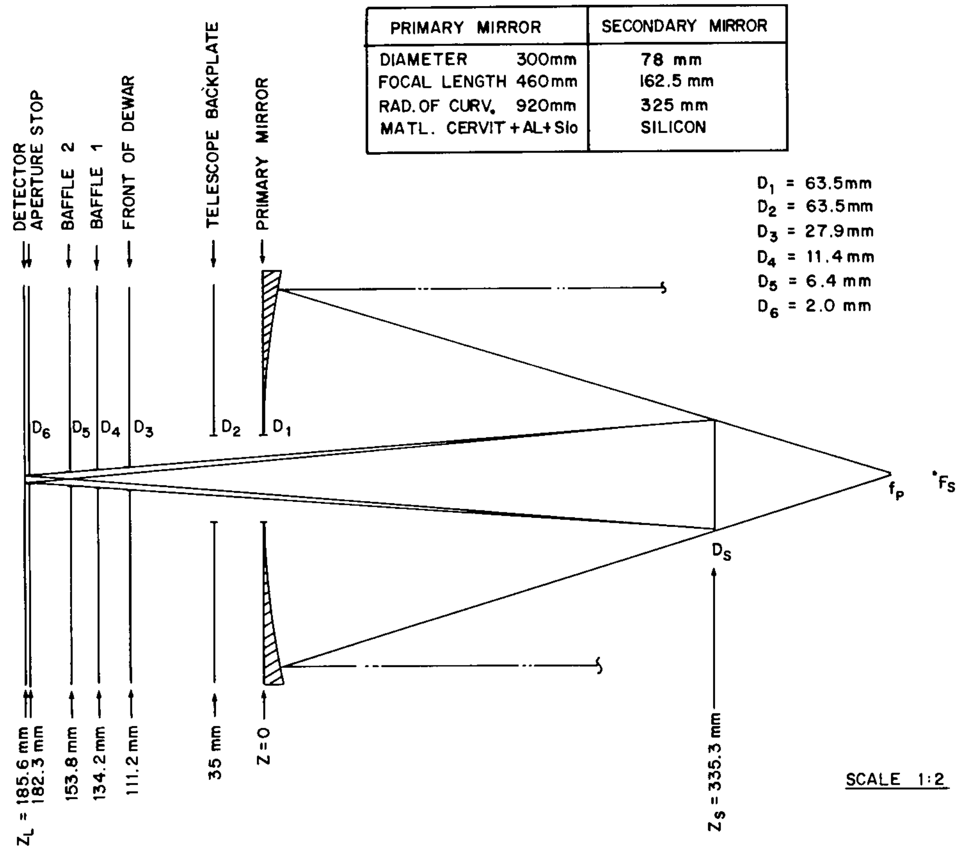

Fig. 2 — Optical schematic of the detector-baffle system for the Lear jet telescope

Table 1
Characteristics of Detectors and Filters

Detectors	Dimensions† lXwXt (mm)	Concentration‡ n (cm^3)	Mobility μ(cm^2/V-sec)	Warm Filter (300 K)	Cold Filters (4.2 K)
Ge:Ga No. 61	7X2X2	1.2×10^{14} (300 K)	3.4×10^3 (300 K)	Crystal quartz t = 2 mm	a. Two pieces of black polyethelene t = 0.1 mm each b. One piece of crystal quartz t = 1 mm
GaAs B6(11 — 1)	5X2X265μm	1.3×10^{13} (300 K)	7500 (300 K) 1.55×10^5 (77 K)	Crystal quartz t = 2 mm	Two pieces of black polyethelene embedded with alkali halides t = 0.3 mm

†l = length, w = width, and t = thickness.

‡n = $N_D - N_A$, where N_D = donor concentration and N_A = acceptor concentration.

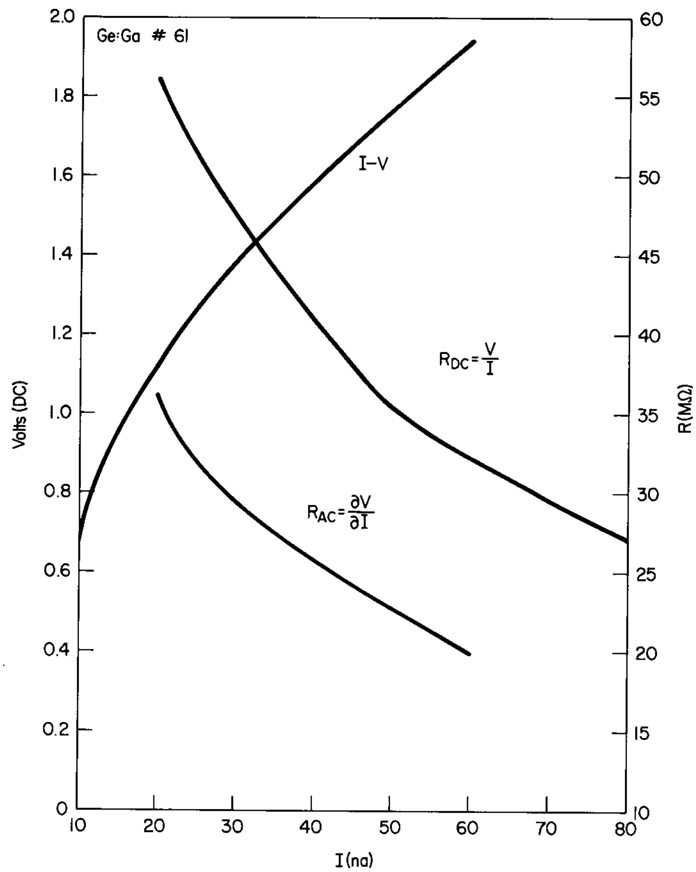

Fig. 3 — Voltage (DC) characteristics of Ge:Ga

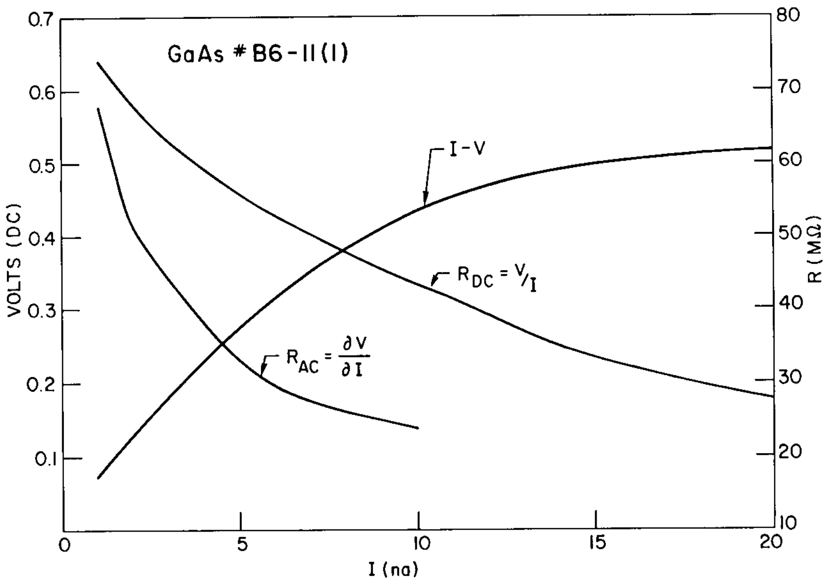

Fig. 4 — Voltage (DC) characteristics of GaAs

The experimental arrangement used for the blackbody calibration is shown in Fig. 5. A 500-K, infrared blackbody source modulated by a three-bladed aluminum chopper at 95 Hz was placed at 30 cm from the entrance aperture of the dewar. A low-noise, room-temperature preamplifier, as shown in Fig. 6, was used to amplify the signal from the detector, and a wave analyzer was used to measure the preamplifier output. Signal and noise were measured for each detector at various bias voltages, and the bias was optimized for the best signal-to-noise ratio, as shown in Fig. 7. The optimum electrical characteristics of the detectors are shown in Table 2.

Spectral Calibrations

The spectral response of these detectors (Fig. 8) relative to the response of a Golay detector was measured using a modified Perkin-Elmer 301 grating spectrophotometer (Fig. 9) with a mercury-arc source modulated at 345 Hz for the photoconductive detectors and 13 Hz for the Golay detector. The spectral response of the GaAs detector was also measured using a Fourier transform interferometer [7] to confirm that there was no response below 200 μm.

Responsivity and Noise Equivalent Power

With a 9.5-mm blackbody aperture, the etendue of the calibrating system was 1.08 $\times 10^{-5}$ cm^2 sr.† The gain of the amplifier used in all the measurements was 575. The responsivity was defined by

$$R = \frac{V\ \text{(volts)}}{W\ \text{(watts)}} \qquad (1)$$

†See Appendix A.

V = detector output (volts) and

W = power incident on detector (watts) or

where $W = A\Omega N_{\lambda_p}(T)\Delta\lambda$

$A\Omega$ = etendue (cm^2 sr)

$N_{\lambda_p}(T)$ = blackbody radiance (W/cm^2 sr μm)†

T = blackbody temperature (K)

λ_p = peak wavelength (μm)

$\Delta\lambda$ = bandwidth (μm)

The noise equivalent power (NEP) is defined by

$$NEP = \frac{N}{R} \text{ (watt/Hz}^{1/2}\text{)}$$

where

R = responsivity (volts/watt)

N = noise in unit bandwidth (volts/Hz$^{1/2}$) .

To estimate the blackbody spectral radiance $N_{\lambda_p}(T)$, we measured the outputs of both the detectors for three different blackbody temperatures. The linearity of the signal vs temperature graph as indicated in Fig. 10 verified the Rayleigh-Jeans relationship. Extrapolating to zero signal output gave the chopper temperature as 260 K. Hence, the blackbody spectral radiance using a 500-K source temperature is given by

$$N_{\lambda_p}(T) = N_{\lambda_p}(500 \text{ K}) - N_{\lambda_p}(260 \text{ K}) .$$

Blackbody spectral radiances were calculated for each of the detectors by using eq. (A2) in Appendix A, applying the peak wavelength and bandwidth as measured from the spectral calibrations shown in Fig. 8. The responsivity and noise equivalent power for each of the detectors are presented in Table 3.

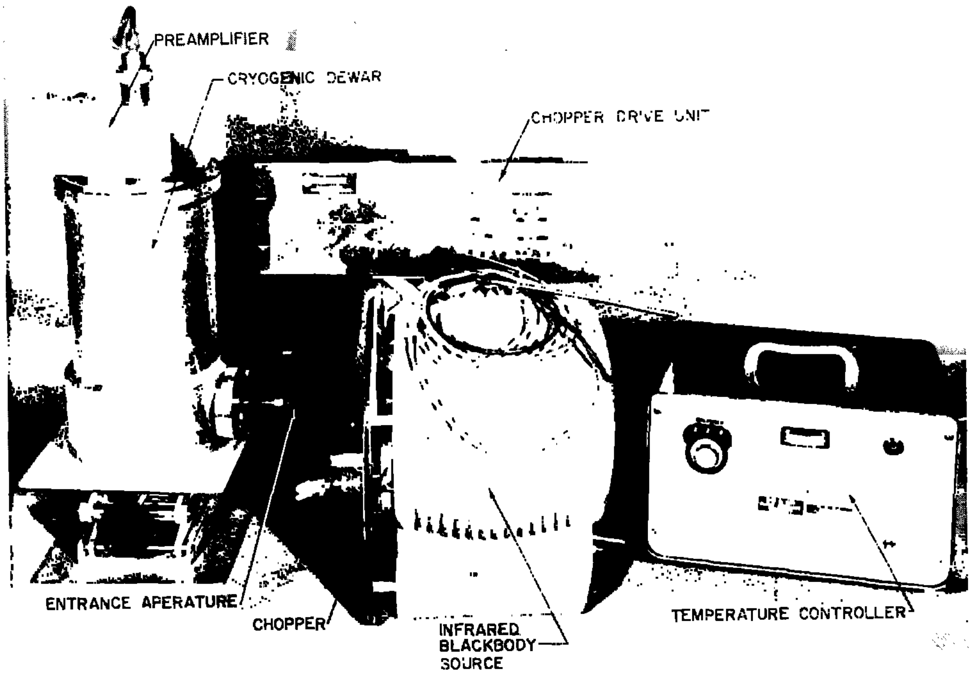

Fig. 5 — Experimental arrangement used for blackbody calibration

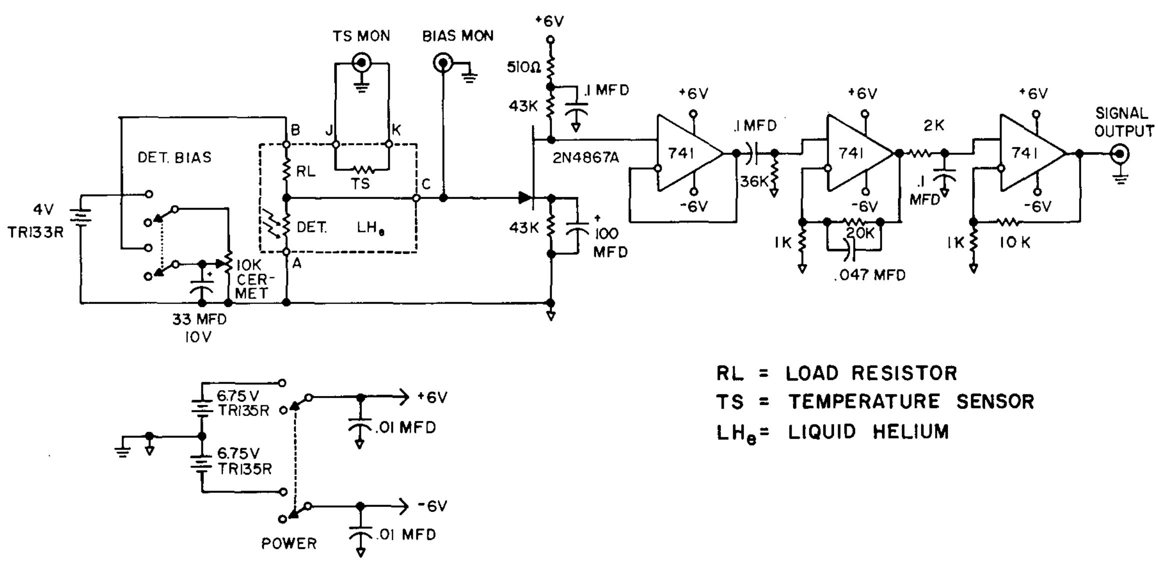

Fig. 6 — Preamplifier and bias circuitry for detectors

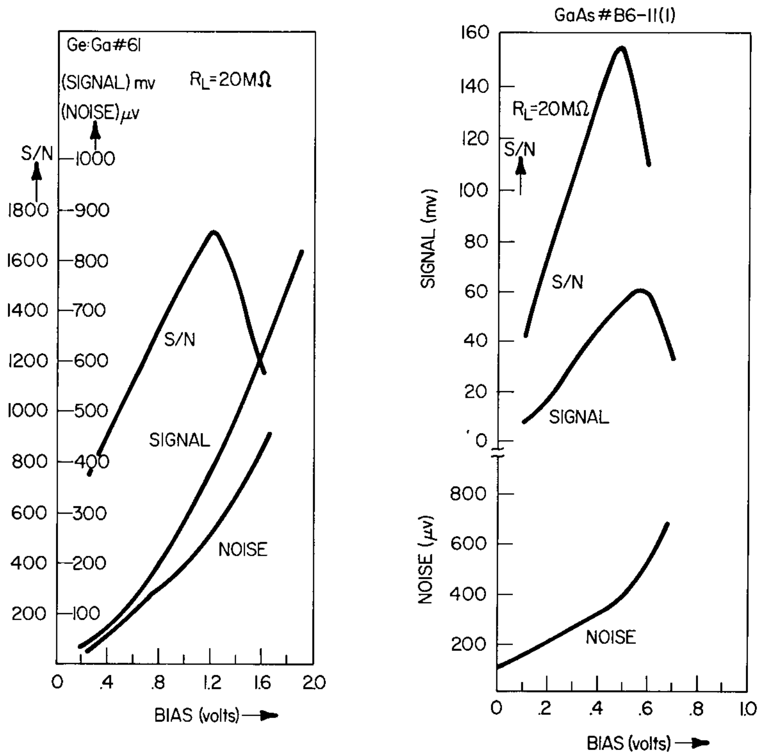

Fig. 7 — Bias optimization for Ge:Ga and GaAs detectors

Table 2
Electrical Characteristics of Detectors

Detector	Bias (*V*)	R_L† (*M*Ω)	R_{DC}‡ (4.2 *K*) (*M*Ω)	R_{AC}‖ (4.2 *K*) (*M*Ω)
Ge:Ga No. 61	1.2	20(300 *K*) 36(4.2 *K*)	57	32
GaAs B6(11–1)	0.5	20(300 *K*) 36(4.2 *K*)	33	18

†R_L = Load resistor.
‡R_{DC} = *DC* resistance.
‖R_{AC} = *AC* impedance.

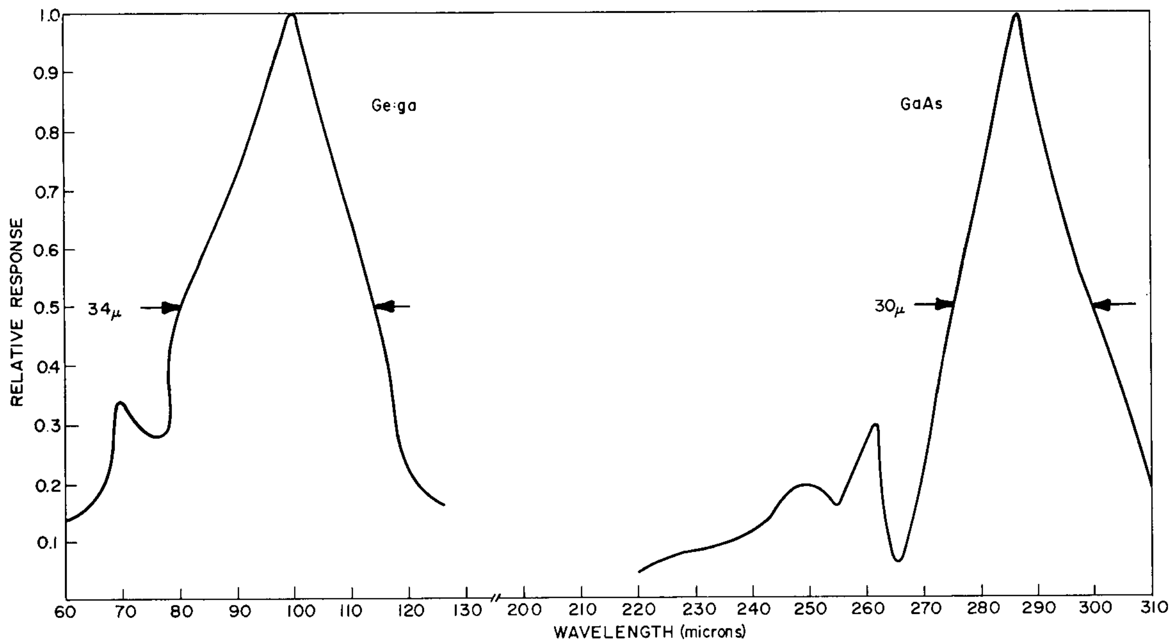

Fig. 8 — Spectral response of Ge:Ga and GaAs detectors

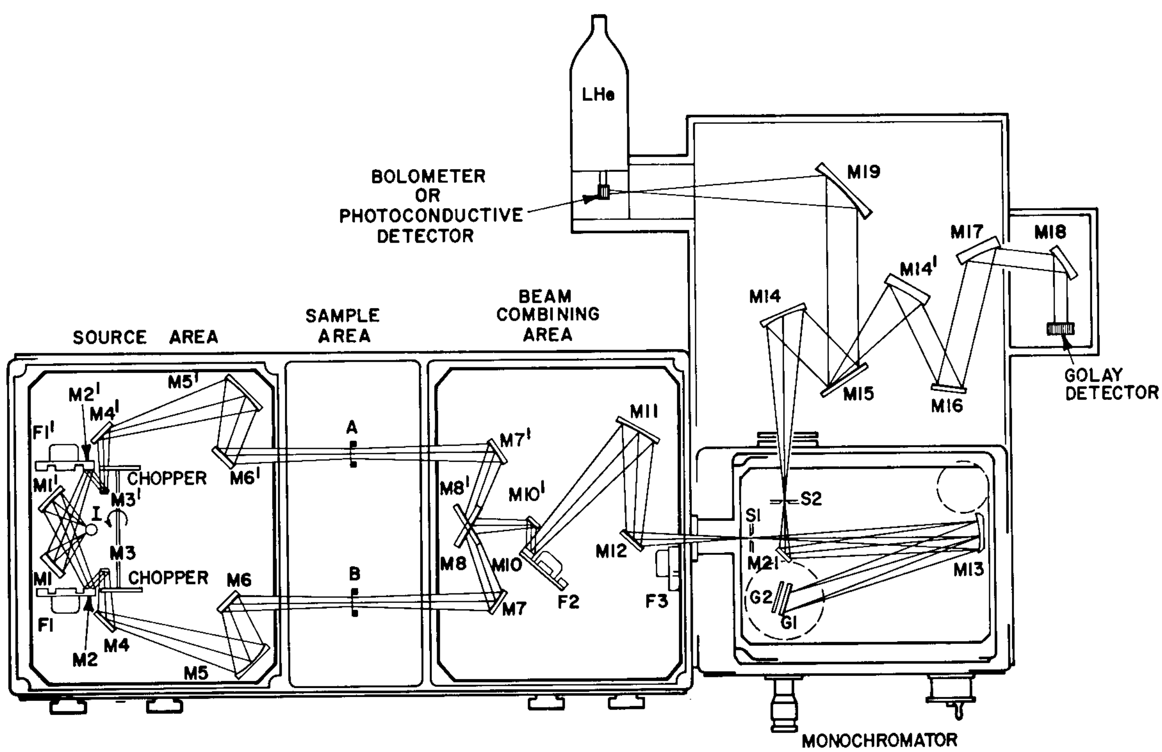

Fig. 9 — Double beam far-infrared spectrophotometer

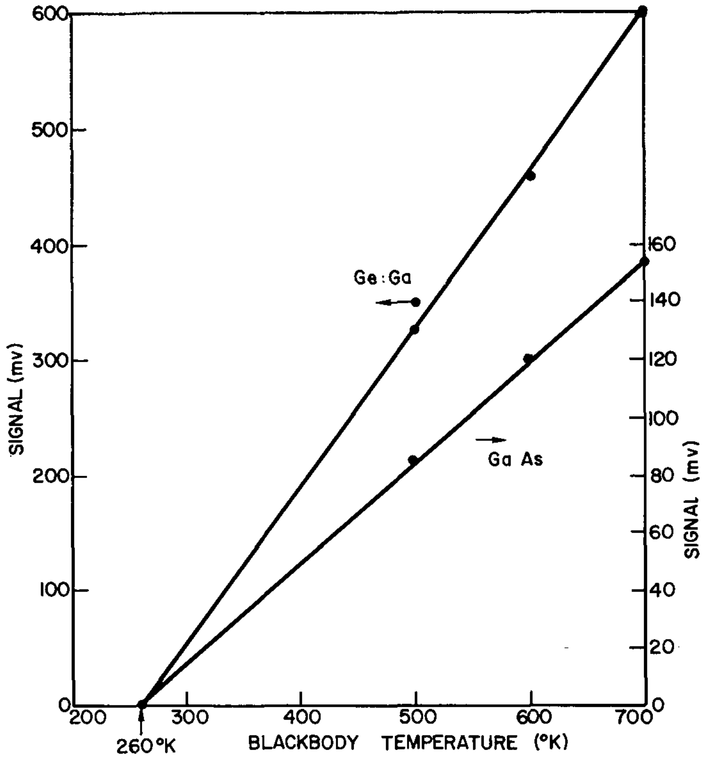

Fig. 10 — Signal output as function of blackbody temperature

Table 3
Responsivity and Noise Equivalent Power of Detectors

Detector	Signal† (*Mv*)	Noise† ($\mu V/Hz^{1/2}$)	Peak wave-length λ_p (μm)	Band-width $\Delta\lambda$ (μm)	Respon-sivity (V/W)	*NEP* ($W/Hz^{1/2}$)
Ge:Ga No. 61	0.64	0.4	100	34	8.8×10^5	4.5×10^{-13}
GaAs *B*6(11–1)	0.11	0.5	285	30	1.3×10^7	4.0×10^{-14}

†Referred to detector output.

Moore and Shenker [5] reported an NEP of 8.0 $\times$ 10^{-13} $W/Hz^{1/2}$ for a Ge:Ga detector in the wavelength range of 40μm to 125μm with a room-temperature background and an etendue ($A\Omega$) of 9.4 $\times$ 10^{-3} $cm^2 sr$. Stillman, Wolfe, and Dimmock [8] reported an average NEP of $10^{-13} W/Hz^{1/2}$ for three GaAs detectors at 282μm with a warm background. The results of this experiment were in agreement with published results, except that the GaAs detector showed an improvement factor of 10 due to reduction of background by use of narrowband filters.

AIRBORNE MEASUREMENTS

Description of the Telescope

The telescope was mounted on the Lear jet described previously by Low, Aumann, and Gillespie [9]. However, modifications in the operation and performance of this system have since been made. The telescope was a Dall-Kirkham model that had a Cervit ellipsoidal primary mirror with a coating of aluminum plus an overcoating of silicon monoxide and a spherical secondary mirror with a coating of silicon. The optical characteristics of the mirror systems are shown in Table 4 below.

Table 4
Characteristics of Optical System

Optical Systems	Material	Diameter (cm)	Radius of Curvature (cm)	Focal Length (cm)
Primary	Cervit	30	92	46
Secondary	Silicon	7.8	32.5	16.25

Modulation and background cancellation were achieved with the secondary mirror oscillating at 95 Hz and the switching beams set at about 10 arc-min.

When the Lear jet was in its standard configuration, the telescope was mounted to point in a direction 20 degrees above the horizon. The telescope was gyro stabilized to compensate both for roll (elevation) and for yaw (azimuth) and was pointed by means of an optical guide scope and a joystick control. A grid representation on the guide scope determined the field of view.

Observational Results

The flights were carried out at an altitude of 14 km. In two separate flights Venus and the Orion Nebula (M42) were observed. Venus was used as a calibration source to compare the detector responsivity and noise equivalent power to the laboratory measurements. The following parameters were used:

Diameter of Venus (April 15, 1974): 24.4 secs
Area of unobstructed telescope: 683cm^2
Etendue: 7.51×10^{-6} cm^2 sr
Blackbody temperature of Venus: 280 K.

Because of uncertainties in the atmospheric transmission at the observing altitudes and lack of information on the optical transmission properties of the telescope at 100μm and 285μm, no corrections were made in the airborne responsivity measurements as presented in Table 5.

Table 5
Comparison of Laboratory and Airborne
Detector Sensitivities

Detector	Laboratory (Table 3)		Airborne (Venus)		Minimum Flux density (W/m^2 Hz)
	Responsivity (V/W)	*NEP* ($W/Hz^{1/2}$)	Responsivity (V/W)	*NEP* ($W/Hz^{1/2}$)	
Ge:Ga No. 61 λ_p = 100μm $\Delta\lambda$ = 34μm	8.8×10^5	4.5×10^{-13}	2.7×10^5	4×10^{-12}	5.7×10^{-23}
GaAs *B*6(11–1) λ_p = 285μm $\Delta\lambda$ = 30μm	1.3×10^7	4×10^{-14}	4.2×10^6	3×10^{-13}	5.0×10^{-23}

Use of the 30-cm Lear jet telescope gave a minimum flux density of 5.7×10^{-23} W/m^2 Hz for the 100-μm detector and 5.0×10^{-23} W/m^2 Hz for the 285-μm detector. Harper [10] reported a minimum detectable flux density of 2.5×10^{-23} W/m^2 Hz in his photometry of far-infrared sources. The preliminary measurements in this experiment indicated that the sensitivity was within a factor of 2 when compared to Harper's photometer system.

Airborne noise measurements were a factor of 10 higher than the laboratory measurements because of the noise created by microphonics, fluctuating pointing errors, and low-frequency modulation.

The intensity calibrations for the Orion nebula were based on an effective blackbody temperature for Venus of 280 K. These calibrations are presented in Table 6 and compared with other observations. The 100-μm observations in this Lear jet operation were in agreement with other similar Lear jet observations. The 285μm observation was the first airborne measurement made at this wavelength.

Table 6
Far-Infrared Lear-Jet Observations of
Orion Nebula (M42)

Experiment	Bandwidth (μm)	Peak Wavelength, (μm)	Beam (arc-min)	Flux (W/m^2 Hz)	Reference
Photometry	80-115 270-300	100 285	4	3.6×10^{-21} 7×10^{-22}	Present work
Photometry	65-110 56-500 125-500	78 99 183	5	4.1×10^{-21} 3.0×10^{-21} 1.4×10^{-21}	Harper [10]
Photometry	50-300	—	8	7×10^{-22}	Low [11]
Grating spectrometer	80-125	100	5	3.4×10^{-21}	Ward et al. [12]
Michelson interferometer	55-200	100	4	3×10^{-21}	Erickson et al. [13]

CONCLUSION

The noise levels observed during flight were ten times those obtained in the laboratory. Possible sources of this noise were microphonics, optical offset, and telescope guiding errors. It is well known that the signal-to-noise ratio of photoconductive detectors improves as the modulation frequency is increased; hence, an improvement in sensitivity could have been achieved by going to higher modulation frequencies.

Harper made his far-infrared observations using broadband filters because of the limitations in the design and fabrication of narrowband filters. The unique capability of a narrow-bandpass detection system at 285 μm with a bandpass of 30 μm and an NEP of 10^{-14} W provides more reliable flux values at 285 μm. This is because the system is not responsive to the shorter wave radiation near 100 μm, radiation which tends to dominate the spectrum of infrared astronomical sources.

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Appendix A
Etendue and Blackbody Spectral Radiance

ETENDUE

The blackbody-detector geometry is as shown in Fig. A1.

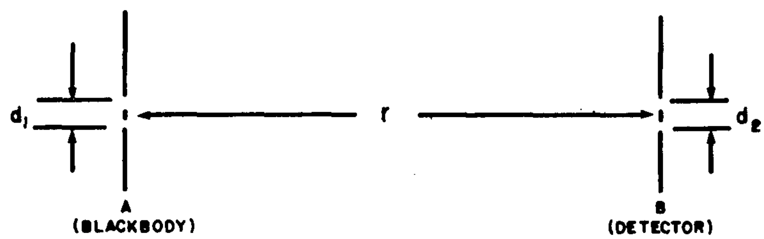

Fig. A1

d_1 = diameter of blackbody aperture, 9.5 mm
d_2 = diameter of detector aperture, 2 mm
r = distance between blackbody aperture and detector, 450 mm.

The etendue is given by

$$U = \frac{A_1 A_2}{r^2} \text{ cm}^2 \text{ sr},$$

where

A_1 = area of blackbody aperture

$$= \frac{\pi d_1^2}{4}$$

A_2 = area of detector aperture

$$= \frac{\pi d_2^2}{4}$$

and by substitution

$$U = \frac{A_1 A_2}{r^2} = \frac{\pi d_1^2}{4} \frac{\pi d_2^2}{4} \frac{1}{r^2} \text{ cm}^2 \text{ sr}.$$

BLACKBODY SPECTRAL RADIANCE

The relationship between spectral emissivity, temperature, and radiant energy for a blackbody is given by Planck's equation

$$N_\lambda\ (T) = \frac{\epsilon_\lambda c_1}{\lambda^5\ (e^{c_2/\lambda T}-1)}\quad W/cm^3\ sr, \qquad \text{(A1)}$$

where

λ = wavelength
ϵ_λ = emissivity of blackbody at wavelength λ
c_1 = Planck's first radiation constant, $\frac{2hc^2}{\Omega_o}$
c_2 = Planck's second radiation constant, 1.438 $cm\ K$
h = Planck's constant
c = velocity of light
Ω_o = solid angle
T = temperature (K)

Using the following values:

Ω_o = 1 sr
h = 6.625×10^{-27} erg sec
c = 3×10^{10} cm/sec
ϵ_λ = 1

$$c_1 = \frac{2hc^2}{\Omega_o} = 1.20 \times 10^{-12}\ W\ cm^2/sr$$

and substituting them eq. (A1) above, we get

$$N_\lambda\ (T) = \frac{1.2\times10^{-12}}{\lambda^5\left(e\ \frac{1.44}{\lambda T} - 1\right)}\ W/cm^3\ sr$$

Normalizing the irradiance to unit bandwidth by using 1 cm = 10^4 μm gives the blackbody spectral radiance as

$$N_\lambda\ (T) = \frac{1.2\times10^{-16}}{\lambda^5\left(e\ \frac{1.44}{\lambda T} - 1\right)}\ W/cm^2\ sr^1\ \mu m \qquad \text{(A2)}$$