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Date December 1987

LINEARITY AND SPECTRAL CHARACTERISTICS
OF INTEGRATING SPHERE SOURCES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Randy Alan Nicholson

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ABSTRACT

In order to calibrate long wavelength infrared (LWIR) sensors, low temperature sources which approximate blackbody radiators are required. To calibrate a sensor over its entire operating range, the dynamic range of these sources must be large. One technique for extending the dynamic range of such sources and attaining the low irradiance levels required involves the use of integrating spheres as attenuation devices. Aperture wheels are used with these sources. Questions concerning linearity performance and spectral qualities arise when these types of sources are employed. This study addresses these issues by examining the performance of two different types of integrating sphere sources as monitored during several calibration efforts. The two types of sources considered were a unisphere (a cavity radiator with a single integrating sphere) and a capsule (a dual integrating sphere arrangement with a capsule heater mounted inside one of the spheres).

A radiation monitor telescope (RMT) was used to calibrate the integrating sphere sources. This device contains a reference cavity source which has been calibrated and is traceable to the National Bureau of Standards. The detector in the RMT is a photoconductor (Ge:Cu) which can detect sources over seven orders of magnitude. A filter wheel in the RMT is used to provide spectral characterization of sources.

The responsivity of the RMT detector is not as constant with source temperature as desired, even when the relative spectral response of the detector is included in the calculations. It appears that the relative spectral response characteristics of the detector are suspect.

It is recommended that these values be checked and the true spectral response characteristics determined.

Several methods of linearity characterization were evaluated. All of the methods examined were found to be valid. The preferred method was determined to be the one based on signal attenuation ratios. The results obtained at the different aperture positions were highly repeatable. Thus, linearity characteristics can be accounted for in source output calculations. It was determined that a single calibration constant can be determined and applied to all apertures associated with a particular source without greatly increasing the source output uncertainty.

Based on theoretical considerations, the RMT source has an effective emissivity greater than 0.99. The RMT source spectral ratios obtained with the filter wheel do not agree as closely with predicted blackbody ratios as hoped, even when the spectral response of the detector is accounted for. The unisphere and capsule values agree reasonably well with the RMT source spectral ratios. When a large aperture is used with the unisphere source, the spectral ratios obtained are closer to those predicted for a blackbody. All of the sources examined follow the Stefan-Boltzmann relationship over the temperature range investigated. The calibration constants determined did not vary significantly with source temperature. Although no indication of any major spectral problems associated with the integrating spheres was found for the conditions evaluated, several significant improvements need to be made in order to provide accurate spectral calibrations of such sources.

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LIST OF SYMBOLS

English Symbols

A	Area of the source output aperture
A_d	Area of the RMT detector
A_p	Area of the collecting mirror
A_r	Inverse of the attenuation ratio
AR	Attenuation ratio
c	Speed of light in a vacuum
C	Diffraction constant
C_1	Constant in Planck's expression
C_2	Constant in Planck's expression
d	Distance from output aperture to detector
$F_{\lambda_1-\lambda_2}$	Fraction of total emissive power in the interval λ_1 to λ_2
G	Gain ratio correction factor
h	Planck's constant
H	Irradiance
k	Boltzmann's constant
K	Source calibration constant
K_d	Diffraction correction term
P	Power on the detector
r	Reflectance of the collimating mirror
R	Detector responsivity
$R(\lambda)$	Relative spectral response
S	Total surface area of a cavity
S_0	Surface area of a sphere of diameter equal to cavity depth
T	Absolute source temperature

V	Detector output signal
V_d	Detector output signal for a particular aperture
W	Radiant emittance over all wavelengths
W_λ	Spectral radiant emittance
$W_{d\lambda}$	Radiant emittance over a wavelength band
Z	Constant of proportionality

Greek Symbols

ϵ	Total or average emissivity
$\epsilon(\lambda)$	Spectral emissivity
ϵ_0	Effective emissivity
λ	Wavelength
λ_m	Wavelength at which radiant emittance is a maximum
σ	Stefan-Boltzmann constant
Ω	Solid angle

CHAPTER I

INTRODUCTION

Long wavelength infrared (LWIR) sensors are often used to detect and track low-temperature targets in space. To simulate the environment in which the sensors operate, ground testing of LWIR sensors is generally performed in a vacuum, cryogenic environment. To calibrate and evaluate the performance of LWIR sensors, sources which are broadband spectral radiators are required. Cavity radiators which closely approximate a blackbody source are readily developed. Such sources typically have effective emissivity values of greater than 0.99. However, the range of irradiance levels (dynamic range) of these sources is limited, and extremely low levels of irradiance are not attainable with such sources.

One technique which has been developed to increase the source dynamic range and provide the low irradiance levels required by the more sensitive sensors involves the use of integrating spheres. These spheres attenuate incoming radiation through multiple reflections, then pass it through an output aperture. Single and double integrating sphere sources have been developed and utilized. Aperture wheels are commonly used with these sources to regulate the amount of energy entering the output sphere, thereby controlling the source output. With the aperture wheel technique, the source output can be varied without changing the source temperature.

Concerns which commonly arise when integrating spheres are employed are how the spectral qualities of the source may be affected by the sphere and how well the output associated with the various apertures

can be predicted. Source calibrations are performed to characterize the spectral and linearity qualities of the integrating sphere sources. In this effort, the results of several calibration efforts have been compiled and analyzed to achieve an overall assessment of how well these issues can be addressed. Various methods of characterization have been evaluated and compared, limitations of the methods addressed, and recommendations made for improving current capabilities.

Two types of sources were considered for this investigation. One of these involves a cavity radiating into a single integrating sphere. It is referred to as a unisphere source. The other source involves a small, heated capsule suspended in an integrating sphere. This source is arranged in a dual integrating sphere configuration and is commonly referred to as a capsule source.

For the source output to be known accurately, the manner in which the output varies with changing aperture position must be known. In the ideal case, the relationship between source output and aperture area should be linear. Plots of detector output versus aperture area were developed to determine how well this criteria is satisfied and to describe the actual relationships that exist. A second technique which was evaluated involves the calculation of an attenuation ratio and comparison with a theoretical prediction. For this method, theoretical values based upon the ratio of aperture areas were compared with experimentally determined results. The attenuation ratio method was applied to both sources. For the unisphere source, a theoretical prediction based upon throughput calculations was also made and compared to the experimental results. As a final linearity consideration, source

calibration constants were calculated for each aperture position to determine if the predicted output deviates substantially when a single calibration constant is applied for all apertures.

No matter which linearity technique is used, the most crucial factor is whether the same output can be produced consistently. If the results obtained occur in a repeatable fashion, the source linearity characteristics can be accounted for in the required calculations. Results showing the repeatability of signals obtained when aperture wheels are utilized are presented.

Spectral qualities of sources are of major interest. The integrating sphere sources are typically operated over a range of temperatures. If the reflectance of the integrating sphere surface is a strong function of wavelength, the spectral curve shifts associated with changing source temperature and the absorption of energy at some wavelengths may induce errors in the predicted output of the source. A valid way of spectrally characterizing low-intensity LWIR sources directly is not currently available. Several techniques can be employed to indicate how the spectral qualities of the integrating sphere sources compare to those of a blackbody. The primary evaluation involves comparing the spectral output of an integrating sphere source with that of a cavity source. This technique makes an inherent assumption that the reference source developed closely simulates the spectral qualities of a true blackbody. Several efforts were made to attempt to substantiate this assumption.

All spectral data collected were analyzed to determine as much as possible about the spectral qualities of the sources. Plots of

detector output signal versus source temperature were developed to determine if the sources obey the Stefan-Boltzmann relationship. Programs were written to predict the output signal for a given wavelength band, taking into account the relative spectral response of the measuring device. These results were compared with measurements made with a filter wheel in a radiation monitoring device. These results were also compared with those predicted by blackbody radiation tables. As a final analysis method, calibration constant values were calculated at several different source temperatures to determine if the source characteristics change significantly with temperature.

CHAPTER II

APPARATUS

The apparatus involved in this investigation was designed and developed by other investigators. The author was involved in the operation of the apparatus and acquisition and analysis of data during several source calibration efforts. The primary elements involved in the calibration of the infrared sources are a source, a collimating mirror, and a radiation monitor telescope (RMT). All of these elements are located inside the test chamber. They are arranged as shown in Figure 1. The source is located near the focal point of the collimating mirror. The radiant energy from the source is reflected from the collimating mirror to the RMT. Since the radiation is collimated, the source appears to the RMT detector as an object located at infinity. The source can be driven in two directions to position the source aperture at the mirror focal point and achieve the best focus.

2.1 Infrared Sources

Two types of infrared sources were considered for this investigation. One was a single integrating sphere (unisphere) source. The other was a dual integrating sphere configuration which is referred to as a capsule source. Both the unisphere and the capsule were classified as point sources; their output apertures were 0.050 inches in diameter and produced spot sizes which were smaller than the dimensions of the detector in the RMT.

Chamber Liner

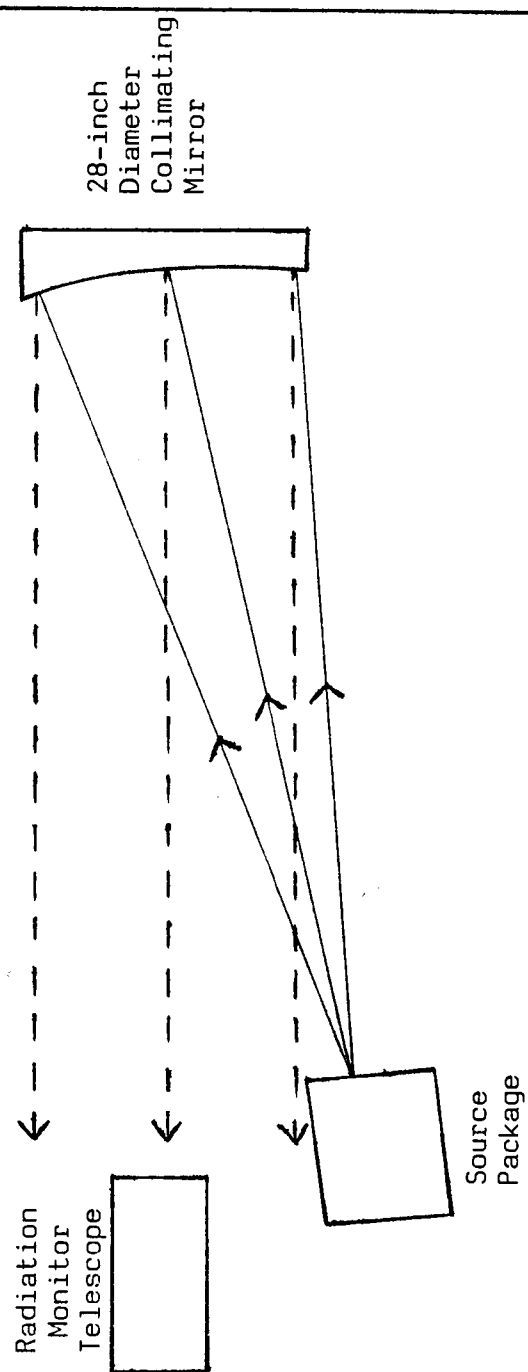


Figure 1. Schematic of the Calibration Configuration.

2.1.1 Unisphere Source

The unisphere source (Figure 2) consists of a bare cavity thermal source that projects radiation into a single integrating sphere. The thermal source is a conical-cavity radiator with a one-inch diameter output aperture. The temperature of the cavity can be varied from 100K to 400K. The inner surface of the 1.75-inch diameter integrating sphere was made highly diffuse by depositing 180-grit powder over a thin silicon-alkyd resin coating. A second coating of resin was added, and a final coating of vacuum-evaporated gold was applied. Reflectance of surfaces prepared in this manner is nominally 90 percent. To prevent energy from the source from passing directly through the integrating sphere, the sphere output orifice was located at an angle of 90 degrees with respect to the centerline of the conical-cavity radiator.

A 12-position aperture wheel is located between the thermal source and the integrating sphere to provide a means of varying the amount of energy entering the sphere. This wheel contains 11 apertures and one blank position. The diameter and area of each aperture is listed in Table 1.

Three temperature sensors are mounted on the cavity of the unisphere source. A chopper is located in front of the sphere output aperture to chop the radiation from the source and generate a modulated signal which can be measured.

2.1.2 Capsule Source

A capsule source (Figure 3) is used to provide very low irradiance levels. The assembly consists of two integrating spheres: a 1.5-inch diameter input sphere, and a 1.5-inch diameter output sphere. The

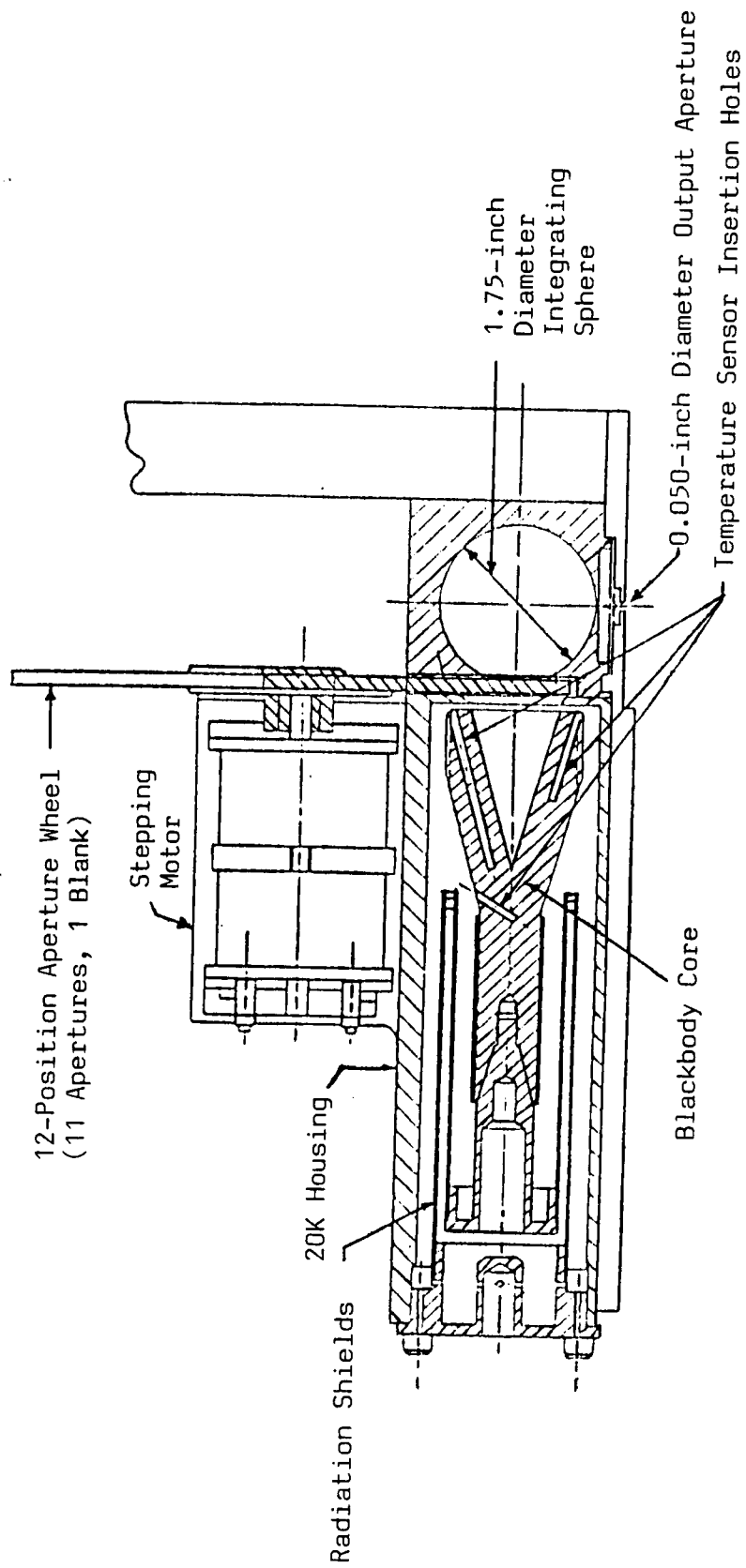


Figure 2. Unisphere Source Assembly.

Table 1. Unisphere Aperture Characteristics.

Aperture Number	Aperture Diameter (in)	Aperture Area (in ²)
12	0.720	4.072×10^{-1}
11	0.414	1.346×10^{-1}
10	0.274	5.896×10^{-2}
9	0.200	3.142×10^{-2}
8	0.140	1.538×10^{-2}
7	0.100	7.854×10^{-3}
6	0.0700	3.848×10^{-3}
5	0.0500	1.963×10^{-3}
4	0.0355	9.898×10^{-4}
3	0.0256	5.147×10^{-4}
2	0.0170	2.270×10^{-4}

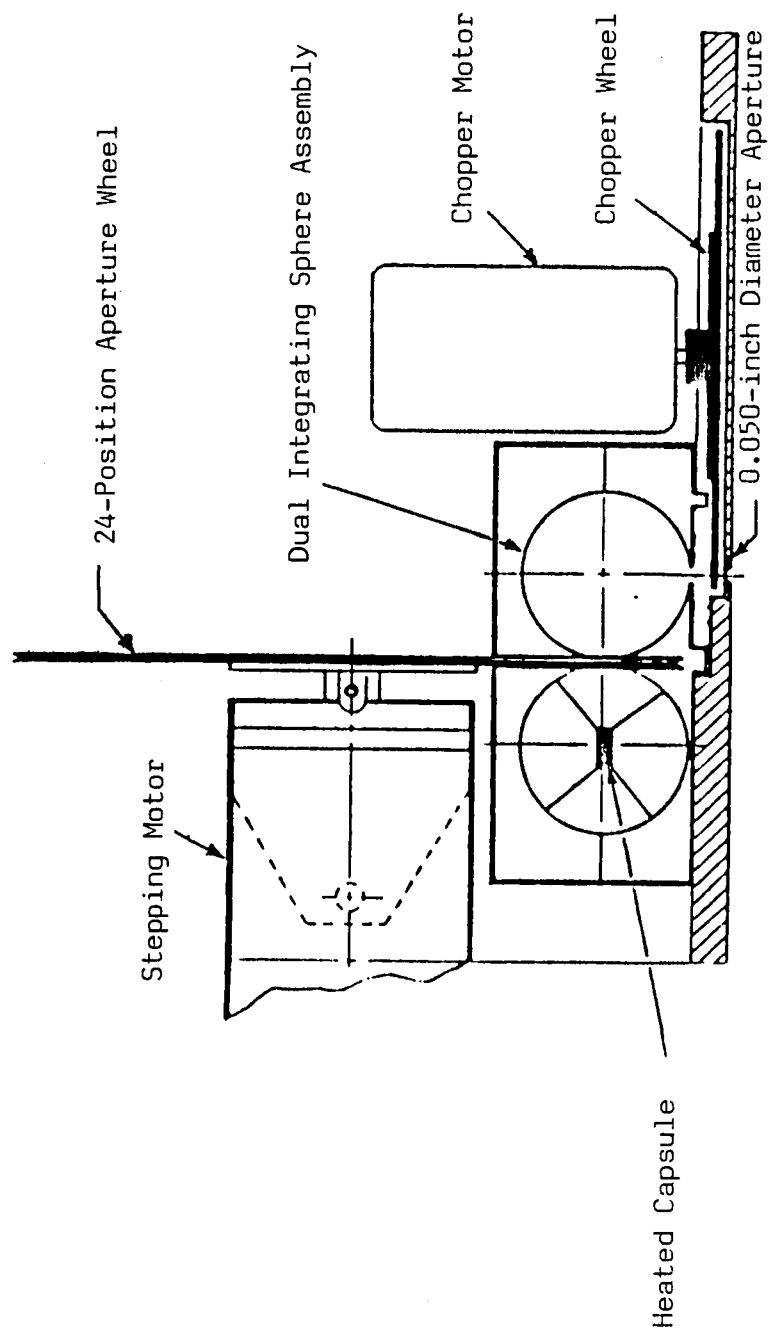


Figure 3. Capsule Source Assembly

integrating spheres are mounted tangentially. The inner surfaces of the spheres were prepared in the same manner as that described for the unisphere.

The capsule, which is mounted inside the input sphere, is an anodized aluminum cylinder. A 0.125-watt carbon resistor and a thermistor are embedded in the cylinder. The resistor is the heat source, and the thermistor is the capsule temperature sensor. The cylinder is coated with 3M Nextel® velvet black paint. The spectral emissivity of an aluminum surface painted with this substance is provided in Table 2.

Radiation from the capsule heater is dispersed uniformly within the input integrating sphere. A portion of this energy passes through an aperture wheel into the output integrating sphere. The aperture wheel contains 23 apertures of various sizes and one blank position. A list of the nominal aperture diameters and areas is provided in Table 3. The position of the aperture wheel is controlled with a 24-position stepping motor. A chopper wheel is located in front of the output aperture of the output sphere.

2.2 Radiation Monitor Telescope

The radiation monitor telescope (RMT) is a device used to provide a transferrable calibration of infrared sources. A schematic of the RMT is provided in Figure 4. The RMT assembly is approximately 8 inches high, 9.5 inches wide, and 30 inches long. A gaseous helium-cooled (GHe) liner provides a 20K enclosure for the entire assembly.

The reference source in the RMT is a small re-entrant conical cavity with a 0.0256-inch diameter output aperture and a nominal

Table 2. Capsule Spectral Emissivity Values.

λ (μm)	ϵ	λ (μm)	ϵ	λ (μm)	ϵ
2.00	0.978	12.46	0.959	19.86	0.964
2.20	0.973	15.62	0.959	19.97	0.965
2.45	0.970	15.69	0.962	20.08	0.962
2.90	0.976	15.77	0.963	20.19	0.962
3.30	0.973	15.91	0.961	20.29	0.958
6.64	0.973	16.04	0.961	20.40	0.956
6.98	0.972	16.18	0.964	20.50	0.954
7.30	0.979	16.31	0.964	20.55	0.952
7.60	0.977	16.44	0.963	20.60	0.951
7.75	0.975	16.57	0.966	20.70	0.946
7.89	0.977	16.71	0.962	20.80	0.943
8.18	0.969	16.84	0.959	20.90	0.936
8.46	0.953	16.97	0.960	21.00	0.930
8.73	0.945	17.04	0.966	21.10	0.941
9.00	0.911	17.10	0.957	21.20	0.932
9.26	0.901	17.23	0.967	21.84	0.932
9.52	0.919	17.36	0.960	21.94	0.935
9.77	0.931	17.60	0.960	22.02	0.938
10.02	0.941	17.71	0.964	22.11	0.940
10.25	0.948	17.83	0.962	22.20	0.938
10.36	0.952	17.94	0.965	22.31	0.937
10.47	0.958	18.06	0.968	22.42	0.941
10.69	0.957	18.20	0.967	22.52	0.932
10.89	0.956	18.56	0.967	22.57	0.936
11.09	0.951	18.68	0.973	22.62	0.934
11.28	0.949	18.80	0.972	22.73	0.935
11.47	0.959	18.92	0.969	22.81	0.943
11.66	0.962	19.40	0.967	22.91	0.939
11.85	0.964	19.46	0.970	23.00	0.952
12.05	0.965	19.52	0.972	32.00	0.952
12.25	0.965	19.63	0.967		
12.35	0.963	19.75	0.968		

Table 3. Capsule Aperture Characteristics.

Aperture Number	Aperture Diameter (in)	Aperture Area (in ²)
24	0.1950	2.9865×10^{-2}
23	0.14976	1.7615×10^{-2}
22	0.14062	1.5530×10^{-2}
21	0.11220	9.8873×10^{-3}
20	0.09008	6.3730×10^{-3}
19	0.07514	4.4344×10^{-3}
18	0.06013	2.8397×10^{-3}
17	0.05008	1.9698×10^{-3}
16	0.04009	1.2623×10^{-3}
15	0.02998	7.0592×10^{-4}
14	0.02561	5.1512×10^{-4}
13	0.02082	3.4045×10^{-4}
12	0.01715	2.3100×10^{-4}
11	0.01414	1.5703×10^{-4}
10	0.01108	9.6421×10^{-5}
9	0.00904	6.4184×10^{-5}
8	0.00700	3.8485×10^{-5}
7	0.00608	2.9033×10^{-5}
6	0.00500	1.9635×10^{-5}
5	0.00402	1.2692×10^{-5}
4	0.00300	7.0686×10^{-6}
3	0.00251	4.9481×10^{-6}
2	0.00194	2.9559×10^{-6}

- | | |
|-----------------------------|-------------------------------------|
| 1. Collected Radiation Path | 7. Resonant Chopper Blade |
| 2. Collecting Mirror | 8. Ge:Cu Detector |
| 3. Folding Mirror | 9. Filter-Wheel Positioning Motor |
| 4. RMT Reference Source | 10. Resonant Chopper Driver |
| 5. Chopper Wheel | 11. Joule-Thompson Expansion Cooler |
| 6. Filter Wheel | 12. 20K Housing |

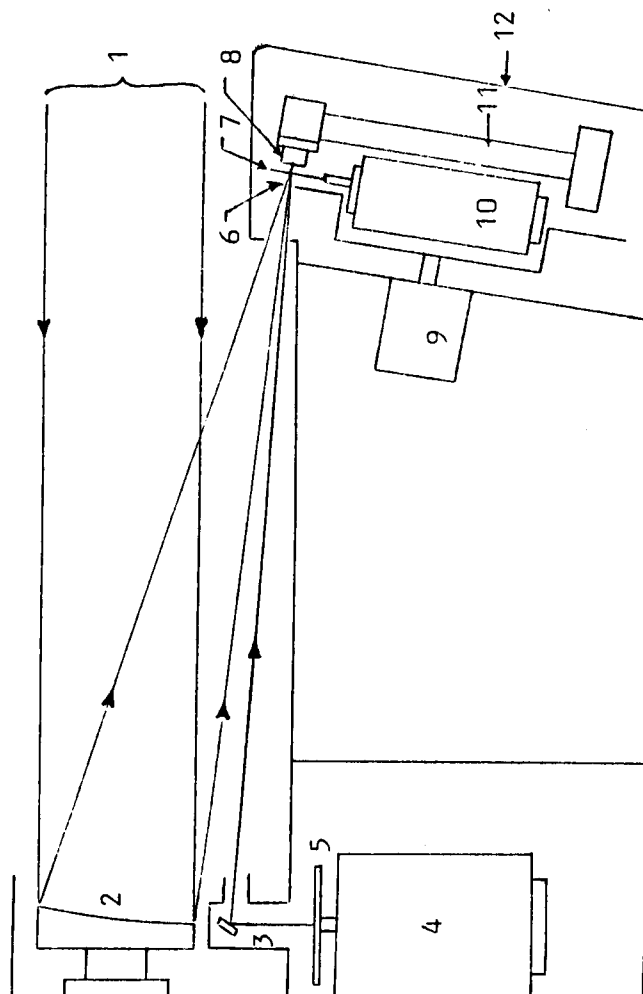


Figure 4. Schematic of the Radiation Monitor Telescope.

temperature range of 150K to 400K. Calibration of this source was accomplished and transferred to the National Bureau of Standards (NBS) with a standard infrared source and a Molelectron bolometer [1].

There are two mirrors in the RMT. An off-axis parabolic mirror collects radiation from a source outside the telescope. This mirror is five inches in diameter and is gold-coated for high reflectance. It has a focal length of 24.245 inches. The other mirror in the telescope reflects the energy from the reference blackbody source onto the detector. It is a plane surface folding mirror with a nominal diameter of one inch.

There are two choppers in the RMT. A variable-speed chopper is located in front of the output aperture of the reference source. The blade of this chopper may be used as a shutter to control background conditions on the detector. When the chopper is in the open position, radiation from the reference source is able to pass by to the detector. When the chopper is in the closed position, the radiation is blocked. The other chopper is located directly in front of the RMT detector and can be used to chop radiation from both the internal source and external sources.

The radiation monitoring device in the RMT is a photoconductive, copper-doped germanium (Ge:Cu) detector. Three separate gain states give the RMT the ability to see IR sources over seven orders of magnitude. The average dimensions of the detector are 0.015083 inch by 0.014917 inch. During operation, the detector is maintained at a temperature of approximately 5K by a Joule-Thompson expansion cooler. The detector responds to radiation at wavelengths ranging from 1 to 32

microns. The spectral responsivity characteristics of the RMT detector are summarized in Table 4. A plot of the relative spectral response is provided in Figure 5.

Spectral filtering capability of infrared sources is provided by a filter wheel in the RMT. This filter wheel contains 12 equal-size openings. Ten of these openings contain various filters, one is covered with a polystyrene sample, and one is simply an open hole which allows the entire quantity of incoming radiation to pass through to the detector. The filter wheel is controlled by a 24-position stepping motor. All of the even-numbered positions are between openings on the filter wheel and allow no radiation to pass. A summary of the filter characteristics for each of the odd-numbered positions is contained in Table 5.

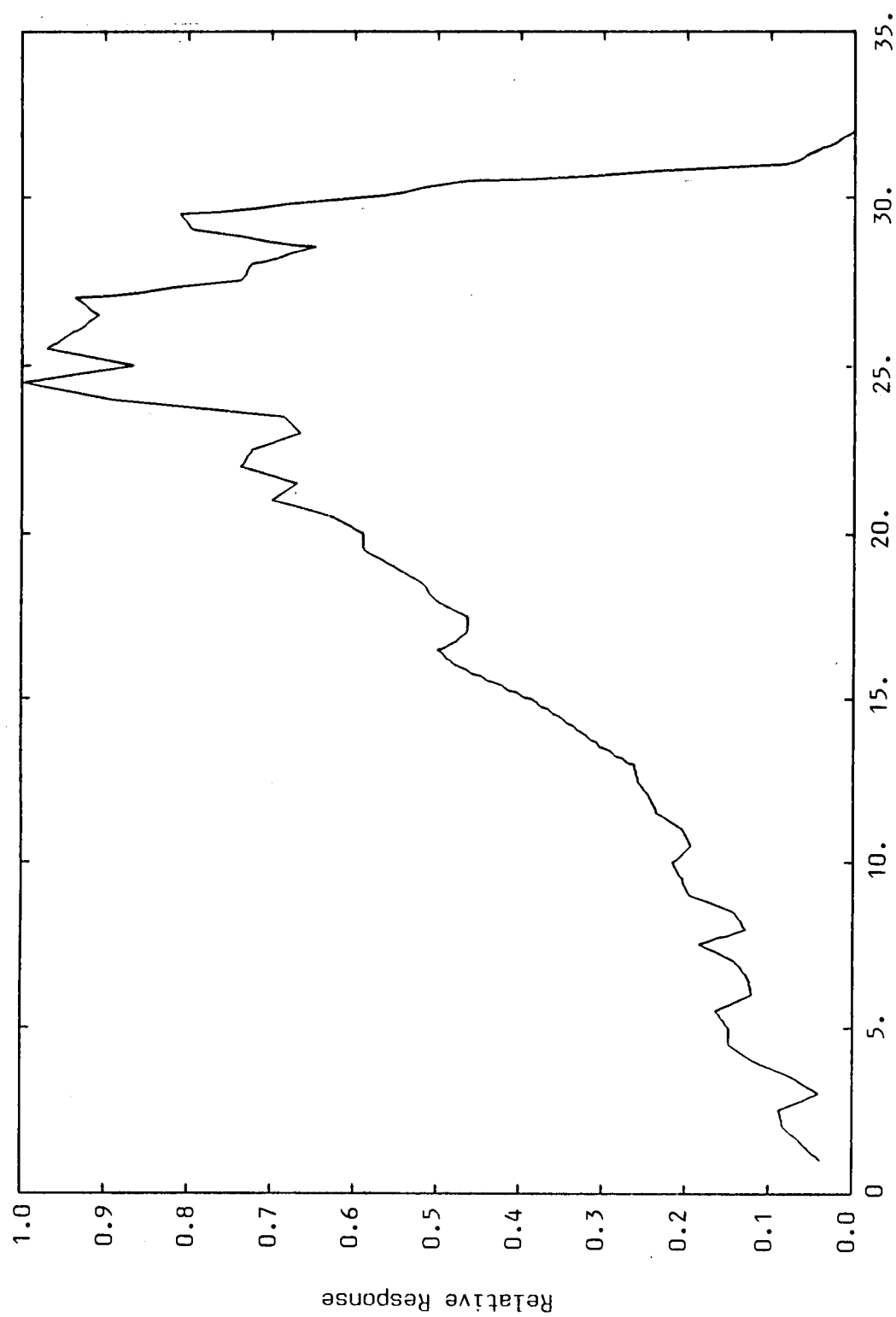
2.3 Collimating Mirror

The collimating mirror used for calibration of the unisphere and capsule sources is a six-degree, off-axis parabola. It is 28 inches in diameter and 3 inches thick, and it has a focal length of 104.5 inches. The mirror was constructed from 6061 aluminum. It has a polished nickel surface which was gold-coated to provide high infrared reflectance.

The collimating mirror is supported in a rigid three-point aluminum mounting ring. Both the mount and the mirror are cooled to 20K with GHe. The mirror and mount assembly are attached to the chamber optical bench by two flexural pivots. The mirror is driven about the pitch axis (defined as the horizontal axis through the vertex and perpendicular to the optical axis of the parabola) by a ball screw/stepper motor

Table 4. RMT Detector Spectral Response Values.

$\lambda(\mu\text{m})$	$R(\lambda)$	$\lambda(\mu\text{m})$	$R(\lambda)$	$\lambda(\mu\text{m})$	$R(\lambda)$
0.1	0.0	12.0	0.245	22.5	0.725
2.0	0.083	12.5	0.259	23.0	0.667
2.5	0.088	13.0	0.263	23.5	0.687
3.0	0.041	13.5	0.299	24.0	0.893
3.5	0.074	14.0	0.326	24.5	1.000
4.0	0.119	14.5	0.355	25.0	0.867
4.5	0.148	15.0	0.387	25.5	0.971
5.0	0.149	15.5	0.432	26.0	0.939
5.5	0.165	16.0	0.476	26.5	0.908
6.0	0.121	16.5	0.500	27.0	0.937
6.5	0.126	17.0	0.466	27.5	0.739
7.0	0.142	17.5	0.465	28.0	0.726
7.5	0.185	18.0	0.504	28.5	0.648
8.0	0.129	18.5	0.519	29.0	0.795
8.5	0.144	19.0	0.553	29.5	0.812
9.0	0.197	19.5	0.590	30.0	0.592
9.5	0.206	20.0	0.591	30.5	0.466
10.0	0.216	20.5	0.628	31.0	0.083
10.5	0.194	21.0	0.701	31.5	0.039
11.0	0.205	21.5	0.671	32.0	0.0
11.5	0.236	22.0	0.738		



Wavelength (Microns)

Figure 5. RMT Detector Spectral Response Plot.

Table 5. RMT Filter Wheel Characteristics.

Filter Wheel Position Number	Lower Wavelength Limit λ_1 (μm)	Upper Wavelength Limit λ_2 (μm)
19	13.71	21.44
17	7.73	13.54
15	2.87	8.27
13	10.24	12.47
11	8.04	9.29
9	21.97	37.40
7	14.07	15.94
5	4.97	8.10
3	13.61	23.11

actuator. Pitch position of the collimating mirror is measured using a 10-turn rotary potentiometer.

2.4 Instrumentation

The unisphere and capsule sources are maintained at a constant temperature by Artronix feedback-type controllers. The RMT reference source temperature is controlled and maintained with a Lakeshore cryogenic temperature controller. Analog outputs from the temperature sensors on the sources are converted to digital format and input to a Fluke digital voltmeter. These voltages are converted to temperatures and displayed by a ModComp control computer.

Source aperture positions are indicated by liquid crystal displays (LCDs). The RMT filter position is also displayed on an LCD. Control systems are available to provide proper positioning of the aperture wheels and the filter wheel. Systems are also provided to control the operation and the speed of the various choppers. Light indicators were used to indicate the chopper blade position when the chopper was not running. The open position was defined as a position for which the chopper blade did not block the source output aperture.

The RMT detector signal is measured with a Brookdeal 5206 phase-lock amplifier. The output of this device is displayed in a digital format. A variable load resistor in the detector electronics package is used to provide the three separate detector gain states. The desired gain state is established using a three-position selector switch.

CHAPTER III

THEORY

3.1 Source Types

The output of a thermally radiating body is a function of the nature of the emitting surface, the source temperature, and the wavelength. Thermal sources can be divided into several different types. One method by which sources may be categorized is according to the manner in which the emissivity varies with wavelength. Spectral emissivity may be used to classify sources as blackbodies, graybodies, or selective radiators.

3.1.1 Blackbodies

A blackbody source is a perfect emitter of radiant energy at all wavelengths. The blackbody is a theoretical concept. Although it is not possible to build a true blackbody, it is possible to produce sources which emit energy which closely approximates that from a blackbody.

The spectral radiant emittance from a blackbody is described by Planck's law [2], which can be written as

$$W_{\lambda} = \frac{C_1}{\lambda^5} \frac{1}{e^{\frac{C_2}{\lambda T}} - 1} \quad , \quad (1)$$

where

W_{λ} = Spectral emittance

$$C_1 = 2 \cdot \pi \cdot h \cdot c^2 = 37418.32 \text{ W}\mu\text{m}^4/\text{cm}^2$$

$$C_2 = c \cdot h / k = 14387.86 \text{ } \mu\text{mK}$$

$$\lambda = \text{Wavelength (}\mu\text{m)}$$

$$T = \text{Absolute temperature (K)}.$$

The spectral radiant emittance varies with source temperature. A plot of radiant emittance versus wavelength at various temperatures is provided in Figure 6. The radiant emittance increases with increasing source temperature at all wavelengths. The location at which the radiant emittance is a peak value shifts to lower wavelengths as the temperature is increased. The wavelength at which the radiant emittance is a maximum (λ_m) is given by Wien's law [3], which states that

$$\lambda_m T = 2897.6 \text{ } \mu\text{mK}. \quad (2)$$

A table of source temperature versus peak wavelength is provided in Table 6.

For a radiating blackbody, the emittance over a given wavelength band can be determined by integrating Planck's expression over the appropriate limits. In equation form,

$$W_{d\lambda} = \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^5} \left[\frac{C_1}{e^{\frac{C_2}{\lambda T}} - 1} \right] d\lambda. \quad (3)$$

In this expression, λ_1 is the lower wavelength limit and λ_2 is the upper wavelength limit. If this integration is performed over all wavelengths, the result is given by the Stefan-Boltzmann relationship [4], which states that

$$W = \sigma T^4, \quad (4)$$

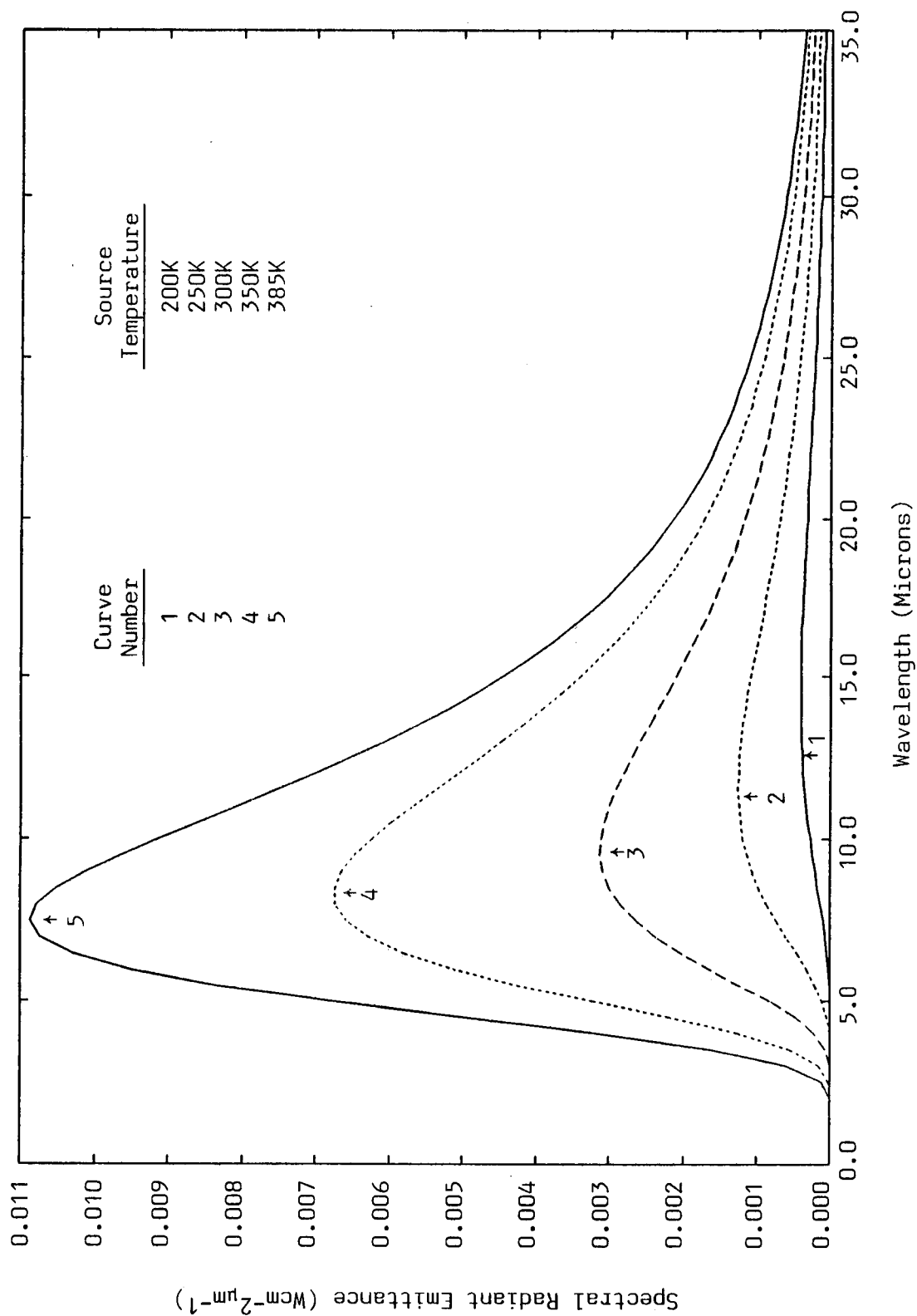


Figure 6. Spectral Radiant Emittance Curves for Various Source Temperatures.

Table 6. Peak Wavelengths for Various Source Temperatures.

Source Temperature (K)	Peak Wavelength $\lambda_m - (\mu\text{m})$
200	14.5
250	11.6
300	9.7
350	8.3
385	7.5

where σ is the Stefan-Boltzmann constant, with a value of $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$. This relationship clearly indicates that the output of a blackbody is directly proportional to the absolute source temperature raised to the fourth power.

The percentage of energy in a given wavelength band can also be determined using blackbody table fractions. The fraction of the total emissive power that is emitted in a given wavelength band is designated by $F_{\lambda_1 - \lambda_2}$. It is determined from an expression of the form

$$F_{\lambda_1 - \lambda_2} = \frac{\int_{\lambda_1}^{\lambda_2} W_{\lambda} d\lambda}{\sigma T^4} \quad (5)$$

The total output of a blackbody depends only on the source temperature. General tables have been produced which list values of $F_{0 - \lambda T}$ as a function of the product λT [5]. By calculating λT and determining the corresponding value of $F_{0 - \lambda T}$ from the tables for both limits of the wavelength band, the blackbody fraction for that wavelength band may be determined from the relationship

$$F_{\lambda_1 - \lambda_2} = F_{0 - \lambda_2 T} - F_{0 - \lambda_1 T} \quad (6)$$

where λ_2 is the upper wavelength limit and λ_1 is the lower limit.

3.1.2 Graybodies

When the output of a source is less than the maximum possible, the source is not a blackbody. A factor called the emissivity is introduced to account for the fact that the output is only a fraction of the total possible. The emissivity, which is represented by the

symbol ϵ , is the ratio of the radiant emittance (W') of the source to the radiant emittance of a blackbody at the same temperature. It is a numeric value which lies between zero and one. For a blackbody, $\epsilon = 1$. A more common case and one of special interest is that of a graybody. A graybody is a source for which the value of ϵ is constant (but not unity) for all wavelengths. If ϵ is constant and its value is known, then the total radiant emittance is given by

$$W = \epsilon \sigma T^4. \quad (7)$$

Blackbody fraction tables can still be applied to determine the output in a given wavelength band for a graybody.

3.1.3 Selective Radiator

A selective radiator is a source for which the emissivity varies with wavelength. The ratio of the source output to that of a blackbody is not the same for all wavelengths. For this type of source, the Stefan-Boltzmann relationship does not hold and the blackbody fraction tables cannot be applied. If the spectral emissivity characteristics are known, they can be accounted for and used to determine the total radiant emittance or the emittance in a given wavelength band. The expression used is of the form

$$W_{d\lambda} = \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^5} \frac{C_1 \epsilon(\lambda)}{\left[\frac{C_2}{\lambda T} - 1 \right]} d\lambda, \quad (8)$$

where $\epsilon(\lambda)$ is the emissivity as a function of wavelength.

3.2 Data Correction Methods

3.2.1 Spectral Responsivity

When the output of any source is measured, the relative response of the measuring device may not be constant at all wavelengths. A thermal detector is one for which the response is proportional to the energy absorbed. The spectral response plot for a thermal detector is a straight line; the relative response value is constant at all wavelengths.

Unfortunately, thermal detectors do not generally have the sensitivity nor the time response required for use on LWIR sensors. For such applications, photon detectors must generally be used. Photon detectors are not energy sensitive; they respond to the total number of photons absorbed [6]. A photon detector has a cutoff wavelength beyond which the detector does not respond. The energy per photon is inversely proportional to wavelength. Therefore, more photons are required at longer wavelengths to maintain a constant energy per unit wavelength interval. Thus, the relative response of a photon detector nominally increases with increasing wavelength until the cutoff wavelength is reached. The spectral response of the measuring device in the RMT, a photoconductive detector, is plotted in Figure 5 (p. 18). It is apparent that the relative response of the detector is a function of wavelength and does, in general, increase with increasing wavelength out to the cutoff wavelength.

The spectral response variation of the measuring device must be accounted for in order to determine the actual output from a source.

To account for this variation, another term must be included in the expression for radiant emittance. The general expression becomes

$$W_{d\lambda} = \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^5} \left[\frac{C_1 \epsilon(\lambda) R(\lambda)}{e^{\frac{C_2}{\lambda T}} - 1} \right] d\lambda, \quad (9)$$

where $R(\lambda)$ is the relative response of the detector as a function of wavelength.

3.2.2 Tare

For the calibration technique in which choppers are used, the signal recorded is the difference between that measured when the source is visible to the detector and the reference condition (when the copper blade is blocking the source aperture). A tare is the amount of signal present when the chopper blade is in view of the detector. If the chopper heats up during operation, the tare increases. The detector output signal must be corrected for a tare, particularly when the signal levels due to the source output are low. The tare can be determined by measuring the signal obtained with the source aperture blocked. To block the aperture, the aperture wheel is placed in the blank position. The value of the tare measured should be subtracted from the detector output values recorded at all aperture positions.

3.2.3 Diffraction Corrections

Calculations of the output of a source take into account the diameter of the output aperture of the source. Diffraction is a phenomena which involves interaction between a train of waves and an obstacle. In optical systems, diffraction occurs at the edges of optical

elements and diaphragms used to limit the beam. Diffraction occurs at the output aperture of the source. It reduces the output from the source. A diffraction correction factor (K_d) can be determined. It depends on the temperature of the source (T) according to the expression

$$K_d = 1 - \frac{C}{T}, \quad (10)$$

where C is a constant which is related to the type of source and the size of the output aperture [1,7]. The diffraction correction factor, which is always less than or equal to unity, accounts for the reduction in output from the source due to diffraction losses. Values of C are calculated using the source and collimation system dimensions.

3.3 Detector Calibration

In order to calibrate the radiation from an infrared source, the radiation monitoring device itself must be calibrated. The primary quantity of interest is the RMT detector responsivity. Responsivity is defined as the ratio of output to input, or the detector output signal divided by the power on the detector. This can be written as

$$R = \frac{V}{P}, \quad (11)$$

where R is the responsivity in volts/watts, V is the detector output signal in volts, and P is the power incident on the detector in watts. The detector signal is measured directly using the lock-in amplifier. The power on the detector can be evaluated from the expression

$$P = \frac{W_{d\lambda}}{\Pi} \Omega A K_d, \quad (12)$$

where $\frac{W_{d\lambda}}{\pi}$ is the normal output intensity of the reference blackbody source over a given spectral band, Ω is the solid angle from the aperture to the RMT detector, A is the area of the output aperture of the RMT source, and K_d is the diffraction correction term. The solid angle is given by

$$\Omega = \frac{A_d}{d^2}, \quad (13)$$

where A_d is the area of the detector ($2.25 \times 10^{-4} \text{ in}^2$) and d is the distance between the aperture and the detector (27.43 in). The parameters Ω and A are fixed by the telescope geometry. The values of Ω and A are $2.99 \times 10^{-7} \text{ sr}$ and $3.3294 \times 10^{-3} \text{ cm}^2$, respectively. The diffraction correction term is a function of the RMT source temperature (T) and is calculated from Equation (10). The value of C is 4.726 for the RMT source. The normal output intensity is determined by evaluating the integral contained in Equation (9). Numerical integration can be used to evaluate this expression. The integral is evaluated over the broadband region from 1 to 32 μm . Since the RMT reference blackbody is a cavity-type source, the emissivity is assumed to have a value of one over the entire wavelength band. This integration can be performed using an Infrared Source Radiation Program written for a Digital Equipment Corp. LSI 11/23 microcomputer. The capability of including the spectral response of the RMT detector is incorporated into this program.

3.4 Source Calibration

3.4.1 Gain Ratio

The RMT detector has three separate gain states which enable it to cover a dynamic range of seven orders of magnitude. These states are designated as high, medium, and low, with high being the largest gain and providing the greatest sensitivity. In order to compare results obtained with the sensor operating in different gain states, it is necessary to know the ratio between the states. This ratio is determined by using apertures which produce measurable signals on two adjacent gain states. Signals in these overlapping regions are used to calculate a ratio between the states. All data available are analyzed to determine an average value of gain-state ratios to be used. The results of the overlap study used to determine the ratio between high and medium gains are provided in Table 7.

3.4.2 Source Calibration Constant

Source irradiance (H) can be calculated by dividing the detector output signal by the RMT detector responsivity (R) and the area of the parabolic mirror in the telescope (A_p). This expression can be written as

$$H = \frac{VG}{RA_p}, \quad (14)$$

where G is the gain ratio correction factor used to convert all signals to the same baseline level, independent of the RMT detector gain state. The value of G for runs made at high gain state is defined as one. As

Table 7. RMT Detector High to Medium Gain State Ratios.

Aperture Number	Source Temperature (K)				
	150	200	250	300	350
10	194	---	---	---	---
9	200	---	---	---	---
8	204	192	---	---	---
7	203	201	190	---	---
6	---	214	197	190	---
5	---	218	205	198	193
4	---	---	---	203	202
3	---	---	---	---	210
Average					200.8
Standard Deviation					4.0%

a result of the gain-state overlap study, G was found to have a value of 200.8 for the runs made at medium detector gain.

A general expression for the irradiance of a source as a function of aperture area and source temperature is of the form

$$H = KA_r r K_d W_{d\lambda}. \quad (15)$$

The primary objective of performing a source calibration is to evaluate the source irradiance constant (K). Solving Equation (15) for this constant yields

$$K = \frac{H}{A_r r K_d W_{d\lambda}}. \quad (16)$$

In this expression, H is the irradiance measured and calculated from Equation (14) for a particular aperture, A_r is the inverse of the attenuation ratio corresponding to that aperture, K_d is the diffraction correction determined from Equation (10), r is the reflectance of the collimating mirror, and $W_{d\lambda}$ is the radiant emittance evaluated over the appropriate spectral limits. When calculating the calibration constant for one of the integrating sphere sources, an aperture should be selected which produces an output signal which most nearly matches that obtained during the RMT detector calibration. The values of attenuation ratio are determined during the linearity investigation. The reflectance of the collimating mirror is 98 percent, so that $r = 0.98$. The value of C used in the evaluation of the diffraction correction for the unisphere or the capsule source is 7.767. The arguments which were made in Section 3.3 regarding evaluation of the integral in the expression for $W_{d\lambda}$ are applicable. Since the unisphere is

a cavity-type source, $\epsilon(\lambda)$ is assumed to have a value of one for all wavelengths. For the capsule source, the spectral emissivity values are included in the calculations.

3.5 Source Linearity

The extrapolation technique used to calibrate an infrared source whose output falls several orders of magnitude below that of the standard relies heavily on determining the linearity characteristics of the source. Several different methods can be used to evaluate the linearity characteristics of a source. The methods of evaluation that were used in this investigation are described in the following paragraphs.

The voltage (V) measured by a detector is related to the irradiance (H) of the target and the responsivity (R) of the detector. The relationship that exists is

$$V = HRA_p, \quad (17)$$

where A_p is the area of the collecting mirror. Taking natural logarithms of both sides of this expression yields

$$\ln V = \ln H + \ln RA_p. \quad (18)$$

The term A_p is a constant for a given system. For an ideal detector, the responsivity is constant. Therefore, this expression indicates that the logarithmic relationship between detector signal and irradiance, for an ideal detector, is linear (of the form $y = mx + b$). On a log-log scale, a plot of detector signal versus irradiance should be a straight line. Furthermore, the line should have a slope of one; the line should be oriented at a 45° angle with respect to the positive axes.

For a given source temperature, irradiance is a function only of the aperture area. Therefore, a plot of detector signal versus aperture area, on a log-log scale, should follow the same linear relationship.

Linearity characteristics can also be investigated by comparing the output from different apertures on the unisphere and capsule sources. One method of obtaining this comparison involves calculating the ratio between the detector output signal for a specific aperture and the signal for an aperture which is taken as the reference. The detector output signal is related to the aperture area by the expression

$$V = ZRAf(T,\lambda), \quad (19)$$

where Z is a constant of proportionality, R is the detector responsivity, A is the aperture area, and $f(T,\lambda)$ indicates that the output voltage is a function of the temperature and spectral characteristics of the source. For an ideal detector, the responsivity should be a constant. Therefore, at a constant source temperature, the detector output is directly proportional to the aperture area. Thus, the output signal ratio between a specific aperture and the reference aperture should be equal to the ratio of the areas of the same two apertures. An indication of how much the source deviates from a perfectly linear response can be obtained by comparing the values of these two ratios. In addition, the ratio of the outputs of the apertures provides a more accurate indication of the true source behavior, at least at large apertures which produce signals which can be measured reasonably well.

The ratio of signal values obtained for different aperture settings on a given source is defined as an attenuation ratio. For the

unisphère source, the attenuation ratio (AR) is calculated from the expression

$$AR = \frac{V_8}{V_d} \times 16 \quad (20)$$

where V_8 is the signal measured with the reference aperture (aperture 8) and V_d is the detector signal measured at the aperture of interest.

The factor 16 is included simply to make all of the ratios (except the smallest one) have values which are greater than one. For the capsule source, the attenuation ratio is defined as

$$AR = \frac{V_{20}}{V_d} \times 4 \quad (21)$$

where V_{20} is the signal measured with the reference aperture (aperture 20). To determine the aperture area ratios to which these attenuation ratio values should be compared, the signal values in these two expressions should be replaced with the corresponding aperture areas. For the unisphère source, a theoretical ratio for each aperture was also calculated based on throughput calculations.

3.6 Source Spectral Characterization

3.6.1 Method of Gouffé

In constructing cavity-type sources, the radiation leaving the output aperture closely simulates that of a blackbody if the enclosure is isothermal and the area of the hole is much smaller than the internal surface area of the enclosure. The accuracy of simulation is called the effective emissivity. Many theories have been developed to calculate the effective emissivity for a given source design. One of the

best known theories is the method of Gouffé [2]. Although many have questioned some of its assumptions, it is still the most widely quoted method of addressing the subject. The basic assumption made is that the cavity walls are diffuse reflectors. The effective emissivity of a cavity is given by the expression

$$\epsilon_0 = \epsilon' \left[1 + (1 - \epsilon) \left(\frac{A}{S} - \frac{A}{S_0} \right) \right] \quad (22)$$

with

$$\epsilon' = \frac{\epsilon}{\epsilon(1 - \frac{A}{S}) + \frac{A}{S}} \quad (23)$$

In these expressions, ϵ_0 is the effective emissivity, ϵ is the emissivity of the cavity walls, A is the area of the output aperture, S is the total surface area of the cavity (including that of the opening), and S_0 is the surface area of a sphere whose diameter is equal to the depth of the cavity. The cavity effect is apparent from these expressions; the effective emissivity of a cavity always exceeds that of its surface.

3.6.2 Integrating Sphere Sources

Utilization of attenuation and reflection techniques in infrared source systems may create deterioration in the blackbody performance of those sources. To investigate this phenomena, three methods were used to determine if there are any serious spectral problems inherent in the integrating sphere or the basic cavity-type sources. The first method involves examining the relationship between the RMT detector

signal and the source temperature raised to the fourth power. For a blackbody, the source should obey the Stefan-Boltzmann law, and the relationship between the RMT detector signal and the source temperature raised to the fourth power should be linear. A plot of the signal versus T^4 at different source temperatures should form a straight line with a slope of one.

A second method of source spectral characterization utilizes the filter wheel in the RMT. Output signals recorded at each filter-wheel position are divided by the total output possible, as measured with the filter wheel in the open-hole position. In this manner, the percentage of the incoming radiation which the filter allows to pass through to the detector can be determined. A comparison between these results and those of a calibrated reference source, such as the one in the RMT, can be made. One method of quantifying this comparison involves dividing the normalized output from the source being investigated by that from the RMT source. From these results, a quick indication of how much the spectral characteristics of each source differ from those of the RMT source is provided. This method involves a comparison of the signals from the test source with those from the RMT reference source, and thus depends on the assumption that the RMT source is a spectrally black radiator. In order to obtain the most accurate comparison, filter-wheel data should be obtained at an aperture which provides an open-hole signal which most nearly matches that obtained with the RMT source.

The final method of source spectral characterization involves the source calibration constant. Since this calibration constant is

essentially a geometric factor and its calculation accounts for the spectral response of the RMT detector, it should be a constant for all source temperatures for a given source aperture. Source calibration constants can be calculated for all available source temperatures, using the methods described in Section 3.4, to determine if any large discrepancies exist at any source temperatures. Such discrepancies could be indicative of spectral problems with the source.

CHAPTER IV

TEST DESCRIPTION

To obtain source calibration data, the test chamber was evacuated and cryogenically cooled to nominal test conditions. A chamber pressure of below 1×10^{-7} torr was established and most surfaces in the test volume were cooled to and maintained at nominally 20K. The temperatures of the infrared sources were set to the desired operating points and maintained by the feedback controller units.

For the initial step of the calibration, the integrating sphere source assembly was driven in the lateral direction and the focus direction (toward or away from the collimating mirror) to focus and center the source image on the RMT detector. The collimating mirror was also driven in pitch during this operation. Iterative position adjustments were made in all three directions to maximize the RMT detector signal and establish the best focus condition.

The various choppers and aperture wheels, as well as the RMT filter wheel, were used to control the amount of target energy and the amount of background energy on the RMT detector. The detector output signals were read from the lock-in amplifier and recorded manually on specially designed data forms. All pertinent test parameters were also recorded on these forms.

The first stage of the actual calibration effort involved calibrating the RMT detector using the RMT reference source. Experience has shown that the linearity of the RMT detector is improved if a small amount of background energy is imposed on the detector (Figure 7). An

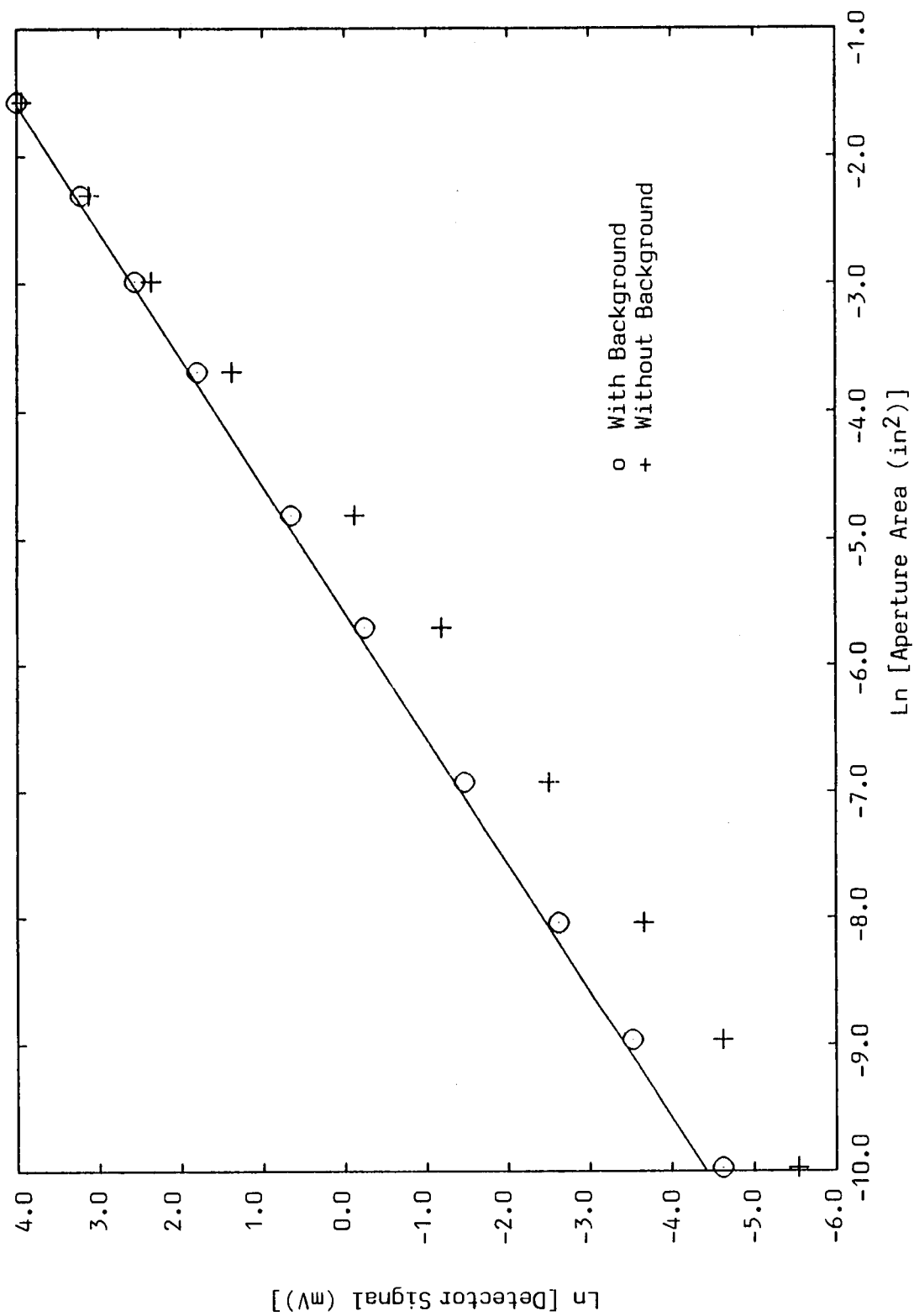


Figure 7. Linearity Characteristics With and Without an Imposed Background.

aperture was selected on the unisphere or capsule source to provide a selected amount of background on the detector. The chopper associated with the integrating sphere source was stopped in the open position such that the chopper blade did not block the source output aperture. The RMT detector was set to the high gain state. The chopper in front of the RMT source was operated at the desired frequency, and the signal measured on the detector was recorded. This operation was repeated for several different RMT source temperatures.

Infrared source linearity and calibration data were obtained by stepping through the apertures on the sources and recording the RMT detector signal at each aperture position. Linearity and calibration data were taken with a controlled amount of background on the detector provided by the RMT source. The RMT detector was set to the desired gain state and the chopper in front of the RMT source was stopped in the open position. The RMT source was set to a temperature which would provide nearly the same amount of background on the detector as imposed by the integrating sphere source during the RMT detector calibration.

Spectral data were obtained by stepping through the odd-numbered filter positions on the RMT filter wheel. These data were always taken with no intentional background imposed on the detector and the RMT detector set to the high gain state. The RMT source output or the integrating sphere source output was blocked when the other source was being calibrated spectrally. When spectral data were obtained for one of the integrating sphere sources, an aperture was usually selected which would provide an open-hole signal which most nearly matched that produced when the RMT source spectral data were taken at the same source temperature.

CHAPTER V

RMT DETECTOR CALIBRATION RESULTS

The responsivity of the RMT detector was calculated using the methods described in Section 3.3. The unisphere and capsule sources were calibrated at two different times. The responsivity of the RMT detector was considerably different during these two installations. Table 8 presents the responsivity values obtained at various source temperatures during the unisphere calibration. Table 9 presents the results obtained during the capsule calibration.

Responsivity values were calculated both with and without the spectral response of the detector included. Both values are listed in Tables 8 and 9. Ideally, one would desire that the detector responsivity not vary with source temperature. A casual observation of these tables reveals that the detector responsivity did vary considerably with source temperature. In all cases, very definite trends existed. When the detector spectral response was not included, the responsivity decreased when the source temperature was increased. The opposite trend existed when the relative spectral response was taken into account; the responsivity increased as the source temperature increased.

The responsivity values obtained during the unisphere calibration are plotted versus source temperature in Figures 8 and 9. The results from the capsule calibration were not plotted because data were obtained over a more limited temperature range and only a limited set of data points was available. The trend of the results obtained during the

Table 8. RMT Detector Responsivity Values (Unisphere Test).

Average Source Temperature (K)	Average Detector Signal (V)	Detector Responsivity ($\frac{V}{W}$)	
		Without Spectral Response	Includes Spectral Response
149.46	0.00735	---	---
172.7	0.01445	1.337×10^{10}	2.507×10^{10}
200.16	0.02858	1.316×10^{10}	2.697×10^{10}
224.87	0.04548	1.233×10^{10}	2.735×10^{10}
250.19	0.07115	1.201×10^{10}	2.887×10^{10}
274.9	0.1017	1.140×10^{10}	2.952×10^{10}
299.43	0.1420	1.103×10^{10}	3.067×10^{10}
323.63	0.187	1.045×10^{10}	3.104×10^{10}
350.30	0.2517	1.008×10^{10}	3.208×10^{10}
373.65	0.3121	9.551×10^9	3.216×10^{10}
384.17	0.3429	9.350×10^9	3.226×10^{10}
Average		1.127×10^{10}	2.960×10^{10}
Standard Deviation		12.7%	8.4%

Table 9. RMT Detector Responsivity Values (Capsule Test).

Average Source Temperature (K)	Average Detector Signal (V)	Detector Responsivity ($\frac{V}{W}$)	
		Without Spectral Response	Includes Spectral Response
250.39	0.0737	1.042×10^{10}	2.503×10^{10}
300.13	0.123	9.476×10^9	2.640×10^{10}
350.65	0.216	8.615×10^9	2.744×10^{10}
Average		9.504×10^9	2.629×10^{10}
Standard Deviation		9.5%	4.6%

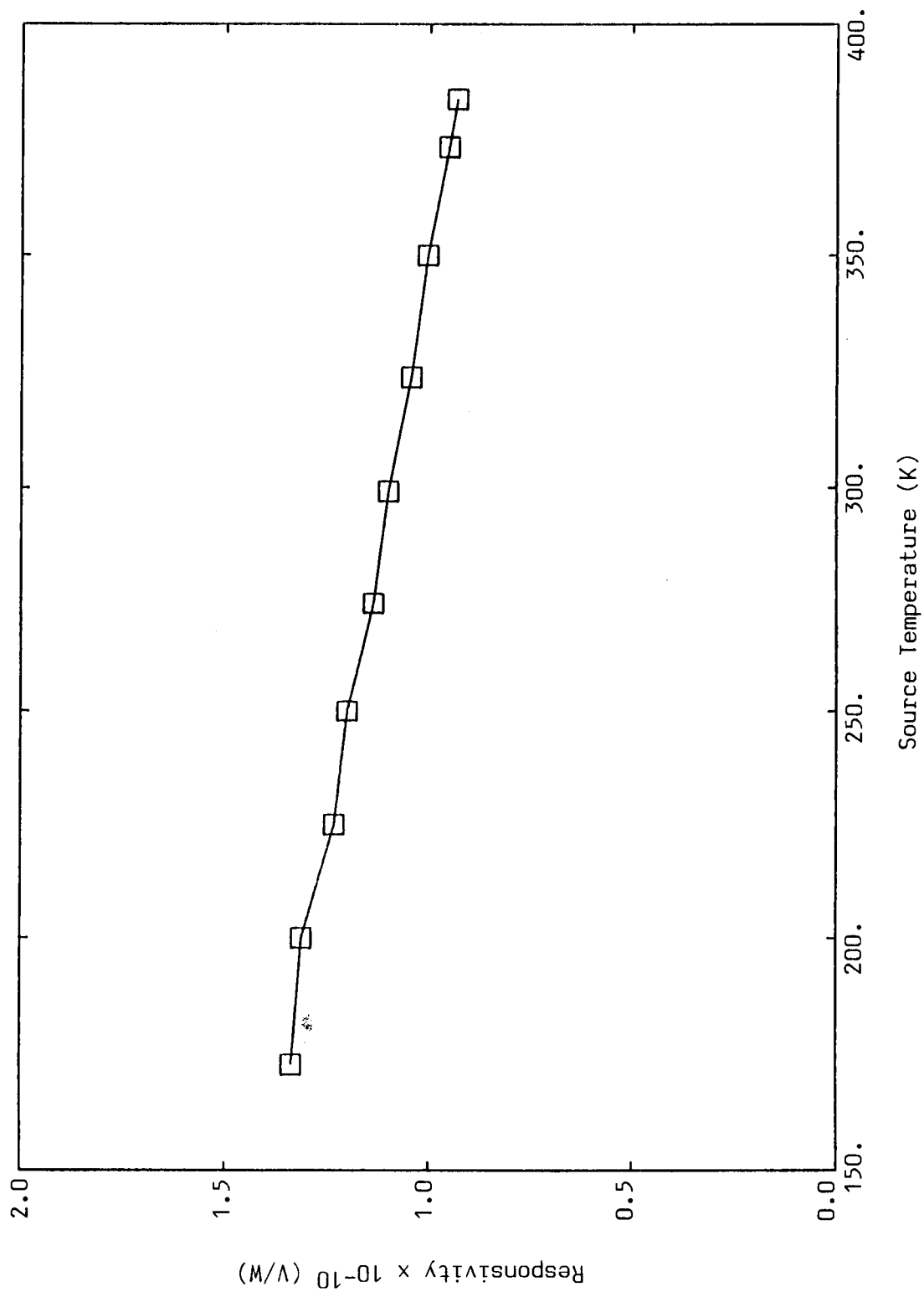


Figure 8. RMT Detector Responsivity (Without Spectral Response).

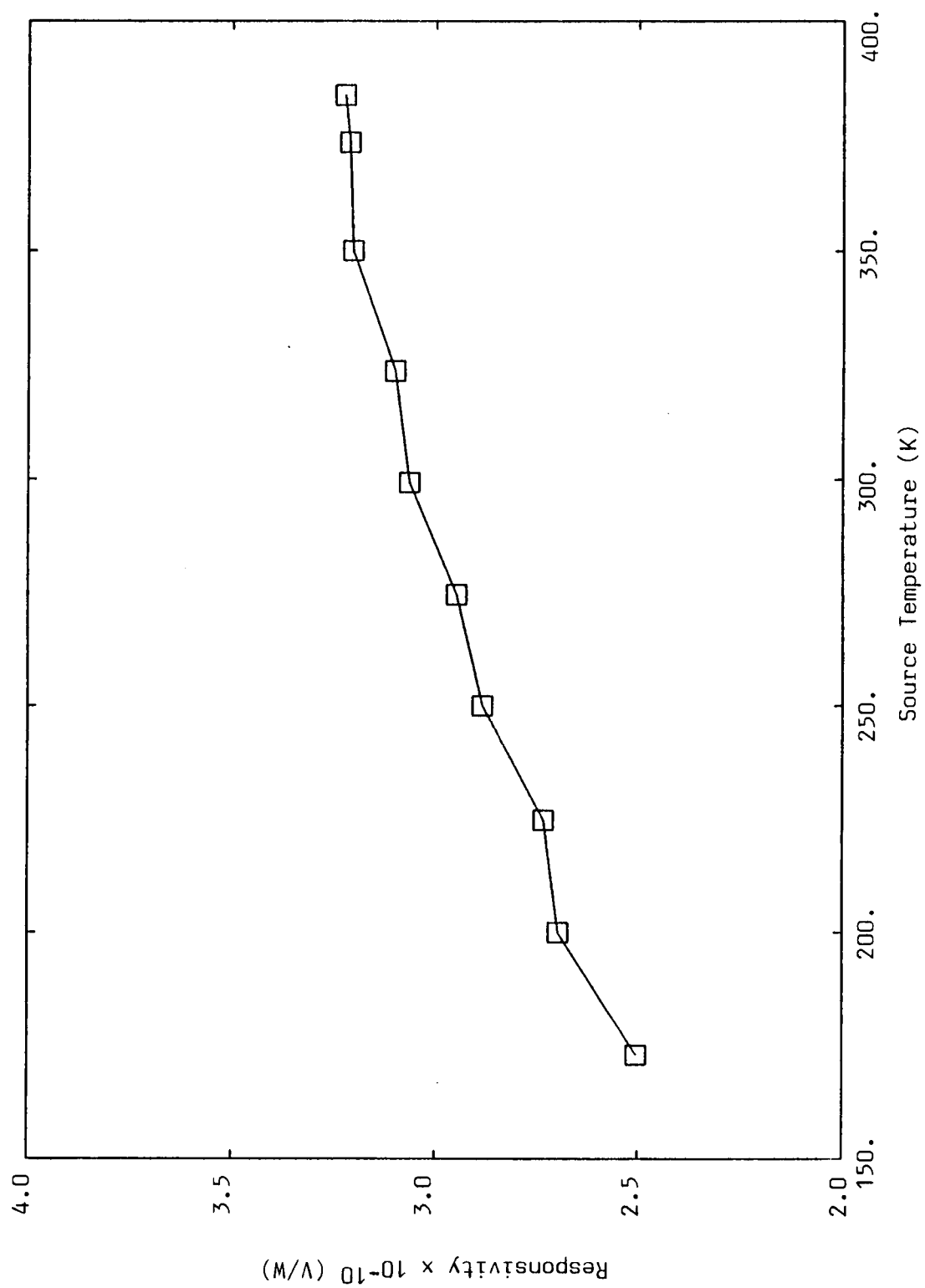


Figure 9. RMT Detector Responsivity (Spectral Response Included).

capsule calibration was similar to that for the unisphere calibration over the temperature range that was covered.

The detector responsivity values calculated without accounting for detector spectral response are plotted versus source temperature in Figure 8. The responsivity decreased steadily as source temperature increased. The percent difference between the values obtained at source temperatures of 175K and 385K was 35.4 percent. The average responsivity for all temperatures was 1.127×10^{10} V/W. The value obtained at 300K was the value closest to the average. The standard deviation of the results was 12.7 percent.

The detector responsivity values calculated when detector spectral response is included are plotted versus source temperature in Figure 9. The responsivity increased steadily as source temperature increased, but began to level out at temperatures above 350K. The percent difference between the values obtained at source temperatures of 175K and 385K was 25.1 percent. The average responsivity was 2.96×10^{10} V/W, which was nearest to the value obtained at a source temperature of 275K. The standard deviation of the results was 8.4 percent.

It is not surprising that the responsivity varies with source temperature when the detector spectral response is not included. Excluding the relative spectral response is equivalent to assuming that $R(\lambda) = 1$ for all wavelengths. Figure 5 (p. 18) illustrates that the $R(\lambda)$ values are much less than one in the shorter wavelength region. As source temperature increases, the radiant emittance peak shifts to shorter wavelengths. As a result, the value inside the integral in the radiant emittance expression (Equation (9)) becomes too large

power on the detector is too high. Since the power term is in the denominator of the responsivity expression, the responsivity values should decrease as the source temperature increases. This expected trend is consistent with the results obtained.

Incorporating the relative spectral response of the detector into the calculations should eliminate this difficulty, and the responsivity calculated should be constant for all source temperatures. The results obtained do not substantiate this claim. Even when the detector spectral response is included, the responsivity varies significantly with source temperature. The most logical explanation for this discrepancy is that the relative spectral response characteristics of the RMT detector are not accurate. In particular, it was noted that the responsivity curve begins to level off at the higher source temperatures. This would suggest that the spectral response characteristics at the shorter wavelengths may be valid. It appears as though the spectral response values at the longer wavelengths may be incorrect.

CHAPTER VI

LINEARITY RESULTS

Several methods were used to evaluate the linearity characteristics of the integrating sphere sources. Plots were made of aperture area versus detector signal to determine if this relationship was linear. Signal ratios were compared with aperture area ratios to assess this technique. For the unisphere source, signal ratios were also compared with theoretical values obtained from throughput calculations for the source geometry. The variation in signal ratio with source temperature was investigated. Calibration constants were calculated at different aperture positions to assess the accuracy of using a single calibration constant for all apertures. Several sets of data were analyzed to determine the repeatability that can be obtained in positioning the apertures and predicting the output associated with each aperture. The results for both the unisphere and capsule sources are presented and discussed in the following sections.

6.1 Unisphere Source

6.1.1 Unisphere Aperture Area Versus Detector Signal

Plots were made of the natural log of aperture area versus the natural log of the detector signal for all unisphere source temperatures. Lines were fitted through the data points using a linear curve-fit program. For a perfect system, the response should be linear and the slope of the line fitted through the data points should have a value of one. The plot for the data obtained at a source temperature of 300K is shown

in Figure 10. All data points were obtained with the RMT detector in medium gain. In most cases, the points fall very close to the fitted line. The most notable exception is the data point corresponding to the largest aperture (aperture 12) and thus the largest detector signal. This point fell significantly below the fitted line for all source temperatures. This discrepancy implies that either the output associated with aperture 12 was not as large as expected, the aperture dimensions were not accurate, or the aperture wheel may not have been positioned correctly for this aperture setting. The slope of the line shown in Figure 10 is 1.003. The slopes of the fitted lines for all source temperatures are listed in Table 10. In all cases, the slope of the fitted line is within 5 percent of the ideal value.

6.1.2 Unisphere Signal Ratio at Various Source Temperatures

The ratios of the detector signals at various aperture positions were calculated for the unisphere according to the method described in Section 3.5 (Equation (20)). The results were calculated based on aperture 8 as the reference. The average results for all source temperatures are listed in Table 11. The inverses of the values listed in this table represent signal attenuation ratios. The results listed involve use of medium RMT detector gain for the larger apertures (6-12) and high gain for the smaller apertures (2-5). An average value was calculated from the results for all source temperatures at each aperture position and listed in the table. The standard deviation of the values was also calculated. In most cases, the results did not change appreciably with source temperature. In all cases, the standard deviation of the samples is less than 4 percent.

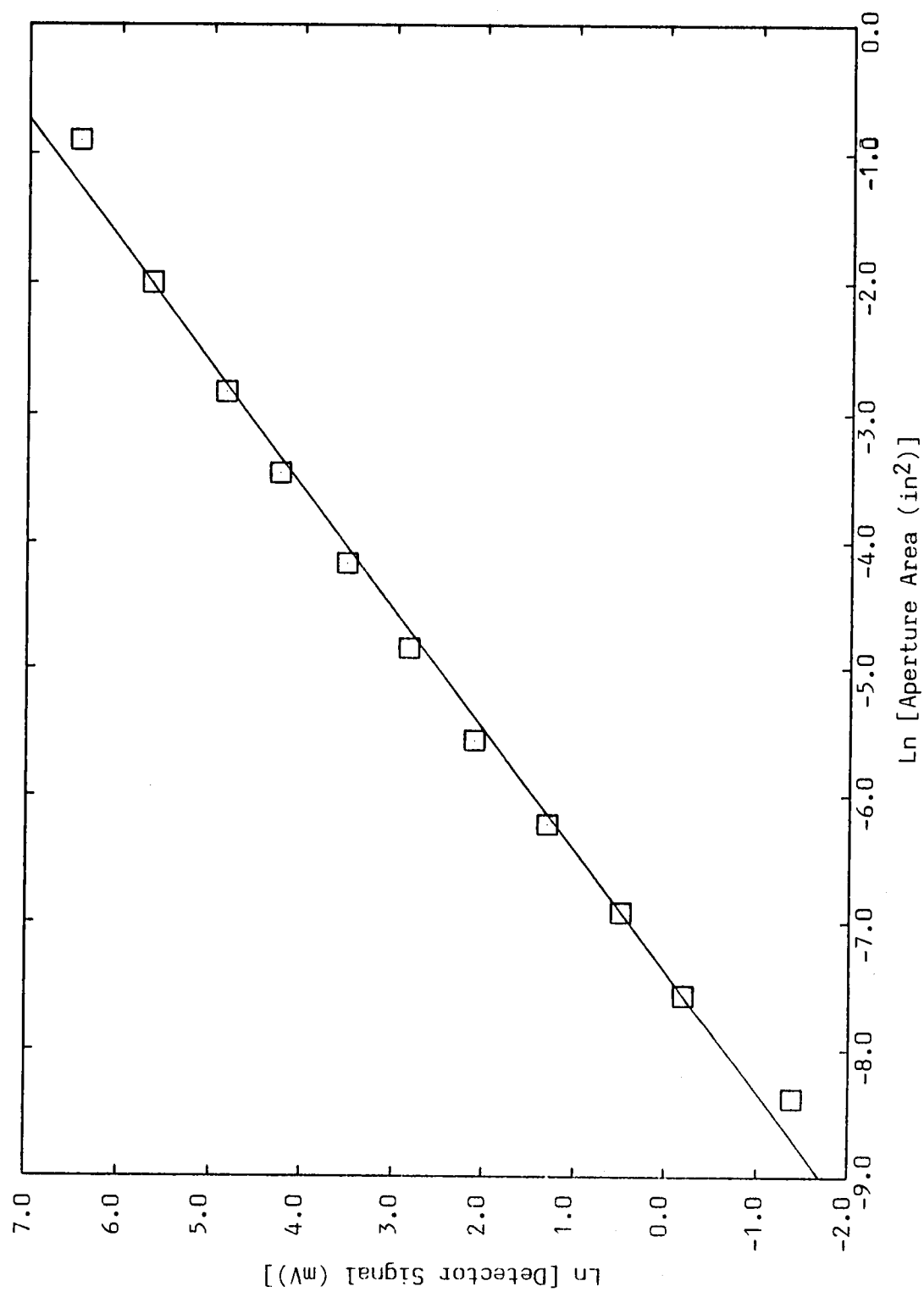


Figure 10. Detector Signal Versus Unisphere Aperture Area.

Table 10. Slopes of Unisphere Linearity Data Plots.

Source Temperature (K)	Slope of Line Fitted Through Data Points
150	0.953
200	0.991
250	1.048
300	1.003
350	1.000
385	0.990

Table 11. Signal Attenuation Ratio Versus Unisphere Source Temperature.

Aperture Number	Source Temperature						Standard Deviation (%)
	150	200	250	300	350	385	
12	0.803	0.835	0.850	0.863	0.865	0.862	0.846
11	1.810	1.869	1.898	1.919	1.935	1.930	1.893
10	4.102	4.166	4.208	4.234	4.259	4.278	4.208
9	7.580	7.591	7.639	7.675	7.699	7.686	7.645
8	16.00	16.00	16.00	16.00	16.00	16.00	16.00
7	31.30	31.84	31.50	31.33	31.14	31.08	31.37
6	61.18	68.04	64.30	64.28	63.55	63.30	64.11
5	140.21	131.11	137.10	139.67	141.82	143.90	138.97
4	293.56	275.05	283.85	283.53	284.99	287.87	284.81
3	534.80	505.25	519.27	514.05	515.31	509.27	516.33
2	1320.4	1246.0	1285.5	1267.0	1244.5	1233.3	1266.1

6.1.3 Unisphere Signal Ratio Versus Aperture Area Ratio

The ratio of the detector signals obtained at different apertures was compared to the ratio of the areas of the corresponding apertures. The results analyzed were those obtained for a source temperature of 300K. These results are presented in Table 12. The aperture area ratio and the average detector signal ratio are listed for each aperture. The ratios were compared by dividing the average signal ratio by the aperture area ratio. For most apertures, the experimental and theoretical values differ by less than 17 percent. The notable exception is the result obtained for aperture 12. The signal ratio for that aperture is 43 percent higher than the aperture area ratio. This finding is again indicative of a problem with the performance achieved when aperture 12 was used.

6.1.4 Unisphere Signal Ratio Versus Theoretical Attenuation Ratio

For the unisphere source, an attempt was made to predict what the attenuation ratios should be for each aperture position based upon theoretical throughput calculations. The predicted values for each aperture position are listed in Table 13. The average values of signal ratio for the results obtained at a source temperature of 300K are also listed in this table. The final column of the table provides a comparison of the theoretical and measured values. In all cases, the results differ by less than 20 percent. However, the comparison is closer than that based on the ratio of aperture areas for only a few apertures. The most notable improvement was obtained for the aperture 12 data. The difference in theoretical and measured values is only 6 percent, whereas the difference in aperture area ratio and measured value is

Table 12. Comparison of Unisphere Aperture Area and Signal Ratios.

Aperture Number	Aperture Area Ratio	Signal Ratio	<u>Signal Ratio</u>
			Aperture Area Ratio
12	0.605	0.863	1.43
11	1.830	1.919	1.05
10	4.177	4.234	1.01
9	7.840	7.675	0.98
8	16.00	16.00	1.00
7	31.36	31.33	0.999
6	64.00	64.28	1.004
5	125.44	139.7	1.11
4	248.84	283.5	1.14
3	478.52	514.1	1.07
2	1085.1	1267.1	1.17

Table 13. Comparison of Unisphere Theoretical and Signal Ratios.

Aperture Number	Theoretical Ratio	Signal Ratio	<u>Signal Ratio</u>
			Theoretical Ratio
12	0.917	0.863	0.94
11	2.13	1.919	0.90
10	4.58	4.234	0.92
9	7.81	7.675	0.98
8	16.00	16.00	1.00
7	30.69	31.33	1.02
6	61.74	64.28	1.04
5	123.76	139.7	1.13
4	244.78	283.5	1.16
3	501.14	514.1	1.03
2	1066.2	1267.1	1.19

43 percent. These results suggest that the theoretical prediction technique might be useful when larger apertures are used with integrating spheres. However, there does not appear to be much to be gained by using this technique for the smaller apertures.

6.1.5 Unisphere Calibration Constant at Various Aperture Positions

The final output of a calibration effort is a calibration constant which is used in the expression to calculate the source output. Only one calibration constant is calculated for a given source. This constant is applied for all source temperatures and apertures. A more accurate technique might be to calculate a different calibration constant for each source aperture. However, these results would be much more cumbersome to apply. To determine if the signal attenuation ratio technique is adequate to allow a single constant to be determined and used for all apertures, calibration constants were calculated for all aperture positions for a source temperature of 300K. Three sets of data were analyzed. The results for all three data sets are summarized in Table 14. The values for the larger apertures involved medium RMT detector gain, while the smaller aperture values were based on high gain results. The signal ratios obtained at each aperture position were used in the calibration constant calculations. The results presented in the table suggest that the technique is valid. The calibration constant values do not vary much with source aperture, except for the very smallest apertures. For the unisphere, aperture 9 is chosen as the reference for the calibration, and the calibration constant is calculated for that aperture. The worst case deviation from that value, obtained for aperture 2, is less than 11 percent. There is no apparent

Table 14. Calibration Constant Versus Unisphere Aperture Position
(Attenuation Ratio Method).

Aperture Number	Calibration Constant $\times 10^9$ (in ⁻²)		
	Set #1	Set #7	Set #9
12	4.09	3.98	4.04
11	4.10	4.00	3.99
10	4.11	3.99	3.97
9	4.09	3.98	4.03
8	4.09	3.98	4.02
7	4.09	4.00	4.00
6	4.09	3.96	3.98
5	4.04	3.80	4.01
4	4.16	4.07	4.13
3	4.29	4.18	4.16
2	<u>4.56</u>	<u>4.44</u>	<u>4.43</u>
Average	4.16	4.03	4.07
Standard Deviation	3.6%	4.0%	3.3%

problem with the aperture 12 results. The standard deviation of the values is less than 4 percent for all three data sets.

To compare the signal ratio method with the aperture area method, calibration constants were also calculated for all source apertures using the aperture area method. Only two sets of data were analyzed. The results are presented in Table 15. It is obvious that a greater variation in calibration constant exists when the aperture area method is used. The standard deviation of the samples is on the order of 10 percent. The deviation in the aperture 9 value and the worst case result is as large as 37 percent. Using this technique, the worst case result is obtained for the largest aperture. These results suggest that using the aperture area method may introduce greater errors in predicted source output when apertures other than the reference aperture are used. Thus it appears that the signal attenuation ratio method is preferable to the aperture area method when a single calibration constant is to be applied to all apertures.

6.1.6 Repeatability of Unisphere Linearity Results

To be able to predict the source output accurately, the attenuation ratios determined must be repeatable. Eleven sets of linearity data were taken with the unisphere source operated at 300K during the unisphere calibration. An average value was determined from these 11 sets for each aperture position. These results are listed in Table 16. Some of the data were taken at medium RMT detector gain; the remainder were acquired at high gain. To assess the repeatability of the results, the standard deviation of the samples was calculated. The standard deviation values are also listed in the table. These values indicate

Table 15. Calibration Constant Versus Unisphere Aperture Position
(Aperture Area Method).

Aperture Number	Calibration Constant x 10^9 (in ⁻²)	
	Set #1	Set #9
12	1.80	1.78
11	2.46	2.40
10	2.55	2.47
9	2.63	2.59
8	2.58	2.53
7	2.58	2.52
6	2.57	2.50
5	2.31	2.29
4	2.25	2.23
3	2.40	2.33
2	2.22	2.16
Average	2.40	2.35
Standard Deviation	10.2%	9.9%

Table 16. Unisphere Linearity Repeatability.

Aperture Number	Detector Gain State	Number of Samples	Average Value	Standard Deviation (%)
12	Medium	11	0.863	0.74
11	Medium	11	1.919	0.59
10	Medium	11	4.234	0.50
9	Medium	11	7.675	0.25
8	Medium	11	16.00	---
7	Medium	11	31.33	0.34
6	Medium	11	64.28	0.70
5	High	11	139.7	1.26
4	High	11	283.5	0.62
3	High	11	514.1	0.89
2	High	11	1267.1	0.76

that the repeatability of the results is excellent. The standard deviation of the 11 samples is less than 1.5 percent for all apertures.

6.2 Capsule Source

6.2.1 Capsule Aperture Area Versus Detector Signal

Plots were made of the natural log of aperture area versus the natural log of the detector signal for all capsule source temperatures. Lines were fitted through the data points using a linear curve-fit program. For a perfect system, the response should be linear and the slope of the line fitted through the data points should have a value of one. The plot for the data obtained at a source temperature of 300K is shown in Figure 11. All data points were obtained with the RMT detector in high gain. In most cases, the points fall very close to the fitted line. The most notable exception is the data point corresponding to the smallest aperture (aperture 2) and thus the smallest detector signal. This point fell slightly above the fitted line for all source temperatures. This error is probably associated with trying to measure the very small signal level associated with the small aperture. The slope of the line shown in Figure 11 is 0.996. The slopes of the fitted lines for all source temperatures are listed in Table 17. In all cases, the slope of the fitted line is within 1 percent of the ideal value.

6.2.2 Capsule Signal Ratio at Various Source Temperatures

The ratios of the detector signals at various aperture positions were calculated for the capsule according to the method described in Section 3.5 (Equation (21)). The results were calculated based on aperture 20 as the reference. The average results for all source

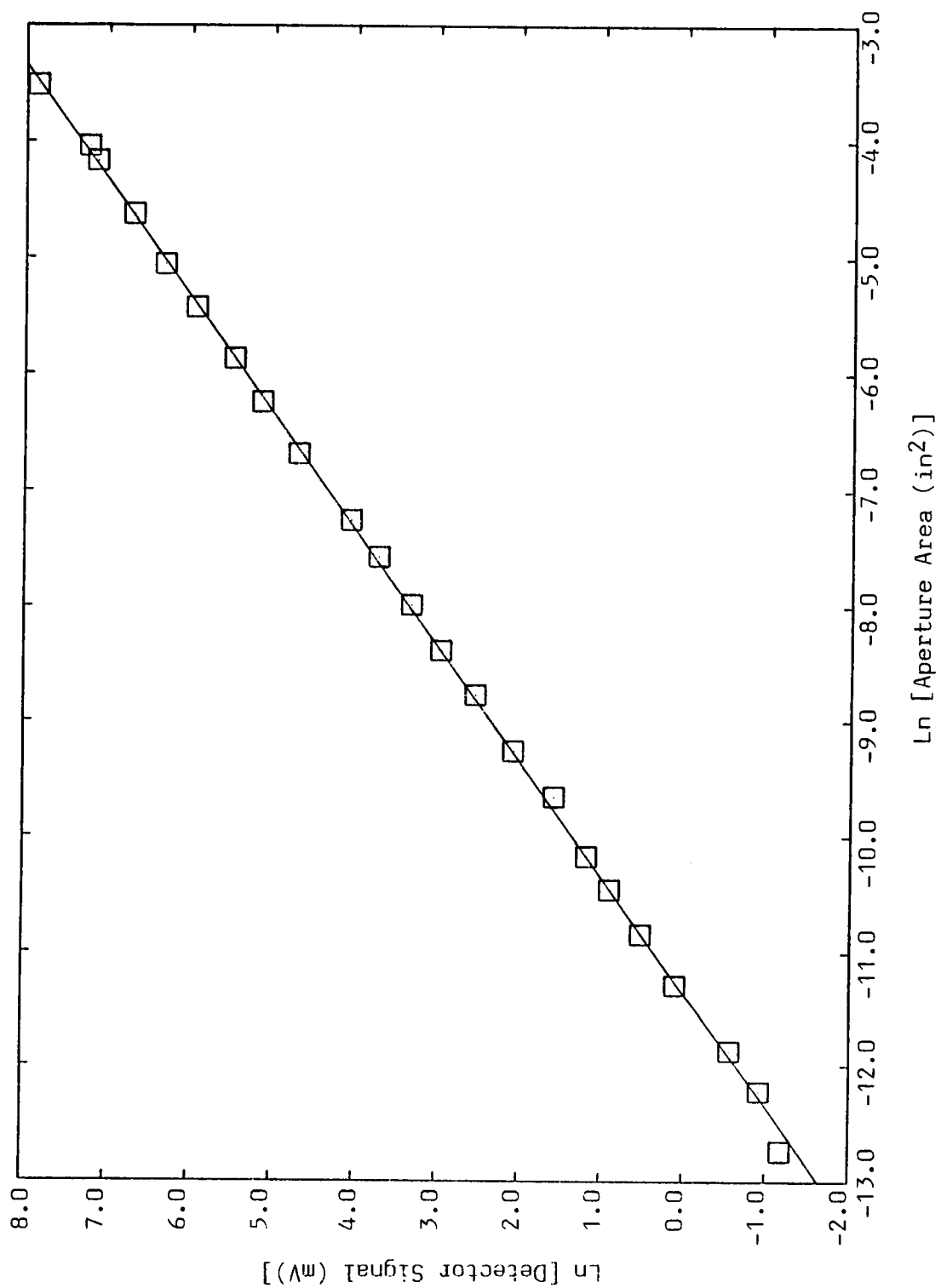


Figure 11. Detector Signal Versus Capsule Aperture Area.

Table 17. Slopes of Capsule Linearity Data Plots.

Source Temperature (K)	Slope of Line Fitted Through Data Points
250	1.009
300	0.996
350	0.994

temperatures are listed in Table 18. The inverses of the values listed in this table represent signal attenuation ratios. The results listed involve use of high detector gain for all apertures. An average value was calculated from the results for all source temperatures at each aperture position and listed in the table. The standard deviation of the values was also calculated. In most cases, the results did not change appreciably with source temperature; the standard deviation of the samples is less than 6 percent. The only deviations which were larger than this value were obtained for the largest and the smallest source apertures.

6.2.3 Capsule Signal Ratio Versus Aperture Area Ratio

The ratio of the detector signals obtained at different apertures was compared to the ratio of the areas of the corresponding apertures. The results analyzed were those obtained for a source temperature of 300K. These results are presented in Table 19. The aperture area ratio and the average detector signal ratio are listed for each aperture. The ratios were compared by dividing the average signal ratio by the aperture area ratio. For most apertures, the experimental and theoretical values differ by less than 10 percent. The only values which are larger are those obtained for aperture 9 (15 percent) and aperture 2 (12 percent).

6.2.4 Capsule Calibration Constant at Various Aperture Positions

To determine if the signal attenuation ratio technique is adequate to allow a single constant to be determined and used for all apertures for the capsule source, calibration constants were calculated for all

Table 18. Signal Attenuation Ratio Versus Capsule Source Temperature.

Aperture Number	Source Temperature			Average	Standard Deviation (%)
	250	300	350		
24	0.769	0.847	0.873	0.830	6.52
23	1.45	1.53	1.56	1.51	3.76
22	1.61	1.71	1.76	1.69	4.51
21	2.62	2.67	2.78	2.69	3.04
20	4.00	4.00	4.00	4.00	---
19	5.67	5.82	5.87	5.79	1.80
18	8.57	8.91	9.29	8.92	4.04
17	12.61	12.88	12.96	12.82	1.43
16	19.48	20.14	20.00	19.87	1.75
15	34.45	36.40	35.92	35.59	2.85
14	49.42	52.74	52.55	51.57	3.62
13	73.42	78.30	77.47	76.40	3.42
12	110.10	114.2	114.60	112.97	2.20
11	163.78	170.1	172.73	168.87	2.72
10	256.81	266.8	271.43	265.01	2.82
9	444.55	455.2	456.96	452.24	1.48
8	657.17	670.0	677.30	668.16	1.53
7	846.43	903.8	925.64	891.96	4.59
6	1202.3	1273.0	1317.5	1264.3	4.60
5	1793.3	1984.5	1994.5	1924.1	5.89
4	3918.7	3907.5	3840.4	3888.9	1.09
3	5290.2	5646.7	5231.9	5389.6	4.17
2	10580.4	7616.3	7220.0	8472.2	21.68

Table 19. Comparison of Capsule Aperture Area and Signal Ratios.

Aperture Number	Aperture Area Ratio	Signal Ratio	<u>Signal Ratio</u>
			Aperture Area Ratio
24	0.854	0.847	0.99
23	1.45	1.531	1.06
22	1.64	1.711	1.04
21	2.58	2.672	1.04
20	4.00	4.00	1.00
19	5.75	5.816	1.01
18	8.98	8.910	0.99
17	12.94	12.88	0.995
16	20.19	20.14	0.998
15	36.11	36.40	1.01
14	49.49	52.74	1.07
13	74.88	78.30	1.05
12	110.35	114.2	1.03
11	162.34	170.1	1.05
10	264.38	266.8	1.01
9	397.17	455.2	1.15
8	662.39	670.0	1.01
7	878.04	903.8	1.03
6	1298.3	1273.0	0.98
5	2008.5	1984.5	0.99
4	3604.4	3907.5	1.08
3	5151.9	5646.7	1.10
2	8624.1	7616.3	0.88

aperture positions for a capsule source temperature of 300K. Only one set of data was analyzed. The results are summarized in Table 20. The values for all apertures were obtained at high detector gain. The signal ratios obtained at each aperture position were used in the calibration constant calculations. The results presented in the table suggest that the technique is valid. The calibration constant values do not vary much with source aperture, except for the very smallest aperture. For the capsule, aperture 16 is chosen as the reference for the calibration, and the calibration constant is calculated for that aperture. The worst case deviation from that value, obtained for aperture 12, is 11.5 percent. The standard deviation of the samples is 2.9 percent.

6.2.5 Repeatability of Capsule Linearity Results

Several sets of linearity data were taken with the capsule source operated at 300K during the capsule calibration. For the larger apertures, 10 samples were obtained. Fewer samples were recorded for the smaller apertures. An average value was determined from the available data for each aperture position. These results are listed in Table 21. All of the data were taken at high RMT detector gain. To assess the repeatability of the results, the standard deviation of the samples was calculated. The standard deviation values are also listed in the table. These values indicate that the repeatability of the results is excellent. The standard deviation of the samples is less than 4 percent for all apertures except the two smallest ones.

Table 20. Calibration Constant Versus Capsule Aperture Position.

Aperture Number	Calibration Constant $\times 10^{11}$ (in ⁻²)
24	4.74
23	4.61
22	4.54
21	4.42
20	4.54
19	4.63
18	4.70
17	4.48
16	4.70
15	4.75
14	4.79
13	4.76
12	4.58
11	4.66
10	4.61
9	4.57
8	4.59
7	4.76
6	4.55
5	4.61
4	4.63
3	4.77
2	4.19
Average	4.62
Standard Deviation	2.9%

Table 21. Capsule Linearity Repeatability.

Aperture Number	Detector Gain State	Number of Samples	Average Value	Standard Deviation (%)
24	High	10	0.847	2.79
23	High	10	1.531	1.77
22	High	10	1.711	1.14
21	High	10	2.672	1.61
20	High	10	4.00	---
19	High	10	5.816	1.26
18	High	10	8.910	1.73
17	High	10	12.88	1.19
16	High	10	20.14	1.38
15	High	10	36.40	2.21
14	High	10	52.74	2.33
13	High	10	78.30	2.30
12	High	4	114.2	0.97
11	High	4	170.1	2.17
10	High	4	266.8	2.46
9	High	4	455.2	0.63
8	High	4	670.0	1.01
7	High	4	903.8	3.23
6	High	4	1273.0	3.09
5	High	4	1984.5	1.17
4	High	4	3907.5	2.02
3	High	3	5646.7	5.62
2	High	3	7616.3	7.52

CHAPTER VII

SPECTRAL RESULTS

7.1 Blackbody Source

7.1.1 Blackbody Fractions

Tables of blackbody fractions were used to determine the percentage of energy which would be transmitted in the spectral bands associated with the RMT filter wheel. The results are summarized in Table 22 for all filters at selected source temperatures between 200K and 385K. These values represent the fraction of energy in a specific band as compared to the amount of energy emitted at all possible wavelengths. They are based on the assumption that the source has blackbody or graybody spectral characteristics, and do not take into account the spectral response of the measuring device.

7.1.2 Corrected Blackbody Fractions

The RMT detector does not respond to radiation at wavelengths greater than 32 microns. Thus, the blackbody fractions cannot be used to directly compare the RMT source spectral characteristics to those of a true blackbody. The fraction should not be based on all wavelengths, but only those which are below 32 microns. The percentage of energy in the 1- to 32-micron band for each source temperature was determined from the blackbody fraction tables. These values are listed in Table 23. To arrive at corrected blackbody fractions, each blackbody fraction value in Table 22 was divided by the percentage of energy in the 1- to 32-micron band for the corresponding source temperature. The results of this operation are presented as corrected blackbody fractions in Table 24.

Table 22. Blackbody Fractions for Various Source Temperatures.

Filter Wheel Position	$F_{\lambda_1 - \lambda_2}$ Source Temperature (K)				
	200	250	300	350	385
19	0.315	0.308	0.271	0.227	0.199
17	0.190	0.302	0.368	0.392	0.393
15	0.025	0.078	0.157	0.249	0.316
13	0.088	0.125	0.142	0.143	0.142
11	0.027	0.056	0.082	0.099	0.108
9	0.285	0.209	0.153	0.113	0.092
7	0.086	0.092	0.086	0.075	0.068
5	0.021	0.068	0.134	0.203	0.244
3	0.372	0.356	0.308	0.256	0.225

Table 23. Percentage of Energy in the 1 - 32 μ m Band for Various Source Temperatures.

Source Temperature (K)	$\lambda_2 T$ (μ mK)	$F_{\lambda_1 - \lambda_2}$
200	6400	0.7692
250	8000	0.8562
300	9600	0.9054
350	11200	0.9335
385	12320	0.9485

Table 24. Corrected Blackbody Fractions.

Filter Wheel Position	$\frac{F_{\lambda_1 - \lambda_2}}{F_{1 - 32}}$ Source Temperature (K)				
	200	250	300	350	385
19	0.410	0.360	0.299	0.243	0.210
17	0.247	0.353	0.406	0.420	0.414
15	0.033	0.091	0.173	0.267	0.333
13	0.114	0.146	0.157	0.153	0.150
11	0.035	0.065	0.091	0.106	0.114
9	0.371	0.244	0.169	0.121	0.097
7	0.112	0.107	0.095	0.080	0.072
5	0.027	0.079	0.148	0.217	0.257
3	0.484	0.416	0.340	0.274	0.237

7.1.3 Predicted Spectral Response

A program was written to calculate predicted values of spectral ratios for a blackbody source. A spectral ratio is defined as the ratio of energy in a specific band to the total energy at all wavelengths. In most cases, it is calculated as the signal obtained for a given spectral band divided by the signal obtained when no filter is used (open-hole signal). The expression for radiant spectral emittance for a blackbody was integrated over the appropriate wavelength limits and a predicted signal was calculated for each spectral band. The open-hole signal was calculated as the value obtained by integrating the expression from 1 to 32 microns. The responsivity of the detector determined at the different source temperatures was used in these calculations. The spectral ratio was calculated as the signal predicted for the filter wavelength band divided by the open-hole signal. The predicted values are presented for all filter positions at source temperatures from 200K to 385K in Table 25. These results, as should be expected, agree closely with the corrected blackbody fractions listed in Table 24. This agreement gives a measure of validity to the program method.

To further validate the program, the predicted open-hole signal was compared with the value actually measured with the RMT detector at different RMT source temperatures. These values are listed in Table 26. The percent difference in the RMT and the predicted values was calculated. In all cases, the difference was less than 1 percent. The values predicted when the spectral response of the detector was included are also listed in the table. These values also differed from the measured RMT value by less than 1 percent.

Table 25. Predicted Blackbody Spectral Ratios.

Filter Wheel Position	Source Temperature (K)				
	200	250	300	350	385
19	0.409	0.359	0.298	0.243	0.210
17	0.246	0.351	0.406	0.420	0.414
15	0.035	0.097	0.183	0.277	0.342
13	0.115	0.151	0.162	0.158	0.149
11	0.035	0.068	0.094	0.109	0.114
9	0.371	0.244	0.168	0.120	0.097
7	0.111	0.108	0.095	0.081	0.071
5	0.029	0.084	0.154	0.225	0.267
3	0.483	0.415	0.341	0.275	0.237

Table 26. Open-Hole Signal Comparisons.

Source Temperature (K)	RMT Signal (mV)	Predicted Signals (mV)					
		Without Spectral Response			Includes Spectral Response		
		Predicted Value	Percent Difference	Percent Difference	Predicted Value	Percent Difference	Percent Difference
200	28.58	28.47	0.39	0.39	28.48	0.35	0.35
250	71.15	70.89	0.37	0.37	70.95	0.28	0.28
300	142.0	143.2	0.84	0.84	142.9	0.65	0.65
350	251.7	250.8	0.36	0.36	251.0	0.28	0.28
385	342.9	346.0	0.90	0.90	345.3	0.71	0.71

7.1.4 Predicted Spectral Ratios with Detector Spectral Response Included

In order to compare the experimental spectral ratios measured for the RMT source with theoretical predicted ratios, the spectral response of the measuring device (the RMT detector) should be accounted for. The spectral response prediction program was designed to allow the detector relative spectral response values to be incorporated into the calculations. When the spectral response is not included, the assumption is inherent that the RMT detector has exactly the same response at all wavelengths. The actual RMT detector response varies significantly with wavelength. The predicted spectral ratios calculated when the detector spectral response is included are listed in Table 27. In most of the spectral bands, the values are considerably different from those obtained when the detector spectral response is not included.

7.1.5 Signal Versus Blackbody Source Temperature

For a blackbody source, the measured detector signal should be proportional to the source temperature raised to the fourth power. A plot of the natural log of the detector signal versus the natural log of the temperature raised to the fourth power should be linear, with a slope of one. A plot demonstrating this relationship for a blackbody is shown in Figure 12. The data points were obtained by assuming a signal of 10 mV for a source temperature of 150K. Ideal values were calculated for other source temperatures ranging to 385K. The values were plotted and a line was fitted through the data points. The slope of the fitted line is 1.0.

Table 27. Predicted Spectral Ratios--Include Detector Spectral Response.

Filter Wheel Position	Source Temperature (K)				
	200	250	300	350	385
19	0.410	0.414	0.393	0.362	0.339
17	0.112	0.181	0.237	0.275	0.291
15	0.010	0.034	0.073	0.126	0.168
13	0.053	0.081	0.100	0.111	0.114
11	0.011	0.027	0.043	0.056	0.063
9	0.428	0.341	0.278	0.230	0.203
7	0.089	0.102	0.104	0.100	0.096
5	0.009	0.029	0.063	0.104	0.134
3	0.513	0.504	0.471	0.429	0.399

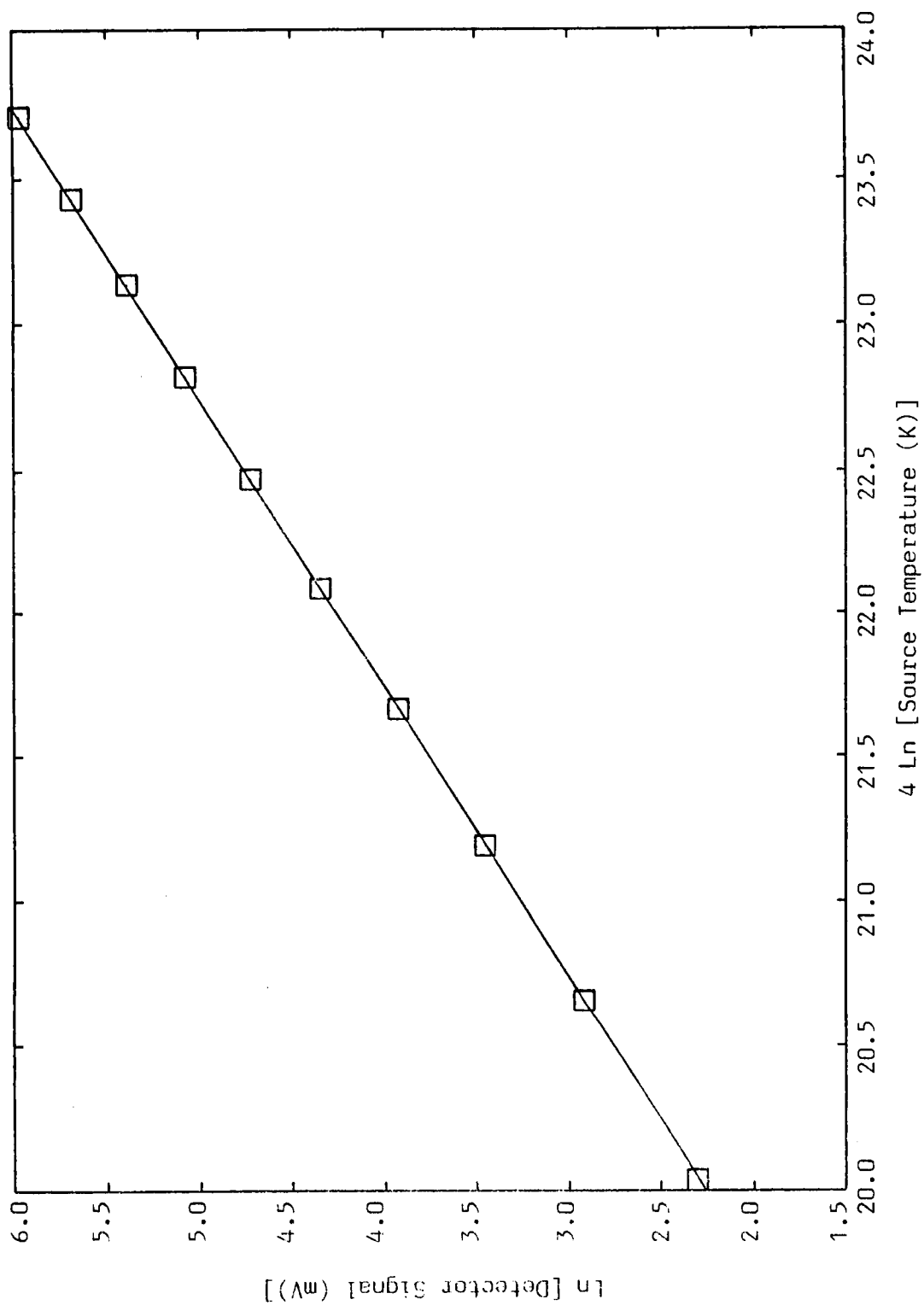


Figure 12. Signal Versus T^4 Plot for a Blackbody Source.

7.2 RMT Reference Source

7.2.1 Method of Gouffé

The method of Gouffé is a theoretical technique used to calculate the effective emissivity of a cavity source. This method was applied to the RMT reference source. Using the dimensions of the source and the average measured spectral emissivity of the cavity wall surface ($\epsilon = 0.94$), the effective emissivity was determined to be greater than 0.99. This technique indicates that the RMT source should provide a close approximation to a blackbody spectral radiator.

7.2.2 RMT Spectral Ratios

Spectral ratios were determined for all filter-wheel positions for various RMT reference source temperatures during both the unisphere and capsule calibrations. During the unisphere calibration, spectral ratios were determined for RMT source temperatures ranging from 200K to 385K. These results are presented in Table 28. During the capsule calibration, spectral ratios were determined for source temperatures of 250K, 300K, and 350K. These results are presented in Table 29. In both cases, the results were obtained with the RMT detector set to high gain.

The values listed in Tables 28 and 29 should represent the percentage of energy in the spectral band transmitted by the corresponding filter as compared to the total energy transmitted at all wavelengths. The values for filter-wheel positions 19, 9, 7, and 3 decrease as source temperature increases. These filters transmit energy almost exclusively at wavelengths greater than 14 microns. For blackbody sources, the wavelength at which the radiant emittance peaks shifts to shorter wavelengths

Table 28. Average RMT Source Spectral Ratios--Unisphere Calibration.

Filter Wheel Position	Spectral Ratios Source Temperature (K)				
	200	250	300	350	385
19	0.349	0.305	0.276	0.250	0.234
17	0.162	0.206	0.262	0.304	0.326
15	0.007	0.014	0.025	0.043	0.061
13	0.038	0.043	0.047	0.051	0.055
11	0.015	0.022	0.030	0.038	0.044
9	0.158	0.102	0.075	0.059	0.052
7	0.062	0.055	0.050	0.046	0.044
5	0.006	0.016	0.029	0.049	0.068
3	0.481	0.409	0.360	0.320	0.297

Table 29. Average RMT Source Spectral Ratios--Capsule Calibration.

Filter Wheel Position	Spectral Ratios Source Temperature (K)		
	.250	300	350
19	0.311	0.274	0.250
17	0.203	0.255	0.301
15	0.013	0.026	0.044
13	0.041	0.046	0.050
11	0.021	0.031	0.039
9	0.108	0.082	0.064
7	0.054	0.049	0.046
5	0.015	0.028	0.048
3	0.412	0.358	0.319

as the source temperature increases. Thus, the trend noted from these results is that which would be predicted by theory. For all other filter-wheel positions, the ratio increases as source temperature increases. Since all of these filters respond only to energy below 14 microns, this trend also agrees with the prediction.

7.2.3 RMT/Blackbody Ratios

To compare the RMT spectral ratios with those which should be obtained for a blackbody, the RMT values obtained during the unisphere calibration were divided by the calculated blackbody values listed in Table 25 (p. 77). These results involved an inherent assumption that an ideal measuring device (relative response constant at all wavelengths) was used for the measurements. The results for all filters at all source temperatures are presented in Table 30. For most of the spectral bands, the values do not vary greatly with source temperature. In almost all cases, the value obtained for a source temperature of 385K is the largest. Filters 19 and 3 show a significant increase in the ratio as the source temperature increases from 250K to 385K. For a few spectral bands, the RMT and blackbody ratios are in reasonably good agreement. Filter positions 19, 17, 7, and 3 show the closest comparison. In other bands, the agreement is not as good. In the worst case, the RMT value is only one-sixth of the calculated blackbody value. The worst case results were obtained for filters 15 and 5.

7.2.4 RMT/Predicted Ratios

A better comparison should be obtained by accounting for the spectral response of the RMT detector. The RMT source spectral ratios were

Table 30. Comparison of RMT Spectral Ratios and Blackbody Ratios.

Filter Wheel Position	RMT Value/Blackbody Value Source Temperature (K)				
	200	250	300	350	385
19	0.85	0.85	0.93	1.03	1.11
17	0.66	0.59	0.65	0.72	0.79
15	0.20	0.14	0.34	0.16	0.18
13	0.33	0.28	0.29	0.32	0.37
11	0.43	0.32	0.32	0.35	0.39
9	0.43	0.42	0.45	0.49	0.54
7	0.56	0.51	0.53	0.57	0.62
5	0.21	0.19	0.19	0.22	0.25
3	1.00	0.99	1.06	1.16	1.25

compared with the predicted blackbody ratios obtained when the detector spectral response was incorporated. The RMT values obtained during the unisphere calibration were divided by the predicted values listed in Table 27 (p. 80). The results are presented for all filter positions at all source temperatures in Table 31. If the RMT source were a true blackbody and the relative spectral response of the detector and the filter cut-on and cut-off characteristics were known accurately, the values listed in this table would all be unity. For most spectral bands, the comparisons shown in Table 31 are closer to ideal than those obtained when the detector spectral response was not accounted for. Significant improvement was noted for filter positions 17, 15, 13, 11, and 5 when the detector spectral response was included. The most significant decline in comparability was noted for filter 9. Filter positions 19, 17, 11, and 3 show reasonably good agreement between theoretical and measured values. The worst case values were obtained for filter 9, for which the RMT value is only one-fourth of the predicted value. For most of the spectral bands, the values were relatively consistent at the different source temperatures. For all cases, the value obtained at a source temperature of 200K was the largest.

7.2.5 Signal Versus RMT Source Temperature

The natural log of the average measured detector signal was plotted versus the natural log of the source temperature raised to the fourth power for the RMT source. The signal values used were all measured at the high RMT detector gain state. The plot is shown in Figure 13. A line was fitted through the data points using a linear curve-fit program. The data points at the intermediate temperatures fall slightly

Table 31. Comparison of RMT Spectral Ratios and Predicted Ratios.
(Detector Spectral Response Included.)

Filter Wheel Position	RMT Value/Predicted Value Source Temperature (K)				
	200	250	300	350	385
19	0.85	0.74	0.70	0.69	0.69
17	1.45	1.14	1.08	1.11	1.12
15	0.70	0.41	0.34	0.34	0.36
13	0.72	0.53	0.47	0.46	0.48
11	1.36	0.82	0.70	0.68	0.70
9	0.37	0.30	0.27	0.26	0.26
7	0.70	0.54	0.48	0.46	0.46
5	0.67	0.55	0.46	0.47	0.51
3	0.94	0.81	0.76	0.75	0.74

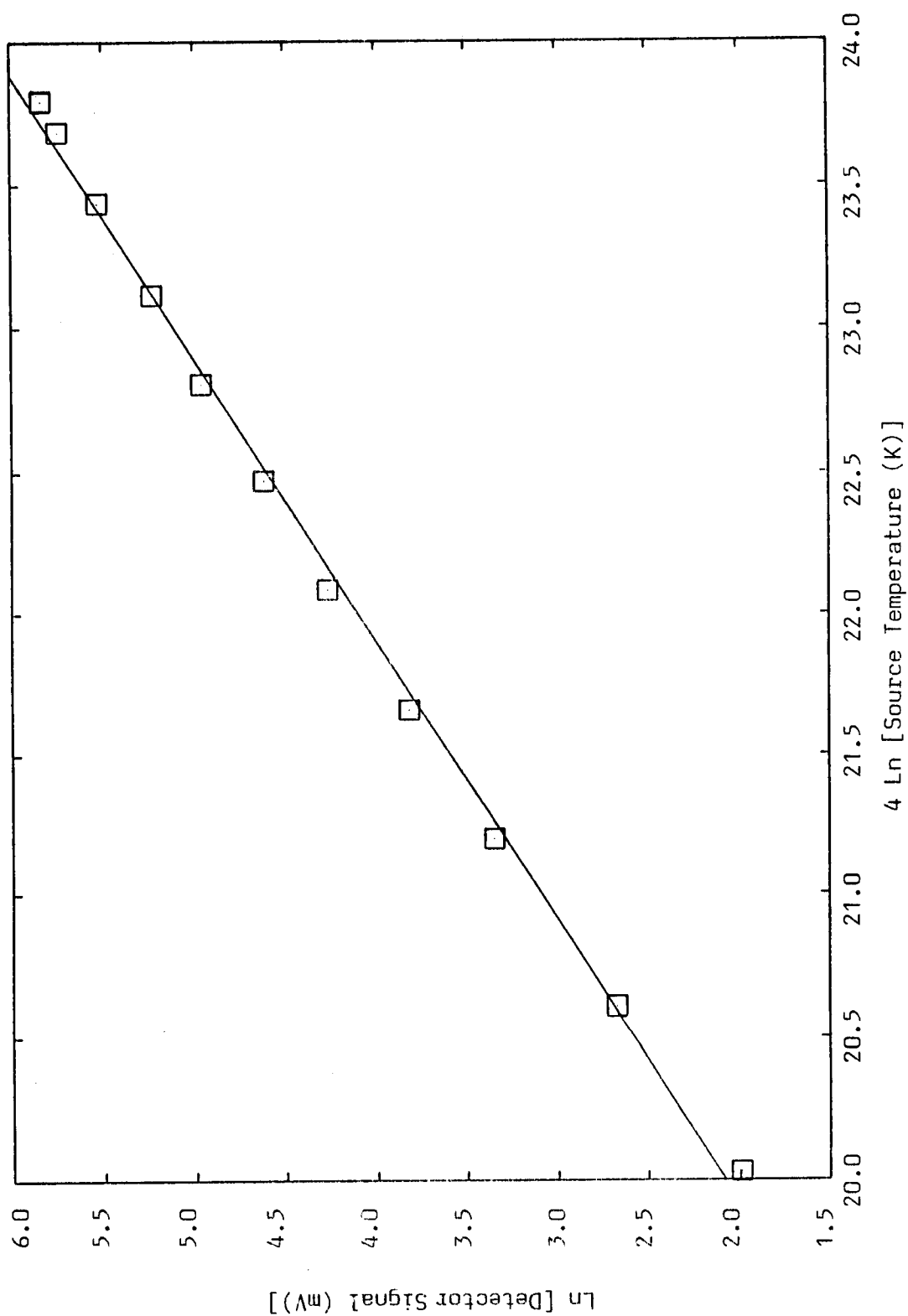


Figure 13. Signal Versus T^4 Plot for the RMT Source.

above the fitted line. The data points at the high and low temperatures are slightly below the line. The slope of the fitted line is 1.008, which is slightly greater than the ideal value of one.

7.2.6 Repeatability of RMT Source Spectral Data

Several sets of spectral data were taken for the RMT source by stepping through all of the RMT filter-wheel positions. RMT source spectral data were obtained during both the unisphere and capsule calibrations. Four complete sets of data were taken with the source temperature maintained at 300K during each calibration. The average spectral ratio values calculated from the four samples for all filter-wheel positions are listed in Table 32. Both the unisphere and capsule calibration results are included in this table. To determine the repeatability of these measurements, the standard deviation of the samples was calculated. These values are also listed in the table. In all cases, for all filter-wheel positions, the standard deviation of the samples was less than 2.2 percent. Perhaps an even greater measure of the repeatability can be made by comparing the average ratios obtained during the unisphere and capsule calibrations. Even though these were two completely separate installations made at completely different times, the average results for all filter-wheel positions agree closely.

7.3 Unisphere Source

7.3.1 Unisphere Spectral Ratios

Spectral ratios were calculated for all filter-wheel positions for various unisphere source temperatures ranging from 200K to 385K. The results are presented in Table 33. The results were obtained with

Table 32. Repeatability of RMT Source Spectral Measurements.

Filter Wheel Position	Number of Samples	<u>Unisphere Calibration</u>		<u>Capsule Calibration</u>	
		Average Value	Standard Deviation (%)	Average Value	Standard Deviation (%)
19	4	0.276	0.2	0.275	1.3
17	4	0.262	0.2	0.256	1.2
15	4	0.025	0.0	0.026	1.8
13	4	0.047	1.1	0.046	0.6
11	4	0.030	0.0	0.031	1.3
9	4	0.075	0.8	0.081	2.1
7	4	0.049	1.0	0.049	1.4
5	4	0.029	1.7	0.029	0.9
3	4	0.360	0.4	0.358	0.7

Table 33. Unisphere Spectral Ratios.

Filter Wheel Position	Source Temperature (K)				
	200	250	300	350	385
19	0.303	0.275	0.238	0.222	0.211
17	0.151	0.209	0.249	0.295	0.317
15	0.005	0.012	0.021	0.040	0.058
13	0.032	0.039	0.041	0.049	0.053
11	0.014	0.022	0.029	0.041	0.049
9	0.124	0.084	0.060	0.049	0.044
7	0.059	0.055	0.049	0.047	0.047
5	0.007	0.017	0.032	0.058	0.082
3	0.463	0.402	0.347	0.311	0.291

the source aperture in position 2 and the RMT detector set to high gain. The values for filter-wheel positions 19, 9, 7, and 3 decrease as source temperature increases, while the values for the other filter-wheel positions display the opposite trend. These trends are the same as those noted for the RMT source and are justified by the same arguments as those presented in Section 7.2.2.

7.3.2 Unisphere/RMT Ratios

To compare the spectral results from the unisphere source with those from the RMT reference source, the RMT source spectral ratio was divided by the value for the unisphere source at the same source temperature. These comparison ratios were determined for all filter-wheel positions for all source temperatures. The results are tabulated in Table 34. In general, the unisphere values agree reasonably well with the RMT source values. In some of the spectral bands, the agreement is better than 5 percent for all or nearly all source temperatures. The values agree within 20 percent for all cases except the filter-wheel position 9 values. The worst case comparison was the 40 percent obtained for filter-wheel position 15 at a source temperature of 200K. In most cases, the values are relatively independent of the source temperature.

7.3.3 Larger Aperture Results

When the unisphere spectral ratios are measured, an attempt is made to select an aperture which provides a signal which most nearly matches that obtained when calibrating the RMT source at the same temperature. For the unisphere source and high detector gain, aperture 2

Table 34. Ratio of RMT Spectral Values to Unisphere Values.

Filter Wheel Position	RMT Value/Unisphere Value Source Temperature (K)				
	200	250	300	350	385
19	1.15	1.11	1.16	1.13	1.11
17	1.07	0.99	1.05	1.03	1.03
15	1.40	1.17	1.19	1.08	1.05
13	1.19	1.10	1.15	1.04	1.04
11	1.07	1.00	1.03	0.93	0.90
9	1.27	1.21	1.25	1.20	1.18
7	1.05	1.00	1.02	0.98	0.94
5	0.86	0.94	0.91	0.84	0.83
3	1.04	1.02	1.04	1.03	1.02

is the one which provides this match. Using this aperture means that the signal level obtained with the open hole is relatively low, and the signal measured with some of the filters is very low. To investigate the comparison to the RMT source results and to the predicted ratio values when larger signals are produced, one set of spectral data was taken with the unisphere source set to aperture 6. This aperture setting provided the largest signal which could be measured with the source temperature at 300K and the RMT detector in the high gain state. The results are presented in Table 35. To accommodate the desired comparisons, the unisphere values obtained at aperture 2, the RMT values, and the predicted ratios obtained with the detector spectral response included are also listed in Table 35. In all cases, the ratio associated with the larger aperture was greater than the corresponding value obtained for aperture 2. In all cases, the aperture 6 results differed from the RMT values more than the aperture 2 values. In all cases, except for the filter-wheel position 17 results, the aperture 6 value was closer to the predicted ratio than the aperture 2 value. These findings suggest that in order to provide a valid comparison with the RMT source spectral results, an aperture should be selected to match the signal levels. The larger signals obtained by using a larger aperture yield results which agree more closely with the predicted ratios.

7.3.4 Signal Versus Unisphere Source Temperature

The natural log of the average measured detector signal was plotted versus the natural log of the source temperature raised to the fourth power for the unisphere source. The plot is shown in Figure 14. The signal values used were those measured with aperture 9 on the

Table 35. Comparison of Unisphere Spectral Results at a Larger Aperture.

Filter Wheel Position	Predicted Ratio	RMT Value	Unisphere Values	
			Standard Aperture (#2)	Larger Aperture (#6)
19	0.393	0.276	0.238	0.319
17	0.237	0.262	0.249	0.329
15	0.073	0.025	0.021	0.037
13	0.100	0.047	0.041	0.074
11	0.043	0.030	0.029	0.052
9	0.278	0.075	0.060	0.101
7	0.104	0.050	0.049	0.081
5	0.063	0.029	0.032	0.055
3	0.471	0.360	0.347	0.430

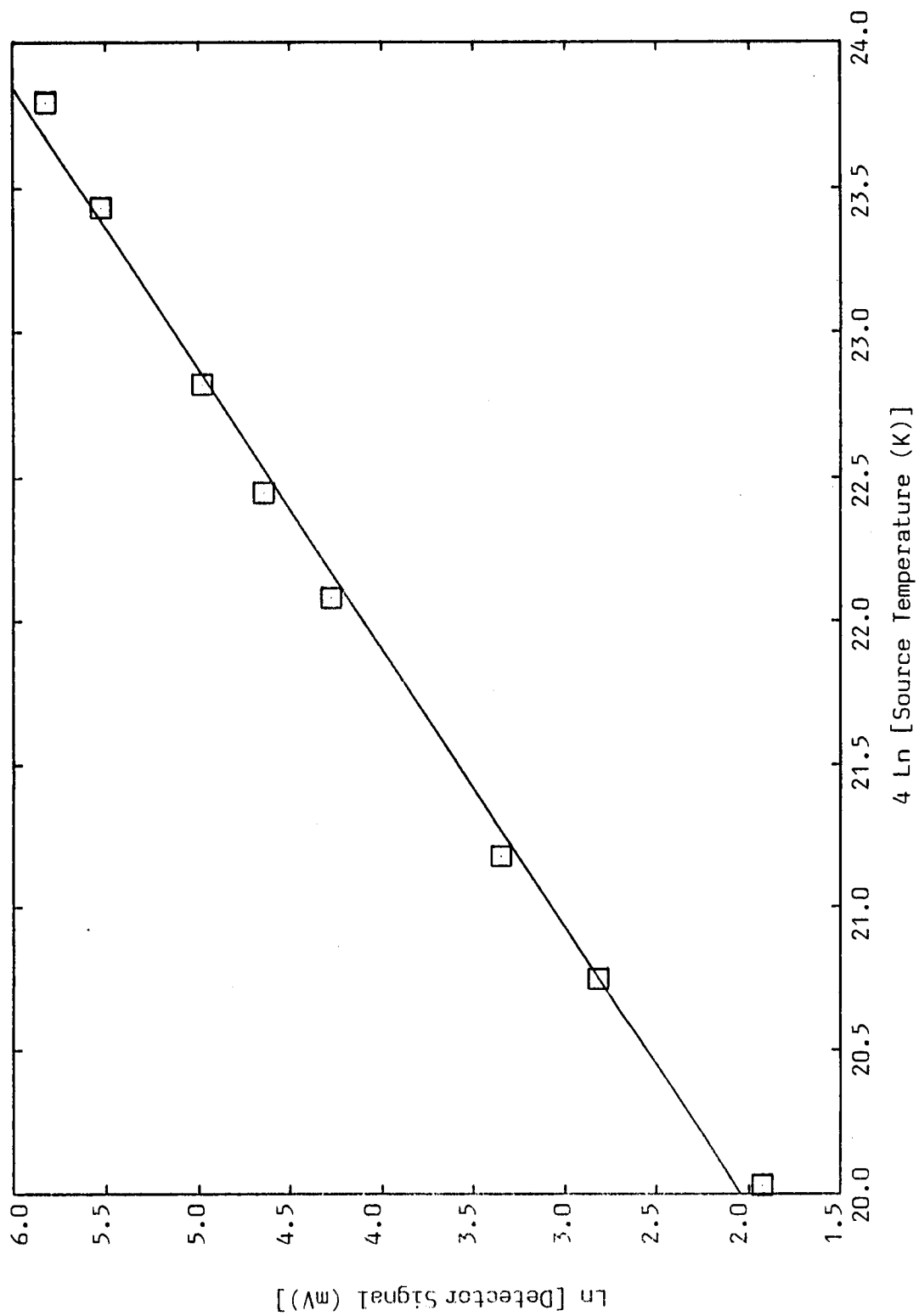


Figure 14. Signal Versus T^4 Plot for the Unisphere Source.

unisphere source at the medium RMT detector gain state. A line was fitted through the data points using a linear curve-fit program. The data points at the intermediate temperatures fall slightly above the fitted line. The data points at the high and low temperatures are slightly below the line. The slope of the fitted line is 1.027, which is slightly greater than the ideal value of one.

7.3.5 Unisphere Calibration Constants at Various Source Temperatures

Since the calibration constant is essentially a geometric factor, its value should be constant at all source temperatures for any given aperture. If any drastic spectral problem exists, it should be reflected in a variation in the calibration constant with source temperature. Source calibration constants were determined for the unisphere at source temperatures ranging from 175K to 385K. The results obtained for unisphere aperture 9 and medium RMT detector gain were used to calculate these constants. The calibration constant values are listed in Table 36. These results indicate that there is no dramatic variation in calibration constant at the source temperatures investigated. The average and the standard deviation of the samples were calculated. The standard deviation is only 1.7 percent, which is well within the uncertainty of the measurements and the calculation methods. Therefore, these results show no indication of major spectral discrepancies associated with the unisphere source.

7.3.6 Repeatability of Unisphere Spectral Results

Several sets of spectral data were taken for the unisphere source by stepping through all of the RMT filter-wheel positions. Three

Table 36. Unisphere Calibration Constants at Various Source Temperatures.

Nominal Source Temperature (K)	Calibration Constant $\times 10^9$ (in ⁻²)
175	4.044
200	4.065
250	4.090
275	4.168
300	4.051
350	4.000
385	3.948
Average	4.052
Standard Deviation	1.7%

complete sets of data were taken with the source temperature maintained at 300K. The average spectral ratio values calculated from the three samples for all filter-wheel positions are listed in Table 37. To determine the repeatability of these measurements, the standard deviation of the samples was calculated. These values are also listed in the table. For all filter-wheel positions, the standard deviation of the samples was less than 9 percent.

7.4 Capsule Source

7.4.1 Capsule Spectral Ratios

Spectral ratios were calculated for all filter-wheel positions for capsule source temperatures of 250K, 300K, and 350K. The results are presented in Table 38. These results were obtained with the source aperture in position 17 and the RMT detector set to the high gain state. The values for filter-wheel positions 19, 9, 7, and 3 decrease as source temperature increases, while the values for the other filter-wheel positions display the opposite trend. These trends are the same as those noted for the RMT source and are justified by the same arguments as those presented in Section 7.2.2.

7.4.2 Capsule/RMT Ratios

To compare the spectral results from the capsule source with those from the RMT reference source, the RMT source spectral ratios were divided by the value for the capsule source at the same source temperature. These comparison ratios were determined for all filter-wheel positions for all source temperatures. The results are tabulated in Table 39. In general, the capsule values agree reasonably well with the RMT source

Table 37. Repeatability of Unisphere Source Spectral Measurements.

Filter Wheel Position	Number of Samples	Average Value	Standard Deviation (%)
19	3	0.238	5.1
17	3	0.249	5.4
15	3	0.021	8.6
13	3	0.041	6.1
11	3	0.029	4.8
9	3	0.060	3.8
7	3	0.049	4.3
5	3	0.032	3.8
3	3	0.347	1.9

Table 38. Capsule Spectral Ratios.

Filter Wheel Position	Spectral Ratio Source Temperature (K)		
	250	300	350
19	0.265	0.248	0.220
17	0.211	0.274	0.298
15	0.010	0.021	0.033
13	0.041	0.050	0.053
11	0.019	0.028	0.035
9	0.078	0.059	0.048
7	0.054	0.052	0.049
5	0.016	0.033	0.055
3	0.392	0.350	0.313

Table 39. Ratio of RMT Spectral Values to Capsule Values.

Filter Wheel Position	RMT Value/Capsule Value Source Temperature (K)		
	250	300	350
19	1.17	1.11	1.14
17	0.96	0.93	1.01
15	1.30	1.24	1.33
13	1.00	0.92	0.94
11	1.11	1.11	1.11
9	1.39	1.39	1.33
7	1.00	0.94	0.94
5	0.94	0.85	0.87
3	1.05	1.02	1.02

values. In some of the spectral bands, the agreement is better than 7 percent for all or nearly all source temperatures. The values agree within 20 percent for all cases except the filter-wheel position 9 and position 15 values. The worst case comparison was the 39 percent obtained for filter-wheel position 9 at source temperatures of 250K and 300K. In most cases, the values are relatively independent of the source temperature.

7.4.3 Signal Versus Capsule Source Temperature

The natural log of the average measured detector signal was plotted versus the natural log of the source temperature raised to the fourth power for the capsule source. The signal values used were those measured with aperture 16 on the source and the high RMT detector gain state. The plot is shown in Figure 15. Only three data points were available since results were obtained at only three source temperatures. A line was fitted through the data points using a linear curve-fit program. The data point at the intermediate temperature falls slightly above the fitted line. The data points at the high and low temperatures are slightly below the line. The slope of the fitted line is 0.899, which is about 10 percent lower than the ideal value of one.

7.4.4 Capsule Calibration Constants at Various Source Temperatures

Source calibration constants were determined for the capsule at source temperatures of 250K, 300K, and 350K. The results obtained for capsule aperture 16 and high RMT detector gain were used to calculate these constants. The values are listed in Table 40. These results indicate that there is no dramatic variation in calibration constant at

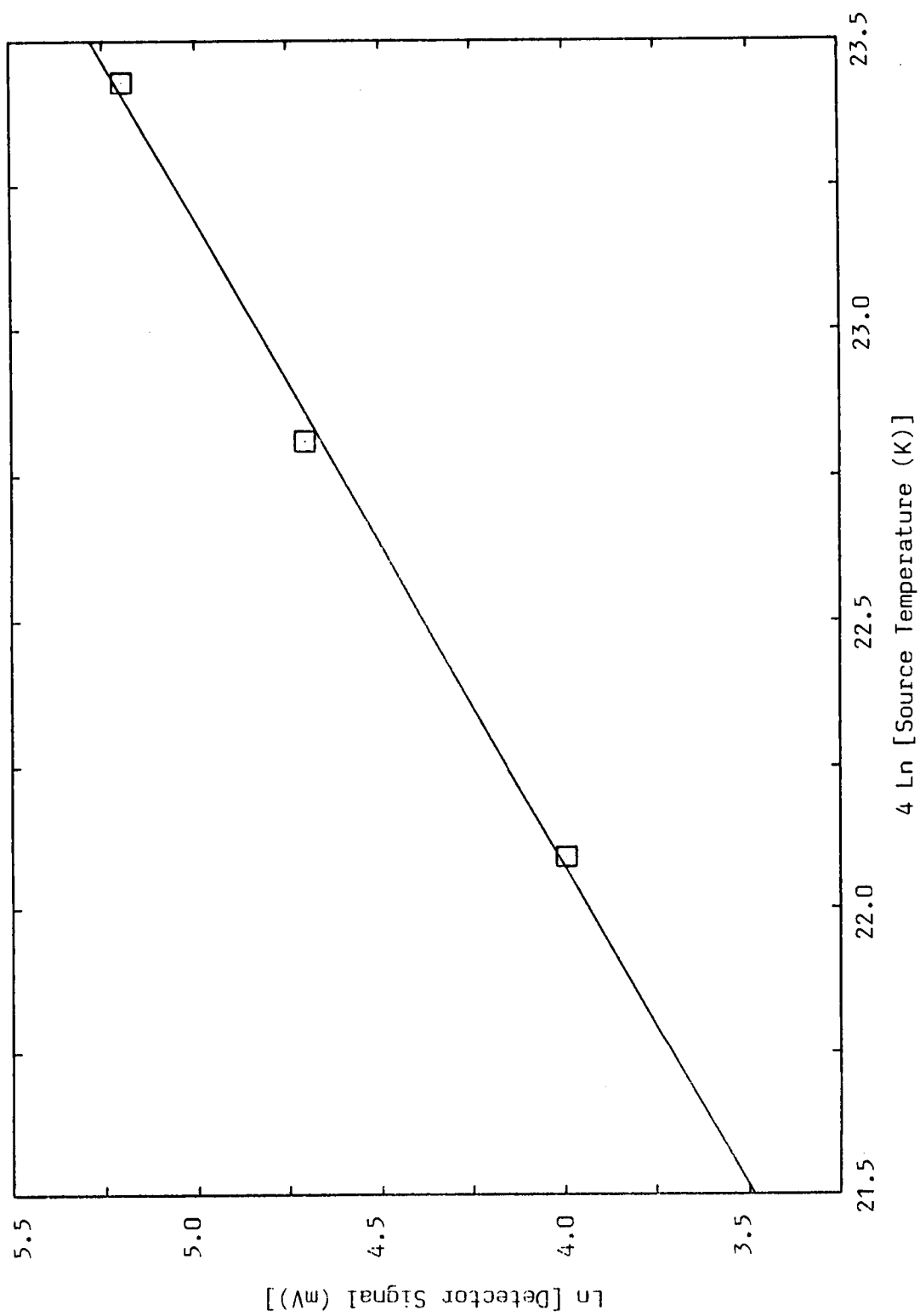


Figure 15. Signal Versus T^4 Plot for the Capsule Source.

Table 40. Capsule Calibration Constants at Various Source Temperatures.

Nominal Source Temperature (K)	Calibration Constant $\times 10^{11}$ (in ⁻²)
250	4.601
300	4.706
350	4.396
Average	4.568
Standard Deviation	3.5%

the source temperatures investigated. The average and the standard deviation of the samples were calculated. The standard deviation is only 3.5 percent, which is within the uncertainty of the measurements and the calculation methods. Therefore, these results show no indication of major spectral discrepancies associated with the capsule source.

7.4.5 Repeatability of Capsule Spectral Results

Several sets of spectral data were taken for the capsule source by stepping through all of the RMT filter-wheel positions. Four complete sets of data were taken with the source temperature maintained at 300K. The average spectral ratio values calculated from the four samples for all filter-wheel positions are listed in Table 41. To determine the repeatability of these measurements, the standard deviation of the samples was calculated. These values are also listed in the table. For all filter-wheel positions, the standard deviation of the samples was less than 4 percent.

Table 41. Repeatability of Capsule Source Spectral Measurements.

Filter Wheel Position	Number of Samples	Average Value	Standard Deviation (%)
19	4	0.248	2.5
17	4	0.274	2.3
15	4	0.021	4.0
13	4	0.050	3.0
11	4	0.028	2.0
9	4	0.059	1.3
7	4	0.052	2.0
5	4	0.033	1.1
3	4	0.350	0.9

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The RMT detector responsivity was not constant for all source temperatures when the detector spectral response was not included in the calculations. This result was not unexpected. When the detector spectral response was accounted for, the responsivity values still varied with source temperature at the lower source temperatures. This finding suggests that the true detector spectral response may be different from that listed in Table 4 (p. 17). In particular, it seems that the relative response values at the longer wavelengths should be higher. This claim was also supported by the spectral results obtained. The spectral results obtained at the shorter wavelength bands agreed more closely with theory when the spectral response of the detector was included in the predictions. For filter-wheel positions 3, 7, 9, and 19, the RMT spectral ratios were closer to the predicted blackbody values when the detector spectral response was not included than when it was included. These filters transmit almost exclusively at wavelengths greater than 14 microns. These findings again suggest that the relative response values at the longer wavelengths should be higher than those listed. The RMT detector spectral response values were determined from the manufacturer's data. It would likely be worthwhile to repeat this characterization and measure the spectral response of the detector, particularly at the long wavelengths.

Several techniques can be used to characterize the linearity of the integrating sphere sources. All of the methods considered in this

investigation appear to be valid. It was found that the relationship between aperture area and detector signal is linear for nearly all apertures on both types of sources considered. The slope of the lines fitted through the data points is nearly one in all cases. It was also determined that a single calibration constant can be determined for a source and applied to all source apertures without adding a great deal to the overall source output uncertainty. The uncertainty is lower when the signal attenuation ratio, rather than the aperture area, is used in the calculation of the calibration constant. Therefore, it is recommended that the signal attenuation ratios be used to account for the linearity characteristics of integrating sphere sources, particularly for apertures which provide signal levels which can be measured with reasonable accuracy. The signal attenuation ratios did not change appreciably with source temperature over the range of temperatures investigated. The linearity results were found to be very repeatable for both the unisphere and capsule sources at most aperture settings.

A problem existed when aperture 12 on the unisphere source was used. The plot of aperture area versus detector signal, as well as the signal attenuation ratio, deviated significantly from the predicted response for this aperture. The only method for which this problem was not evident was when the theoretical ratios obtained from the source throughput calculations were used. Unfortunately, the theoretical attenuation ratio method provided notable improvement for only the largest aperture setting; the results obtained for the smaller apertures were no better than those obtained based strictly on the ratio of aperture areas.

The theoretical attenuation method may be useful when very large apertures are used with a source.

Theoretical prediction techniques such as the method of Gouffé suggest that the RMT source should have an effective emissivity greater than 0.99. The relationship between detector signal and source temperature raised to the fourth power for the RMT source is nearly linear over the source temperature range investigated. This finding indicates that the RMT source follows the Stefan-Boltzmann relationship. The spectral response of the RMT source measured using the RMT filter wheel does not match the predicted blackbody spectral characteristics as closely as would be desired, even when the relative spectral response of the detector is accounted for. One of the factors which might affect this comparison is the fact that the RMT detector spectral response is suspect, particularly at the longer wavelengths. Another problem is that the spectral transmission characteristics of the filters in the RMT filter wheel are not known. It is assumed that the transmission is 100 percent over the spectral band limits. Any variations in the spectral transmission of the filters are ignored. It is also possible that the spectral band limits are not known accurately. The filters in the RMT filter wheel do not constitute an ideal selection. The bandwidths of the filters are not equal. Some bands are very narrow; others are relatively wide. A great deal of uncertainty is introduced when very small signals are measured. The RMT source spectral results were very repeatable, even when the results were obtained during completely separate source installations.

The unisphere and capsule spectral ratios agree reasonably well with the RMT values for most of the RMT filter-wheel positions. The worst case comparison was obtained for filter positions 9 and 15. In most cases, the ratio of the RMT spectral value to that of the integrating sphere source did not vary much with source temperature. This suggests that there are no significant spectral deteriorations introduced by the integrating spheres. The unisphere spectral ratios agreed closely with the RMT ratios when an aperture was selected such that the open-hole signals were matched. When a larger unisphere aperture was used, the results did not agree with the RMT as well, but they did more nearly match the theoretical predictions. This suggests that the results obtained at low signal levels may not be as accurate as when higher signal levels are involved. Unfortunately, the output of the RMT source cannot be increased except by increasing the source temperature. If the spectral output of the integrating sphere source is to be compared directly to the predicted ratios, the aperture which provides the largest measurable signal should be used. If the desire is to compare the spectral ratios with those obtained for the RMT source, then an aperture should be selected to match the signal levels. The spectral ratio measurements made with the unisphere and capsule sources using the RMT filter wheel were quite repeatable.

The plots of detector output signal versus source temperature to the fourth power for the unisphere source indicated that the relationship was relatively linear. There were no major discrepancies noted over the source temperature range investigated. Capsule data were obtained at only three different source temperatures. No definite

conclusions could be drawn from this limited amount of data. It was determined that a single calibration constant could be determined and applied to all source temperatures. The values at source temperatures between 275K and 300K were closest to the average value calculated for all source temperatures. A temperature value in that range should be used to determine the best single value of a calibration constant. The calibration constant values did not indicate any major spectral problems with the sources. While the spectral results obtained are not absolutely conclusive, there was no evidence found to suggest that there are any significant spectral problems associated with the integrating sphere sources.

In the past, sensor calibrations have been primarily concerned with broadband response. Increased emphasis is being placed on the ability to calibrate the sensors spectrally. This will require that the spectral characteristics of sources which are blackbody simulators be known accurately. To improve the ability to spectrally characterize cavity and integrating sphere sources, the filters in the RMT filter wheel need to be characterized. The actual spectral band limits need to be determined and the transmission variation in each band needs to be determined and accounted for. The RMT detector spectral response should be accounted for when evaluating source spectral qualities. Since the relative spectral response characteristics of the RMT detector are suspect, an attempt should be made to determine the actual characteristics. Since the filters in the RMT do not constitute an ideal set, the most effective improvement could be realized by procuring a new set of filters for the filter wheel. These filters should be

selected such that the bandwidths of the various filters are approximately equal. Relatively narrow bandwidths, on the order of 2 to 4 microns, should be used. The filters should be selected such that the entire spectral range of interest is covered.

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