STUDY OF THE PERFORMANCE PARAMETERS OF A FLIR SYSTEM. (U)

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THESIS

STUDY OF THE PERFORMANCE PARAMETERS OF A FLIR SYSTEM

by

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and
Chang Hyun Park

June 1981

Thesis Advisor: E. C. Crittenden

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**Study of the Performance Parameters of a FLIR Systems.**

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**Abstract:**

The performance parameters of Detectivity and Noise Equivalent Temperature Difference for a Forward Looking Infra-Red (FLIR) system were measured after optimization of the system. The achieved performance approached the theoretically evaluated limiting values.
Study for the Performance Parameters of a FLIR System

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ABSTRACT

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I. INTRODUCTION

A. BACKGROUND

Thermal imaging systems are of recent origin. Since the first real-time FLIR was possible in late 1960, the development of the thermal imaging system has been very rapid in its design and technology. It was the direct result of the rapid development of various types of detectors. The superiority in performance in all-weather conditions, and at night made its application wider than expected.

FLIR sensor technology is making significant strides that could earn indispensable roles for these real-time, 24 hour sensors in future aircraft, remotely piloted vehicles (RPV), missiles and air defense systems. Even the immediate prospects for wider deployment of FLIR sensors could hinge on the recent efforts to reduce the cost, size, weight and complexity of the real-time imaging devices. Some types are in the testing phase in ASW, TRAM (Target Recognition Attack Multisensor) and Attack aircraft.

To provide a basis for better understanding of FLIR systems, a basic type of FLIR system was assembled. The several performance parameters were measured, but these values were at first, in poor agreement with the theoretical values. The principal effort has been in bringing theoretical and experimental values into agreement.
B. OBJECTIVE

This paper is a brief review of the basic principles of operation and the performance parameter characteristics. Emphasis is placed on the measurement of $D^*$ (Specific Detectivity) and the direct evaluation of NETD (Noise Equivalent Temperature Difference) in terms of $D^*$.

The main scope of this study is in matching the measured and theoretically calculated NETD values. For this purpose the whole system was re-examined and several new experimental devices have been designed and constructed.
II. THEORY

A. SYSTEM PRINCIPLES

FLIR, Forward Looking Infra-Red, is a thermal imaging system which produces an image, primarily by self emission of a target and by the target's emissivity difference in the Infra-Red wavelength region.

The thermal radiation from a target in the IR region, 8-14 μm, has good atmospheric transmission and also corresponds to the peak thermal radiation from an object at ambient temperature. The radiation is collected and focused onto an IR detector by an optical system. The impinging radiation on the detector excites charge carriers across the bandgap of a semiconductor.

For quantum detectors like HgCdTe, one excess electron-hole pair is created for each photon absorbed. For a photoconductive detector as used here, this changes the conductivity of the material. Since the attached circuit provides a constant current through the material; the voltage drop across the detector varies inversely with the incident radiation intensity. Naturally there is a lower limit to the photon energy below which the detector will not respond. The lower limit is the direct energy bandgap $E_g$ and the wavelength corresponding to this lower photon energy limit is called the cut-off wavelength.
The detector converts the optical signal intensity into the analog electrical signal. This is then amplified and processed for display on a video monitor. One can reproduce the image of a target which generates Infra-Red thermal radiation even in the absence of ambient light. The whole system is described simply by the block diagram shown in Figure 1.

B. SYSTEM PARAMETERS

Several detector and system parameters are used to describe the system performance. These are $R$, $D^*$, NEP, NETD, MRTD and MDTD, which individually represent: Responsivity, Specific Detectivity, Noise Equivalent Power, Noise Equivalent Temperature Difference, Minimum Resolvable Temperature Difference, and Minimum Detectable Temperature Difference. Some of the important parameters among these usually have the definition and expression given below.

1. NEP

Noise Equivalent Power (NEP) is defined as the signal power which produces a Signal-to-Noise ratio of unity.

$$\text{NEP} = \frac{P_d}{(V_s/V_n)} \text{[watt]} \quad (1)$$

where $P_d \text{[watt]}$ : signal power incident on the detector sensitive area, same as $H_d A_d$
FIG. 1 FLIR system
$H_d$ [watt/cm$^2$] : irradiance on the detector

$A_d$ [cm$^2$] : detector sensitive area

$(V_s/V_n)$ : signal-to-noise voltage ratio

2. **$D^*$**

Specific Detectivity ($D^*$) is a detector performance parameter which represents the detector output signal-to-noise ratio for one watt of input signal power for a unit detector area and a unit electrical bandwidth.

$$D^*(\lambda,f) = \frac{(A_d \Delta f)^{\frac{1}{2}}}{H_d A_d} \frac{(V_s/V_n)}{(2)}$$

where

$\Delta f$ [Hz] : system bandwidth

$V_n$ [volts] : detector rms noise voltage measured in the bandwidth of $\Delta f$.

$V_s$ [volts] : detector signal voltage as a function of wavelength and electrical frequency.

$D^*$ comes from the expression of $D$ (Detectivity) which is the reciprocal of NEP.

The assumptions made in the process of derivation require that detector noise varies as $A_d^{\frac{1}{2}}$ and $\Delta f^{\frac{1}{2}}$, [Ref. 1]. The first assumption is valid for photon detectors as long as the detector areas do not vary by more than an order of magnitude. The second approximation requires either that noise is frequency invariant over the amplifier bandwidth, or that it is measured over such a narrow band that a
variation is insignificant. Further details can be found in Lloyd. [Ref. 2].

3. **NETD**

Noise Equivalent Temperature Difference (NETD) is a measure of the ability of a system to discriminate small signals in the presence of noise. NETD is defined as the blackbody target-to-background temperature difference in a standard test pattern which produces a peak signal-to-rms noise ratio of unity when the system views the test pattern. [Ref. 2]. This is given as

\[
\text{NETD} = \frac{\Delta T}{(V_s/V_n)}
\]

where

\[\Delta T \ [^\circ K] : \text{temperature difference between a target and background}\]

NETD is also theoretically derived by Lloyd [Ref. 2] as

\[
\text{NETD} = \frac{\pi (A_d \Delta f)^{1/2}}{\alpha \beta \beta \int_0^{\infty} \frac{D(\lambda) \tau(\lambda) \lambda}{\beta \lambda} d\lambda}
\]

where

\[\alpha, \beta : \text{detector angular subtense which is } a/f, \ b/f \text{ where } a, b \text{ are the size of a rectangular detector cell and } f \text{ is the focal length of the optic system.}\]

\[\tau(\lambda) : \text{IR optical transmission as a function of wavelength.}\]

\[W_\lambda \ [\text{watt/cm}^2] : \text{radiant emittance of a target}\]
For some systems it is possible to assume that
\( \tau_0(\lambda) = \text{const.} \) within specific wavelength region \( \lambda_1 \leq \lambda \leq \lambda_2 \)
and \( \tau_0(\lambda) = 0 \) elsewhere.

Then
\[
\text{NETD} = \frac{(A_d \Delta f)^{1/2}}{\alpha \beta A_0 \tau_0} \frac{1}{\int_{\lambda_1}^{\lambda_2} \frac{\partial W_1(T)}{\partial T} D^*(\lambda) \, d\lambda}
\]  

(5)

4. MRTD

Minimum Resolvable Temperature Difference (MRTD) is defined as the image signal-to-noise ratio required for an observer to resolve an equally spaced four bar target that is obscured by noise. MRTD is also derived by Lloyd [Ref. 2] under several assumptions.

\[
\text{MRTD} = \frac{3 (\text{NETD}/\Delta f)^{1/2} f_T (\alpha \beta)^{1/2}}{r_s (T_e \hat{F})^{1/2}}
\]

(6)

where

- \( f_T \) [Hz/mrad]: fundamental target frequency
- \( T_e \) [sec]: effective eye integration time
- \( \tau_d \) [sec]: detector dwell time
- \( \hat{F} \) [Hz]: frame rate
- \( r_s \): overall system MTF

5. MDTD

Minimum Detectable Temperature Difference (MDTD) is the blackbody temperature difference required for an
observer to detect the presence of a square target when he is allowed unlimited time to make a decision and knows where to look for the target. Lloyd derived the expression of MDTD under the same assumption as MRTD.

\[
\text{MDTD} = \frac{r_s 1.5 \sqrt{2} \text{MRTD} \left( f_T - \frac{1}{2} w \right)}{\overline{I}(x,y)}
\]

(7)

where

\[
\overline{I}(x,y) : \text{average value of the convolution integral of the image of the square target}
\]

The derivations for the NETD, MRTD, and MDTD are carried out in detail with all assumptions in Lloyd [Ref. 2], so the derivations are omitted here.

The parameters, MRTD and MDTD, have important meaning in expressing the ability of the human eye to resolve or detect the target image on the video monitor. However, this is not a key point in this study.

\(D^*\) and NETD are by far the most frequently used figures of merit for characterizing the sensitivity of Infra-Red quantum detectors and FLIR systems. Since those two parameters are considered the most basic and fundamental parameters, further study of these was carried out.

C. DIRECT EVALUATION OF NETD IN TERMS OF \(D^*\)

In order to compare measured and theoretical values of NETD, a form is needed which permits use of directly measured quantities. Calculation of the theoretical
value of NETD by the expression from Lloyd is a time consuming job. It also requires knowledge of the spectral variation of $D^*$, not available without additional equipment which is not presently available. A more convenient form of this parameter expression is developed as follows.

1. Derivation of $D^*$

Basically the expression for Specific Detectivity is developed for the ultimate derivation of NETD expression rather than for itself. To derive a new expression of $D^*$ one can imagine a simple experiment set-up as shown in Figure 2.

![Diagram of experiment set-up](image)

Fig. 2 Experiment set-up for detectivity derivation.

Total irradiance at the blackbody [watt]: $H_s A_s$

where

$H_s$ [watt/cm$^2$] : irradiance of the blackbody

$A_s$ [cm$^2$] : area of blackbody perpendicular to the line of sight

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Total irradiance at the blackbody per steradian

\[ \text{[watt/Sr]} : \frac{H_s A_s}{\pi} \]

Detector area expressed in terms of solid angle \( \Sigma \):

\[ \frac{A_d}{Z^2} \]

where \( Z [\text{cm}] \) : distance between detector and blackbody

Total power absorbed into detector \( P_d \)

\[ P_d \text{ [watt]} = \frac{(A_d/Z^2)}{(H_s A_s/\pi)} \] (8)

General expression of \( D^* \)

\[ D^* \text{ [cm Hz/watt]} = \frac{(A_d \Delta f)^{1/2}}{(V_s/V_n)} \]

\[ D^* = \frac{(A_d \Delta f)^{1/2} Z^2 \pi}{A_d A_s H_s} \] (9)

All terms in the expression for \( D^* \) in equation (9) can be directly read or measured in the experimental process.

2. Derivation of NETD

The expression for NETD, directly based on the definition of it, provides a good starting point to derive a more convenient form. This also leads to a form capable of direct experimental verification.

\[ \text{NETD} = \frac{\Delta T}{(V_s/V_n)} \] (10)

Figure 3 shows the simplified optical system, target and detector excluding all of the electronic elements. A pinhole (Area \( A_p \)) is also attached to provide an ability to improve the spatial resolution.
Power absorbed by the detector $P_d = A_e H_s A_s / R^2$ where $R$ is the distance between the telescope primary mirror and a target.

Optics $f/# = r/D = N$

where $D$ is a diameter of primary mirror.

Area of primary mirror: $A_e \text{ [cm}^2\text{]}$

Irradiance of blackbody surface: $H_s \text{ [watt/cm}^2\text{]} = G_s \Delta T$

where $G_s$ is a proportionality coefficient.

Then,

$$P_d = \frac{1}{R^2} \left( \frac{1}{4} \pi \frac{r}{N} \right)^2 \frac{A_s}{\pi} G_t \Delta T$$

$$\text{(11)}$$

where $\Delta T = 4N^2 P_d / A_p G_t$

From Equation (2), (9), (10), (11)

$$\text{NETD} = \frac{4N^2}{A_p G_t} (A_d \Delta f)^{1/2} A_d A_s G_s \Delta T / (A_d \Delta f)^{1/2} Z^2 \left( V_s / V_n \right)$$

Finally we can get a much more convenient form of NETD, that does not involve specifying the wavelength limits.
\[
\text{NETD} = \frac{4N^2A_d A_s}{\pi A_p^2}(V_n/V_s)\Delta T
\]  \hspace{1cm} (12)

where \(G_s/G_t = 1\) if one keeps consistency in temperature.

All terms appearing in this expression for NETD in Equation (12) can be directly read or measured experimentally. It is clear from the Equation (12) that if \(\Delta T\) is kept constant then NETD depends only on the pinhole size.
III. EXPERIMENTAL PROCEDURE AND MEASUREMENT

A. APPARATUS USED FOR EVALUATION

The FLIR system to be evaluated is a HgCdTe single cell, mechanically scanning thermal imaging system assembled at NAVPGSCOL. Since a former study [Ref. 3] described precisely the whole system, only the main feature of elements are briefly discussed here.

1. Optics; Cassegrarian Type Dahl-Kirkham Telescope
   a. Diameter (D) : 15.24 cm
   b. Focal Length (f) : 228.6 cm
   c. Total Collecting Area : 172.8 cm²
   d. To see the effect of the pinhole on the value NETD, an assembly of field lens and a pinhole are located in front of the detector.
   e. Scanning mechanism which consists of 2 mirrors mutually perpendicular to each other is mounted at an angle of 45° to the beam exiting to the back end of the telescope. The scanning system could be located close to the exit aperture which means that it can be operating in the region where the image beam is parallel. The fact that a convergent beam scanner might cause the image deformation by mirror induced focal point shifting can be compensated. Because of the necessity for small mirror motion and the long focal length, the use of the convergent beam scanning technique
would not cause unacceptable image blur through beam focus.

2. Detector
   a. Mercury Cadmium Teluride single cell detector with an IRTRAN-2 window operates in the 8-14 μm wavelength region.
   b. A detector cell is mounted in a side-looking dewar and utilizes liquid nitrogen cooling down to 77 °K and is evacuated to 2×10⁻⁶ Torr.
   c. The spectral response of the detector depends on the composition of the alloy and a wide range of performance is shown in Figure 4 from the supplier's specification [Ref. 4].
   d. Manufacturer: Santa Barbara Research Center
   e. Precise characteristics like Relative Responsivity vs. wavelength, Detectivity vs. Frequency, Responsivity vs. Frequency, Detectivity vs. Temperature can be referred to SBRC. [Ref. 4].

![Fig. 4 Range of spectral detectivity](image)
3. **Blackbody Heat Source**

A blackbody heat source is required for measuring the D* and NETD. Initially a U-shaped heating element with a long aluminum bar was used as a blackbody with a powerstat to control the temperature of the heating element. But it was not good enough as a blackbody target due to the low emissivity of the target and very fast heat dissipation and severe fluctuation of temperature due to the ambient background.

So, a new blackbody target covered with asbestos and fiber glass as an insulator to prevent heat loss into the ambient background, was designed and built as shown in Figure 5.

![Diagram of Blackbody Heat Source](attachment:image.png)

**Fig. 5 Blackbody Heat Source**

The cone inside this aluminum cylinder is used to increase internal reflections. Three screws at three different places are used to connect the thermocouples. A thermocouple attached to this blackbody heat source is used to measure the temperature with an accuracy of ± 0.1 °C.
4. **Electronic Equipment**

The electronic equipment is described in detail in the former study. [Ref. 5]. A brief summary of the equipment follows:

a. Hewlett Packard 3310 A Function Generator  
   : Raster control

b. General Scanning CCX 101 scanner control  
   : mirror drive

c. Wavetek 180 Function Generator  
   : Raster control

d. Princeton Applied Research Model 113 Preamplifier  
   : detector signal amplifier

e. Hewlett Packard 3400A RMS Voltmeter  
   : noise voltage measurement

f. Monsanto AM-6419/USM-368 OSC.  
   : display

Since HgCdTe is used as a photoconductor, a special electric circuit is needed to provide the conduction current. Figure 6 shows this electric circuit.

![Electric Circuit Diagram](image)

Fig. 6 Electric Circuit

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B. MEASUREMENT AND CALCULATION

1. $D^*$

To determine the detectivity it is necessary to measure the signal-to-noise voltage ratio. For this purpose a simple experiment is set up as shown in Figure 7.

Since the detector can detect only a change of radiation, a chopper is used to convert the steady radiation from the blackbody heat source into intermittent radiation. An aluminum plate, which has a hole in it, and is insulated with asbestos and fiber glass on both sides to prevent any thermal effect from the chopper or from any other heat source except blackbody heat source itself, is used as a real blackbody target. The fact that this aluminum plate with a hole, not the blackbody heat source, acts as a real blackbody can be easily verified by observing that the signal voltage is dependent on the distance between the aluminum plate and the detector, not on the distance from the detector to the blackbody heat source.

\[
\Delta f = 3000 \, \text{Hz} \\
A_d = 0.04 \, \text{cm}^2 \\
A_s = \pi \, \text{cm}^2 \\
Z = 50 \, \text{cm} \\
H_s = 0.059 \, \text{watt/cm}^2 \text{ using calculator program} \\
\]

[Appendix] where the inputs are

\[
\lambda_1 = 8 \, \mu\text{m} \\
\lambda_2 = 14 \, \mu\text{m} \\
\]
Aluminum plate with a hole in it insulated by asbestos and fiber glass

Fig. 7 Detectivity measurement experiment set-up
\[ T_c = 163 \, ^\circ C \text{ (Blackbody Temperature)} \]
\[ T_b = 22 \, ^\circ C \text{ (Background Temperature)} \]
\[ \frac{V_s}{V_n} = 400 \text{ where measured value of} \]
\[ V_s = 0.6 \text{ volts (Reading from the Oscilloscope)} \]
\[ V_n = 0.0015 \text{ (System Noise Voltage, reading} \]
from the rms Noise voltage meter)  

Calculation of \( D^* \) using the previously derived  
detectivity expression, Equation (9) yields  
\[ D^* = 0.46 \times 10^{10} \text{[cmHz}^{\frac{1}{2}}\text{/watt]} \]
This value is the lower limit of detectivity in Figure 5  
where the values are from the SBRC. [Ref. 4].  

2. NETD  
The experimental NETD can be measured, using the  
FLIR system under the same condition of blackbody temperature as for the \( D^* \) measurement by measuring the signal-to-noise voltage ratio for each size of pinhole. In this  
step it is important to ensure that the signal on the oscilloscope comes from the target, and not from any reflection.  

The first thing to be checked was the shape of the  
image formed at the back focal point. An incandescent  
light bulb was used as a target at a long distance so that  
the incident light is considered as a parallel beam. Then,  
the image should be round and clear.  

Secondly, the shape of a signal on the oscilloscope  
should have a flat top while turning the telescope
horizontally. This is based on the linear filter theory which map object distributions into image distributions by the process of convolution. This theory says that the image function is a weighted sum of the system response to the component delta functions of the object.

Every part of the system which might cause an image degradation due to the poor alignment and the reflection by system itself was checked. This procedure included checking the relative angle of the reflecting mirror to the beam exit from the telescope, the exact location of the pinhole at the back focal point, and the adjustment of the field lens assembly. Also an effort was made to keep the direction of the telescope scanning across the objective screen and the axis of the field lens-detector assembly on a horizontal path line.

Difficulty in keeping the target temperature constant was solved by using a newly designed blackbody heat source shown in Figure 5.

The chromel-alumel thermocouple was used with its reference junction in ice water.

Table 1 shows the measured signal and noise voltages and the calculated NETD based on this measurement using the Equation (3).
<table>
<thead>
<tr>
<th>D of pinhole (cm)</th>
<th>$V_s$ volts</th>
<th>$V_n$ volts</th>
<th>$V_s/V_n$</th>
<th>NETD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0368</td>
<td>0.05</td>
<td>0.0015</td>
<td>33.3</td>
<td>4.23</td>
</tr>
<tr>
<td>0.05</td>
<td>0.09</td>
<td>&quot;</td>
<td>60.0</td>
<td>2.35</td>
</tr>
<tr>
<td>0.75</td>
<td>0.135</td>
<td>&quot;</td>
<td>90.0</td>
<td>1.57</td>
</tr>
<tr>
<td>0.1</td>
<td>0.188</td>
<td>&quot;</td>
<td>125.3</td>
<td>1.12</td>
</tr>
<tr>
<td>0.15</td>
<td>0.241</td>
<td>&quot;</td>
<td>160.7</td>
<td>0.87</td>
</tr>
<tr>
<td>no pinhole</td>
<td>0.38</td>
<td>0.0021</td>
<td>180.9</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 1  NETD - Experimental Value
IV. ANALYSIS

Table 2 shows the theoretically calculated NETD and also the experimentally measured value as a function of pinhole size.

<table>
<thead>
<tr>
<th>D. of pinhole</th>
<th>NETD theoretical</th>
<th>NETD experimental</th>
<th>difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0368</td>
<td>3.77</td>
<td>4.23</td>
<td>0.46</td>
</tr>
<tr>
<td>0.05</td>
<td>2.04</td>
<td>2.35</td>
<td>0.31</td>
</tr>
<tr>
<td>0.075</td>
<td>0.91</td>
<td>1.67</td>
<td>0.76</td>
</tr>
<tr>
<td>0.1</td>
<td>0.51</td>
<td>1.12</td>
<td>0.61</td>
</tr>
<tr>
<td>0.15</td>
<td>0.23</td>
<td>0.87</td>
<td>0.64</td>
</tr>
<tr>
<td>no pinhole</td>
<td>0.1</td>
<td>0.78</td>
<td>0.68</td>
</tr>
</tbody>
</table>

Table 2 NETD - Theoretical and Experimental Value

The data of Table 2 are plotted in Figure 8. For reference, those values of NETD, measured and calculated in the former study [Ref. 5] are also included in Figure 8.

An analysis of the values of the performance parameter, NETD, in the table above, reveals several important points.

The experimentally measured values of the NETD are in reasonable agreement with the theoretical values calculated with Equation (11). Even though the difference is small enough, this discrepancy is understood as that, first, the temperature difference $\Delta T$ still fluctuates on a certain scale which affects the measured signal-to-noise ratio.
Fig. 8 NETD Comparison - theoretical and measured value

---

measured value (former study)
theoretical value ("")
measured value
theoretical value
The temperature difference between the front end and back end of the blackbody furnace was 15 °C at the target temperature of 163 °C and ambient background temperature 22 °C. Considering that the approximate rate of change \( \frac{d \text{NETD}}{dT} \) with respect to the temperature difference is about 0.02, the nonuniformity of the blackbody heat source can cause error in the NETD of 0.3 °C, which is half of the NETD difference in Table 2.

Second, this experiment basically assumed background limited noise conditions. But there should be another kind of noise, for example, 1/f noise.

Third, the alignment problem is another factor decreasing the accuracy of the measured experimental value. Using the more precise way of aligning, the result is believed to be much better.

The expected dependency of the thermal sensitivity of the system expressed by NETD upon the various size of pinhole was well observed. As expected, as the pinhole size gets larger, the system shows more sensitive response to the thermal radiation. The smaller size of the pinhole shows better resolution. Consequently, when all of the other factors like \( T, f/# \) are fixed, the NETD is a function only of area of the pinhole. This relation is well shown in Figure 8.
V. CONCLUSIONS

One of the basic performance parameters of the FLIR system, the NETD, was measured. Every effort was made to match the theoretical values and the experimentally measured values. For that purpose, a more convenient and direct form of NETD expression was derived. A new black-body heat source was designed to more closely approximate a true blackbody. Most of the laboratory effort was spent in establishing precise optical alignment and in keeping the target and the background temperature difference constant. As a consequence the discrepancy between the theoretical and experimental values of NETD decreased to 0.3-0.7 °C, close enough to be considered in agreement.

The result of measuring and calculating the NETD for 5 different sizes of pinholes show the variation of NETD with the pinhole size to be as theoretically anticipated.

As a secondary objective, the detectivity was measured and found to be $0.46 \times 10^{10}$ cm Hz$^\frac{1}{2}$/watt. This value is the lower limit of detectivity in the characteristics provided by the detector manufacturer. Even though the value of $D^*$ is somewhat lower than expected, it can be understood to be a quality decrease due to a long term use, and one can say that $D^*$ is still in a tolerable region.
APPENDIX

CALCULATING "IN BAND" FLUX DENSITY OF BLACKBODY SOURCES USING TI-59

To use: press RST

enter $\lambda_1$ microns R/S

enter $\lambda_2$ " R/S

enter $T$ A for °K

B for °F

C for °C

enter number of intervals

D for watt/cm$^2$

E for photons/sec/cm$^2$

000 42 STO 021 00 00 041. 69 OP
001 01 01 022 69 OP 042 06 06
002 99 PRT 023 06 06 043 69 OP
003 91 R/S 024 69 OP 044 00 00
004 42 STO 025 00 00 045 75 -
005 02 02 026 91 R/S 046 03 3
006 99 PRT 027 76 LBL 047 02 2
007 91 R/S 028 12 B 048 95 =
008 76 LBL 029 42 STO 049 65 x
009 11 A 030 00 00 050 05 5
010 42 STO 031 02 2 051 55 +
011 00 00 032 01 1 052 09 9
012 02 2 033 00 0 053 85 +
013 06 6 034 00 0 054 02 2
014 00 0 035 00 0 055 07 7
015 00 0 036 00 0 056 03 3
016 00 0 037 69 OP 057 95 =
017 00 0 038 04 04 058 42 STO
018 69 OP 039 43 RCL 059 00 00
019 04 04 040 00 00 060 91 R/S
020 43 RCL
061 76  LBL  111 08  8  161 01  1
062 13  C  112 93  .  162 00  0
063 42  STO  113 03  3  163 07  7
064 00  0  114 02  2  164 04  4
065 01  1  115 03  3  165 52  EE
066 05  5  116 03  3  166 04  4
067 00  0  117 04  4  167 42  STO
068 00  0  118 55  ÷  168 08  08
069 00  0  119 02  2  169 95  5
070 00  0  120 07  7  170 42  STO
071 69  op  121 55  ÷  171 09  09
072 04  04  122 03  3  172 01  1
073 43  RCL  123 00  00  173 22  INV
074 00  00  124 54  )  174 23  LNX
075 69  OP  125 54  )  175 42  STO
076 06  06  126 75  -  176 06  06
077 69  OP  127 01  1  177 36  PGM
078 00  00  128 54  )  178 09  09
079 43  RCL  129 54  )  179 14  D
080 00  00  130 35  1/X  180 22  INV
081 85  +  131 65  x  181 52  EE
082 02  2  132 43  RCL  182 99  PRT
083 07  7  133 08  08  183 98  ADV
084 05  3  134 54  )  184 91  R/S
085 95  =  135 92  RTN  185 76  LBL
086 42  STO  136 76  LBL  186 15  3
087 00  00  137 14  D  187 98  ADV
088 91  R/S  138 98  ADV  188 42  STO
089 76  LBL  139 42  STO  189 05  05
090 16  A'  140 05  05  190 99  PRT
091 42  STO  141 99  PRT  191 98  ADV
092 07  07  142 98  ADV  192 53  (  
093 53  (  143 53  (  193 43  RCL
094 53  (  144 43  RCL  194 02  02
095 43  RCL  145 02  02  195 75  -
096 07  07  146 75  -  196 43  RCL
097 45  YX  147 43  rcl  197 01  01
098 43  RCL  148 01  01  198 54  )
099 09  09  149 54  )  199 55  ÷
100 65  x  150 55  ÷  200 43  RCL
101 53  (  151 43  RCL  201 05  05
102 53  (  152 05  05  202 95  =
103 43  RCL  153 95  =  203 42  STO
104 06  06  154 42  STO  204 03  03
105 45  YX  155 03  03  205 01  1
106 53  (  156 03  3  206 93  .
107 01  1  157 93  .  207 08  8
108 04  4  158 07  7  208 08  8
109 03  3  159 04  4  209 03  3
110 08  8  160 01  1  210 06  6

35
211 05  5
212 01  1
213 06  6
214 52  EE
215 02  2
216 03  3
217 42  STO
218 08  08
219 04  4
220 42  STO
221 09  09
222 01  1
223 22  INV
224 23  LNX
225 42  STO
226 06  06
227 36  PGM
228 09  09
229 14  D
230 22  INV
231 52  EE
232 99  PRT
233 98  ADV
234 91  R/S
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