# State-of-the-Art Transfer Radiometer for Testing and Calibration of FLIR Test Equipment

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## 1. ABSTRACT

State-of-the-art FLIR performance has reached an NETD of a few hundredths of a degree. The test systems designed to test these FLIR's project images which have accuracies, stabilities and uniformities of hundredths of a degree as well so that these FLIR's can be tested accurately for their true performance.

Traditionally, FLIR test systems are tested in one of two ways:

1) Thermometric calibration of the blackbody source and bar target used to generate a projected pattern.
2) Radiometric calibration of the image projected by the entire test system.

While in the thermometric calibration only one component of the test system is calibrated (the blackbody/target combination), the radiometric method calibrates the radiation, which is projected to the Unit Under Test (UUT).

For older FLIR test systems, where the performance of the calibration was non-critical (in fact accuracies of several tenths of a degree were acceptable), both methods were acceptable in principle. If the optical performance of the FLIR test system was significantly degraded (for example the transmission of the collimator or emissivity of the blackbody or target), the thermometric method was typically not acceptable and radiometric calibration would have to be performed.

For newer FLIR test systems, a systems-level test and calibration should be used to correct for any change in emissivity of the source, the transmission of the collimator and the thermal calibration of the source itself.

This paper discusses and presents the performance of a radiometer which would be required to perform these system-level tests as defined above.

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## 2. INTRODUCTION

A FLIR test system is basically a projector of very precisely controlled infrared radiation, spatially modulated by special patterns, which allow quality testing of the FLIR image.

Transfer radiometry, or the art of testing and calibrating FLIR test systems and infrared sources by radiometric methods dates back to the efforts that were made both in the Navy[1] and in commercial companies to establish standard methods for the measurement of the temperature of infrared sources. The theoretical problems connected with IR source emissivity, background radiation, and system stability were analyzed thoroughly by R.C. Anderson.[2] CI Systems has worked[3] on the calibration of high temperature sources and has shown that a stable and accurate spectroradiometer, combined with the appropriate software, can be a very useful tool to calibrate infrared sources radiometrically.

The main difficulty in infrared measurements stems from the fact that every object emits infrared radiation, and therefore the environment plays an important role, as both a reference for accurate measurements and a source of spurious signals. It is for this reason that all the work being done using radiometry as a means of temperature measurement, includes precautions to prevent unknown signals from affecting the measuring system.

This paper describes the results of work performed with a spectroradiometer, which was recently modified to test the stability, uniformity and accuracy of radiance differentials of state-of-the-art FLIR test systems. These results show that important information is gained by the radiometric tests, which is not otherwise available with traditional contact temperature probes.

We took the straightforward approach that since the FLIR test system is actually an infrared scene generator, we must have a means of analyzing this scene radiometrically, and also of testing how well controlled this radiation is in every part of the scene. In order to do this we first review the parameters of FLIR's and FLIR test systems. Then we analyze the important parameters of the spectroradiometer that are essential for the measurements of the test system itself. Finally, we show the results of stability measurements performed on an existing specially modified spectroradiometer; from these results, conclusions can be drawn on whether and to what extent the radiometer is adequate for testing the FLIR test system itself.

## 3. PRESENT PERFORMANCE OF FLIR TEST SYSTEMS

FLIR test systems have improved over the last years to keep abreast of the improvement of the FLIRs themselves. A modern FLIR test system is basically described in Fig.1.

It is composed of an accurate extended area blackbody source with target patterns. The source temperature is very accurately controlled with respect to the background temperature. The source is placed on the focal plane of a collimator, which collects the blackbody radiation and projects it in a parallel beam towards the UUT, to simulate an object at infinity.

It is obvious that the accuracy, resolution, stability and uniformity of the FLIR test system must be significantly better than the performance of the FLIR itself, in order for the tests to be useful.

But how do we know whether a FLIR test system is up to the job that it has been designed for? As the tests become more and more demanding, the importance of this question increases as well.

Since the radiometer's main task is the measurement of the radiant output of the test equipment, the most important parameters of the FLIR to be considered here are the MRTD and the uniformity of response. MRTD figures of state-of-the-art FLIR'S are below one tenth of a degree for the lowest spatial frequencies, while the uniformity is of the order of 5% to 10% over its field of view.

Test equipment must be able to project scenes that are approximately one order of magnitude more precise than FLIR performance; therefore the accuracy and stability of the effective temperature differential between the blackbody emitter and the background must be of the order of 5 millidegrees.

In practice, however, state-of-the-art test equipment does not reach better performance than ten millidegrees or slightly higher, due to technological limitations. For example, since the reflectivity of the best extended area blackbodies is near 3%, a change of half a degree in ambient temperature causes an instability of 0.015C in the output of the test equipment.

The uniformity of the beam across the collimating aperture of the test system is less important but it is sometimes tested because this aperture is usually larger than the aperture of the FLIR, and therefore its uniformity ensures repeatability of the measurements when taking the FLIR out and in the test set up. The requirement on this parameter should be of the order of 10 millidegrees.

A radiometric test of the response time of the test equipment is also done because there is a delay between the blackbody temperature as measured by the internal sensor and the corresponding radiance out of the collimator. This delay should be as short as possible to shorten duration of the FLIR test.

## 4. REQUIREMENTS ON THE RADIOMETER PERFORMANCE

A fixed field of view radiometer is ideal for radiometric tests, because it is intrinsically more sensitive than the FLIR itself; this is due to the fact that, since there is a single pixel and no fast scanning as in a FLIR the electronic bandwidth can be smaller and therefore much noise can be integrated out.

In addition, a radiometer is built with an internal blackbody at known temperature as a reference; with properly designed optics and blackbody, environment temperature drifts can be taken into account, and therefore the radiometer accuracy and stability can be better than the FLIR's.

The requirements on the radiometer must be such that they allow characterization of the test equipment to the accuracy and repeatability estimated in the previous section.

The most important parameters of the spectroradiometer are:

i) signal stability;
ii) noise performance;
iii) an automatic mechanism to scan the output beam of the test equipment, as function of the angle between it and the collimator optical axis.

### Signal Stability

This parameter is composed of three contributions:

i) Electronic drifts.
ii) signal changes due to changes of environmental conditions (e.g., ambient temperature);
iii) unknown changes in spurious signals, internal and external.

The first one is due to detector and electronic drifts, and is taken into account by monitoring the DC level periodically and subtracting it. The second one can be taken into account by the software of the radiometer by using the Planck function of both the ambient temperature and the internal blackbody temperature. The third one is parasitic; therefore, it has to be minimized, both by careful optical design and by controlling the environment.

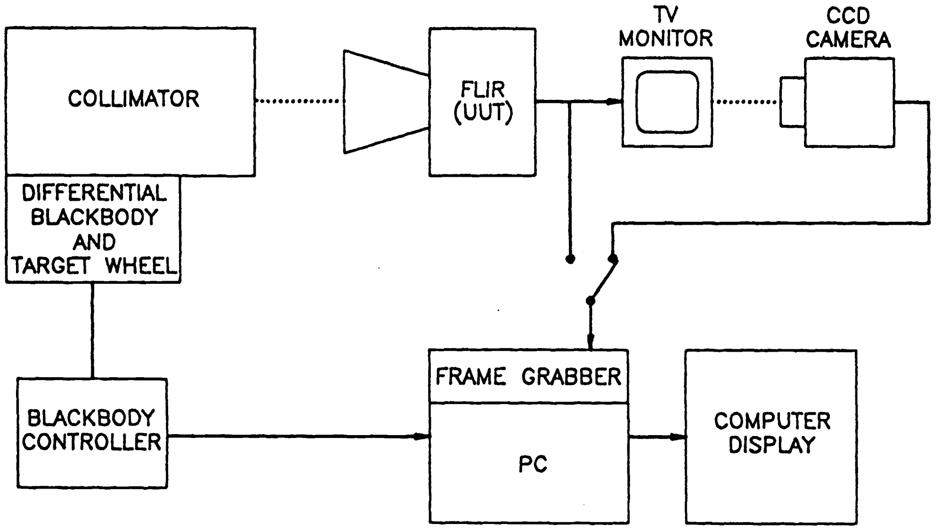


Fig.1 Schematic diagram of a modern FLIR test system.

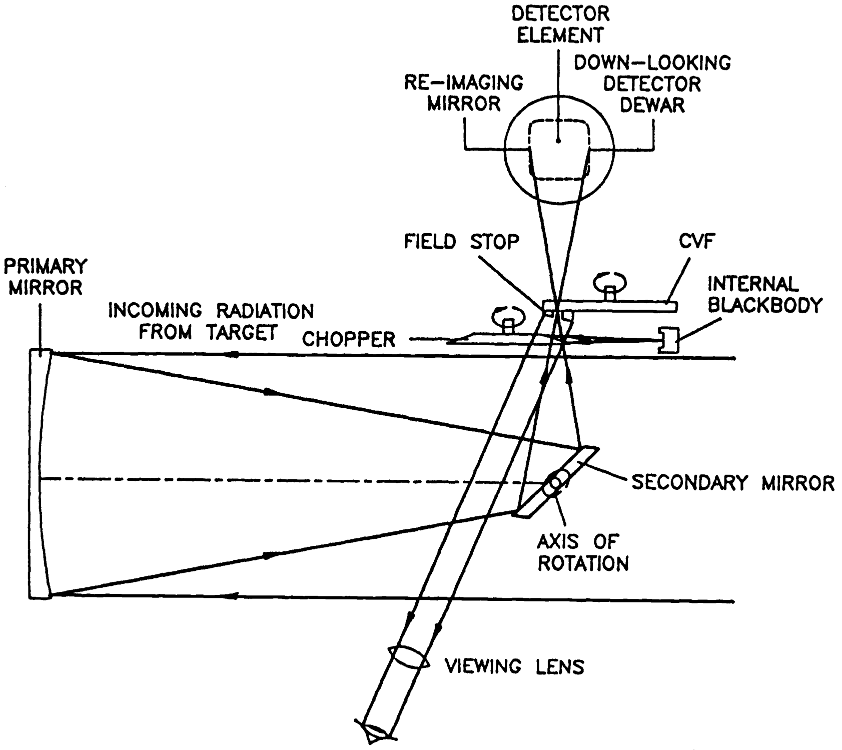


Fig.2 Optical Design of the SR 5000 Spectroradiometer

All the contributions together, after the appropriate corrections, should add up to no more than a few millidegrees when integrating the signal over a few minutes. (The integration is needed in order to get the accuracies required.

### Noise Performance

Noise is a type of short term instability, which limits the resolution of the temperature measurements. In a detector limited system, as we are with an MCT detector, measuring room temperature objects, the main contribution to the noise equivalent power comes from the detector D* and its size. In equivalent temperature units the noise depends also on the optics. A typical number we should strive for is 1 millidegree or better.

A typical NET figure of the state-of-the-art spectroradiometers is 0.5 mdegree for 1Hz bandwidth.

### Scanning the Output Beam

Scan of the output beam can be done in two different ways for two different tests:

i) translation of the radiometer parallel to the optical axis; this is to test the uniformity of the collimated beam. It is important to get repeatable results when the FLIR's aperture is smaller than the collimator aperture;
ii) scanning the field of view of the radiometer; this is to test the uniformity of the source and the radiometric scene on the focal plane of the collimator.

## 5. RADIOMETER DESIGN AND TESTING CONCEPT

In this section we will show the testing concept of a FLIR test equipment and focus only on the most important features of the required radiometer. In the next sections we will give some measurement results and conclusions.

### Testing Concept

The idea is to calibrate the spectroradiometer with a very accurately known blackbody without using the test equipment collimator. This is to avoid the influence of the collimator's parameters (e.g., reflectivity of the mirrors) on the calibration. After calibration, the radiometer is placed in front of the test equipment, in place of the FLIR, and its signals are recorded. Measurements as a function of time, wavelength, field of view and position are performed in order to characterize the test equipment.

### Radiometer Design

Fig.2 shows the optical design of the specially modified

spectroradiometer that CI has built and used for this purpose. The radiation from the test equipment enters the optics in collimated fashion from the right side of the figure, is collected by the spherical primary mirror, deflected by a flat secondary mirror and focused on a field stop plane after being chopped.
The field stop is a small aperture which defines the field of view of the radiometer, typically 6 mrad. The field of view can be reduced down to 0.3 mrad, by changing the size of the field stop. This flexibility is important to test high spatial frequency patterns (by using small fields of view) or to improve the signal to noise ratio when a small spot is not required (large fields of view).

The radiation is refocused at 90° by an ellipsoidal mirror onto a down-looking detector. Figure 2 shows the Circular Variable Filter (CVF), a scanning monochromator which scans the spectrum with a resolution of about 2% of the wavelength. Measuring the spectrum instead of the integral over the range of sensitivity of the detector improves the accuracy of the temperature measurement. The reason for this is that the detector response, the emissivity of the blackbody, the reflectivity of the mirrors of both the collimator and the radiometer, are all wavelength dependent and unknown. An integral measurement is dependent on the product of all these functions. It is difficult, if not impossible, in this case, to unravel this information. On the contrary, in a spectral measurement, once the calibration is done with a known, high emissivity blackbody, the radiant output of the FLIR test equipment can be known without knowing the emissivity of its blackbody and the reflectivity of its mirrors.
Since the radiation is chopped, the signal on the detector is AC. This is a common practice in infrared detection. The AC signal is demodulated by synchronous detection techniques and turned into a DC signal, proportional to the radiance difference between the external object being measured and the internal blackbody. (The chopper reflects, in its "closed" position, a reference blackbody, while in the "open" position the radiation from the target is seen by the detector). The blackbody Planck function of the internal blackbody temperature now serves as a baseline for the signal: by monitoring this temperature, the external object radiance can be reconstructed by simply adding back the internal blackbody Planck function to the demodulated signal.

There are two important features to be specially noted in the design of this radiometer, for the purposes of this work.

1. Scanning of the scene by the rotating secondary mirror.
2. Internal blackbody design.

As is seen in Fig.2, the secondary mirror can rotate around a vertical axis. This movement produces a scan of the field of view of the radiometer in a horizontal direction. This scan allows the measurement of the uniformity of the source and the radiance modulations across a pattern. An alternative scanning method was considered: rotation of the whole optical head of the radiometer;

however, the rotation of the secondary mirror is more similar to the way the detector array of the FLIR receives the radiation from many directions in the FLIR's field of view, and therefore preferable. Another important reason for scanning the source by the rotation of the secondary mirror is the simplicity of the method. The spectroradiometer with the scanning ability does not require any extra scanning mechanism. The position of the secondary mirror can be fully controlled through the same computer and software that controls the measurement.

## Internal Blackbody Design

There are two basic designs for internal reference blackbody of an infrared radiometer: one which is controlled at a fixed temperature, higher than room temperature; and one which is left floating at room temperature, but is continuously monitored.

Here we discuss possible errors of temperature measurements in both designs and compare between the two. The signal in volts is in general related to the radiation reaching the detector, by the following expression:

$$V=K[W-W_c] \tag{1}$$

where:

| | |
|---|---|
| $V$ | signal in volts. |
| $K$ | response function of the spectroradiometer in Volts/Watt. |
| $W$ | power received on the detector when the chopper is open. |
| $W_c$ | power received on the detector when the chopper is closed. |

If we examine more carefully all the contributions to $W_c$, we can write:

$$W_c=[P(T_{IBB})\epsilon+(1-\epsilon)P(T_{interior})]\rho_{CH}+(1-\rho_{CH})P(T_{CH}) \tag{2}$$

Where:

| | |
|---|---|
| $P(T)$ | Planck function at temperature T. |
| $T_{IBB}$ | temperature of the reference (internal) blackbody. |
| $\epsilon$ | emissivity of the internal blackbody. |
| $1-\epsilon$ | reflectance of the internal blackbody. |
| $T_{interior}$ | temperature of the interior of the optical unit. |
| $\rho_{CH}$ | reflectance of the chopper blades. |
| $1-\rho_{CH}$ | emissivity of the chopper blades. |
| $T_{CH}$ | temperature of the chopper blades. |

(Note that some of the parameters are wavelength dependent) and by substituting (2) in (1) we get:

$$V=K\{W-[(P(T_{IBB})\epsilon+(1-\epsilon)P(T_{interior}))\rho_{CH}+(1-\rho_{CH})P(T_{CH})]\} \tag{3}$$

Since the signal in all subsequent data processing is assumed to be

$$V=K[W-P(T_{IBB})] \tag{4}$$

the error in volts is the difference between Eq.(3) and (4):

$$e=K[(1-\epsilon\rho_{CH})P(T_{IBB})-(1-\epsilon)\rho_{CH}P(T_{interior})-(1-\rho_{CH})P(T_{CH})] \tag{5}$$

If the temperature of the reference blackbody, the chopper blades and the interior of the optical unit are all equal, the error is

$$e=K[1-\epsilon\rho_{CH})-(1-\epsilon)\rho_{CH}-(1-\rho_{CH})]P(T_{IBB})=0 \tag{6}$$

which means no error at all. This condition is close to being fulfilled when the instrument uses a floating ambient temperature blackbody, and when it is in thermal equilibrium,because then $T_{IBB}$ $T_{interior}$ and $T_{CH}$ are all equal.

Let us now examine the major drawback expected in a typical radiometer with an elevated temperature reference blackbody: the fact that the calculated temperature is affected by ambient temperature drifts. The meaning of this effect is as follows. Suppose we measure a perfectly stable source: if the ambient temperature changes during the measurement, the signal will drift; this drift will be interpreted as a change in the temperature of the target, since the assumption is that the reference temperature is constant. For a transfer radiometry application a drift due to temperature changes is of crucial importance, while the accuracy is less important.

As an example for both inaccuracy and drift errors we will use the following typical values:

$T_{ambient} = 25°C = T_{interior} = T_{CH}$

$W = P(30C)$; $T_{IBB} = 40°C$

$\epsilon = 97\%$; $\rho_{CH} = 97\%$

By substituting these values into Equation (5) we obtain:

$$e=K[P(40C)-P(25C)]0.0591 \tag{7}$$

which is equivalent, around 10$\mu$, to an inaccuracy of about 0.9C in the calculation of the source temperature. This can be seen by noting that: [P(40C)-P(25C)]0.0591=P(30.9C)-P(30C).

In the same manner, by using the same figures with an ambient temperature of 22°C, we get an accuracy error of 1.07°C. Thus, the calculated temperature this time will be 31.07C which means a <u>drift</u> of the calculated signal by 0.17C!

## 6. RESULTS

Figure 3 shows the result of a secondary mirror scan. The pattern is a 4-bar pattern with a temperature differential of 35C and a spatial frequency of 0.16 cycles/mrad.
The spectroradiometer uses an MCT detector with a 5-12 $\mu$m window, and a field of view of 1mrad. The scan rate was one scan per second.

Figure 4 shows the superior stability of the SR 5000 due to its floating ambient temperature reference blackbody.
In this experiment the SR 5000 measured the temperature of a blackbody set at 50C, with a field of view of 6mrad and one reading every 17 seconds. The graph summarizes the results of an 18 minute experiment. The average temperature measured during this experiment is 50.0006C with a standard deviation of 3.5 millidegrees. The total peak to peak fluctuation is less than ± 0.01C. The graph of Figure 4 shows two kinds of temperature drifts: a short-term drift of 3-5 minutes and a long-term one of 7-10 minutes. The amplitudes are respectively ± 0.003 C and ± 0.01C. We conclude that the radiometer noise cannot be larger than the above figures.

Figure 5 shows a time measurement of infrared radiation, during a change from 70C to a new set point of 69C. This curve shows the transient effects between the initial and final stable situations.

Figure 6 shows an angular scan of the radiation beam emitted by the test equipment: the results show radiance non-uniformities, which could never be seen with contact temperature probes, and which are due to blackbody and to optics non-uniformities.

## 7. CONCLUSIONS

We have modified a spectroradiometer in order to serve as a tester of state-of-the-art test systems. In this paper we have shown the most important design considerations for such a radiometer; we have also reviewed the radiometric stability required of these systems, and of the radiometer itself.

Measurements of FLIR test equipment radiance output have been presented, as function of time and angle with respect to the collimator optical axis.

Because today's FLIR's require more and more accurate test equipment, we conclude that radiometric measurements of the radiance output of this test equipment, are more important than ever.

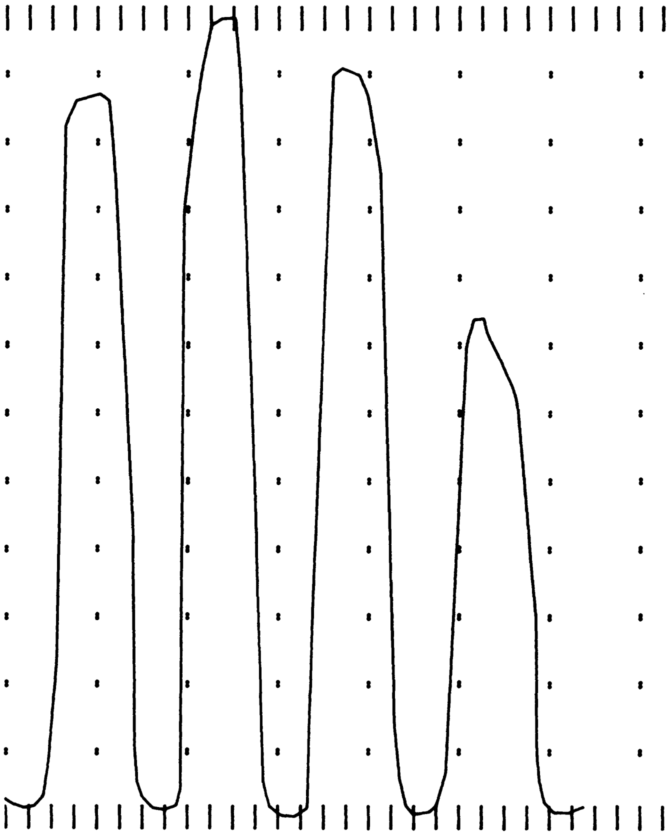
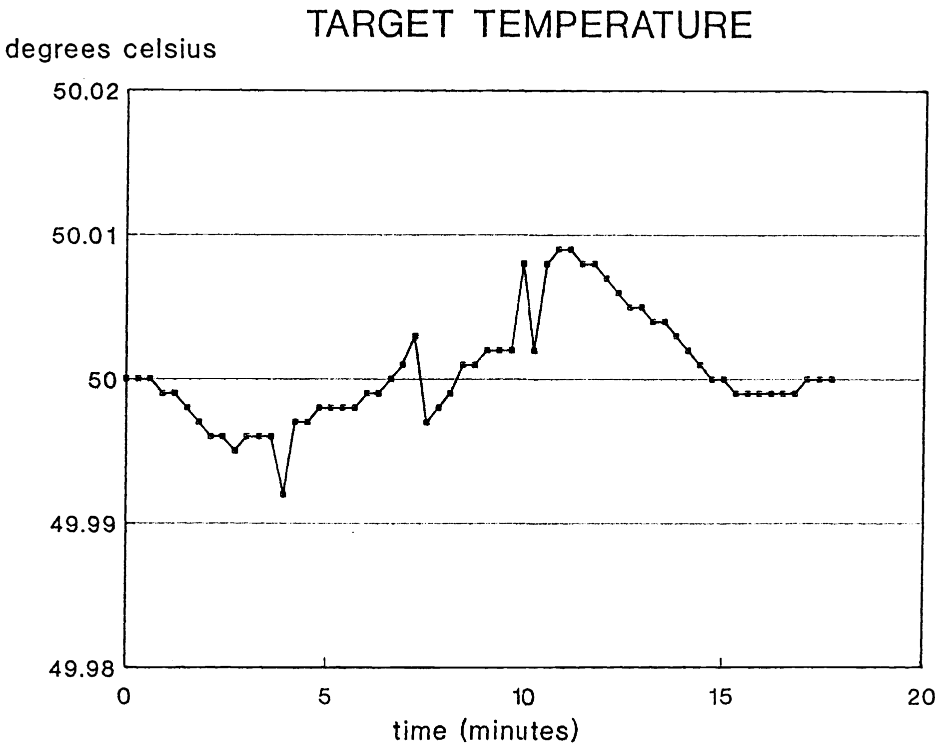


Figure 3. Radiance distribution of a four-bar pattern.



Figures 4 Signal versus time of a state-of-the-art blackbody set at 50C, over a period of 18 minutes.

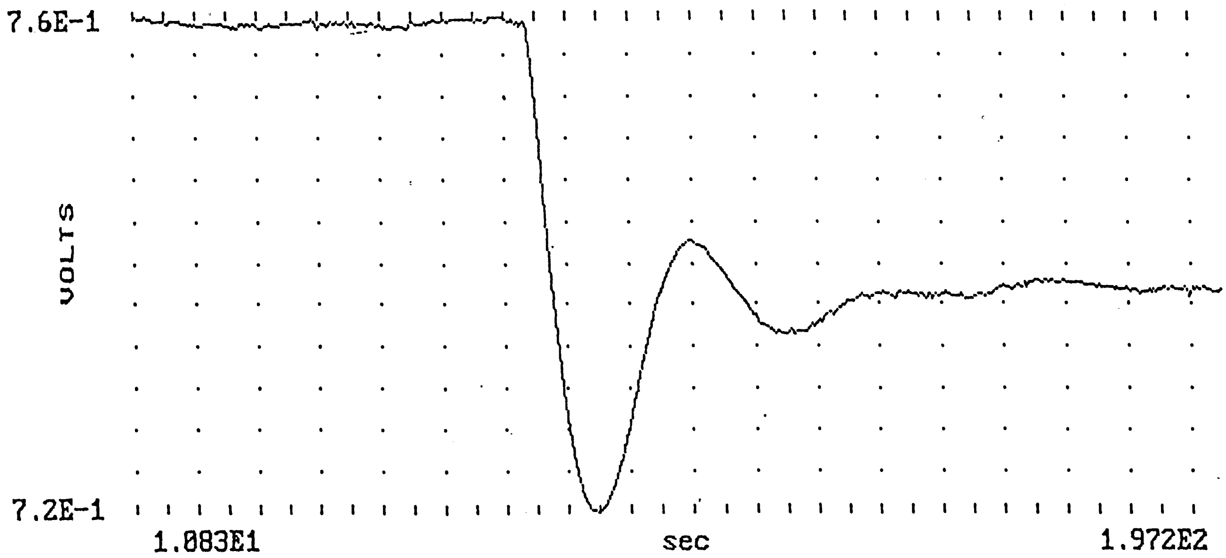


Fig.5 Radiance versus time during a set point change from 70C to 69C.

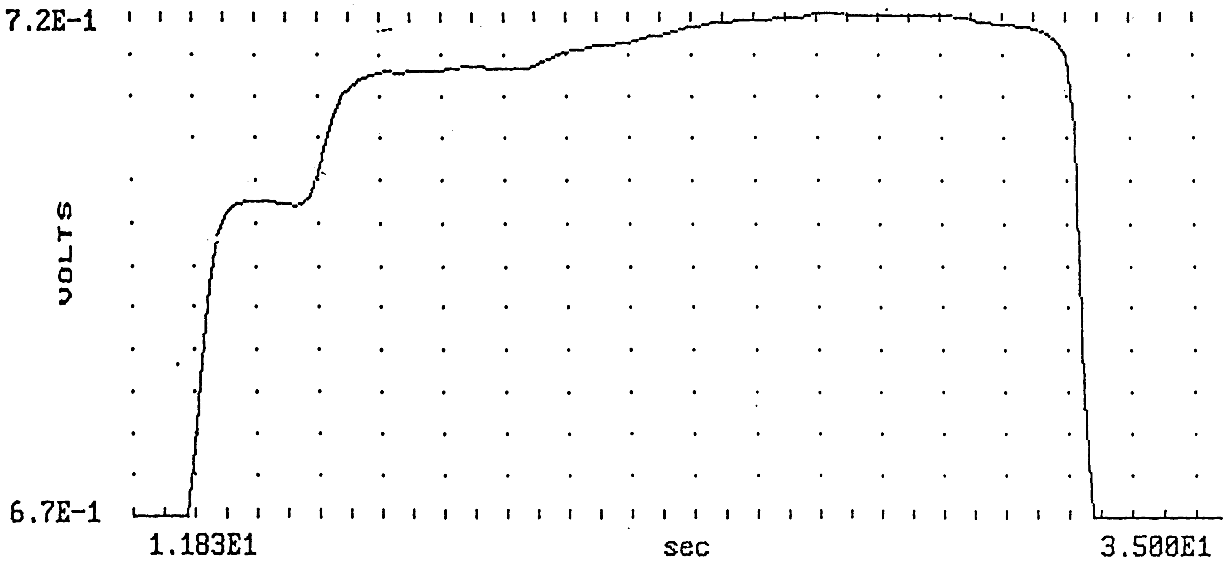


Fig. 6 Radiance versus angle scan out of the test equipment collimator showing otherwise unseen non-uniformities

## 8. REFERENCES

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