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INFRARED RADIOMETRIC TECHNIQUE IN TEMPERATURE MEASUREMENT

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ABSTRACT

One class of commercially available imaging infrared radiometers using cooled detectors is sensitive to radiation over the 3-12 micron wavelength band. Spectral filters can tailor instrument sensitivity to specific regions where the target exhibits optimum radiance. The broadband spectral response coupled with real time two-dimensional imaging and emittance/background temperature corrections make the instruments useful for remote measurement of surface temperatures from -20C to +1500C. Commonly used radiometric techniques and assumptions are discussed, and performance specifications for a typical modern commercial instrument are presented. The potential usefulness of an imaging infrared radiometer in space laboratories is highlighted through examples of research, nondestructive evaluation, safety, and routine maintenance applications. Future improvements in instrument design and application of the radiometric technique are discussed.

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INTRODUCTION

The purpose of this presentation is to discuss the broadband infrared radiometric temperature measurement technique taken by that class of commercially available imaging infrared radiometers using cooled detectors and sensitive in the 3-12 micron wavelength band. These instruments are well suited for quantitative noncontact measurement of surface temperatures as low as -20C. This relatively low temperature capability, coupled with high spatial and thermal resolution, plus near real time scanning to be speeds, make these modern commercial instruments highly useful in a laboratory environment. One such modern infrared imaging radiometer, the Inframetrics 600 system, combines the above capabilities with a built-in temperature reference, the ability to make corrections for target emittance and background radiance, plus the ability to do extensive post processing. The specifications and capabilities of this instrument make it representative of the commercial state-of-the-art of quantitative infrared thermal imaging systems. The capabilities of modern systems suggest possible uses for infrared radiometers as standard instrumentation in space laboratories. Potential applications in Spacelab might include routine nondestructive evaluation, or maintenance/safety checks of laboratory equipment , and research uses in medical, biological, and microgravity science experiments.

COMMERCIAL INFRARED IMAGING RADIOMETERS

The most sensitive commercial infrared radiometric systems typically use detectors cooled to cryogenic temperatures to improve the specific detectivity. Instruments requiring fast response (on the order of microseconds), such as fast scanning or imaging systems, often use photon detectors, as opposed to thermal detectors. Two commonly used detector materials are InSb (indium-antiminide), and HgCdTe (mercury-cadmium-telluride). These detectors typically exhibit spectral sensitivity over at least a portion of the 3-12 micron wavelength band. Within this range, the 5-8 micron band is often avoided due to strong spectral atmospheric attenuation, principally from water vapor and carbon dioxide, while the subbands of 3-5 and 8-12 microns are commonly used. As described by the Wien displacement law, the shift to shorter wavelengths of the peak spectral photon radiance with increasing temperature results in higher temperature sensitivity in the 8-12 micron wavelength band for targets below approximately 400C . At higher temperatures, the 3-5 micron wavelength spectral band offers more sensitivity. By comparison, pyrometers which operate with detectors sensitive in very narrow spectral regions at much shorter wavelengths are better suited to accurate measurement of much higher temperatures, with 400C-800C often representing the low end of the range.

For opaque targets, knowledge of the target emittance and background radiance is required for accurate calculation of the target temperature from the radiosity measurement. Inaccuracy in the calculated target temperature resulting from errors in its assumed emittance increases with decreasing emittance. For targets not fully opaque in the instrument spectral measurement band, additional knowledge of the transmittance is required. Further, signal attenuation due to optical components and absorbing media must be known. The broadband infrared detector response may often be exploited through spectral filtering to reduce the importance of the above effects on temperature measurement accuracy. Selective spectral filtering may be used, for example, to operate in a spectral region where the target exhibits optimal radiance (high emittance and/or low transmittance). It may also be employed to avoid spectral ranges where atmospheric attenuation is high. Where the transmittance through the optical train is dependant on intervening window temperatures, selective spectral filtering might first be used to view the windows where they are known to be opaque and possibly of high emittance. Then, the detector may again be filtered to operate where the window transmittance is high and well characterized as a function of its (known) temperature.

Near real time imaging systems operating, for example, at video rates of 30 frames per second, offer large advantages over nonimaging systems. Rapid observation of steady state and transient temperature gradients over large surfaces may prove highly useful in many applications. Also, the temperature of moving targets within the instrument field of view (FOV) may be observed without the need for active tracking.

PERFORMANCE CRITERIA

Understanding of a few common radiometer performance criteria is essential in evaluation of an instruments' capabilities, and when comparisons are made between several systems. Criteria discussed here are only intended to quantify the most basic thermal and spatial resolution capabilities.

Thermal Resolution Criteria: Two key thermal resolution criteria are the Noise Equivalent Temperature Difference (NETD), and the Minimum Detectable Temperature Difference (MDTD). The NETD is defined as the temperature difference where the change in signal output equals the rms system noise. This is a quantity which can be measured, and is independant of output device, observer, and imaging capabilities. The MDTD is the NETD for an imaging system, and takes into account the reduction of system noise due to the frame integration of the human eye during its 0.2 second persistence period. Typically, the noise is reduced by the square root of the number of frames integrated. For an imaging system operating at video rates of 30 Hz, approximately 6 frames are integrated by the human eye, resulting in an MDTD slightly less than half the system NETD.

Spatial Resolution: Important spatial resolution criteria include the Instantaneous Field of View (IFOV), and the Modulation Transfer Function (MTF). The IFOV is the solid angle subtended by the detector, and must not be confused with the overall Field of View (FOV) of the imager. Obviously, the IFOV represents the smallest target size which may be uniquely resolved by the detector. The MTF is defined as the system response to a sinusoidally varying input radiance pattern, plotted as a function of spatial frequency (ie., cycles/milliradian). The MTF is a function of the IFOV, scan rate, detector spectral range, and detector/instrument time constant. For a given system, the transient response of the detector/instrument to an instantaneous step change in input radiance determines the time required to attain, say, 95% of the steady state output response owing to the step change. At a fixed scan rate, then, this can be translated into the minimum target size, in terms of the detector IFOV, required to reach the nearly steady output signal. At video scan rates, with a typical HgCdTe detector of approximately 0.001 inch square, a convenient "rule of thumb" is that a target must subtend a minimum of five IFOV's for accurate, repeatable, quantitative measurements to be made. It should be noted that merely slowing or even stopping the scan does not reduce the minimum target size requirement to one IFOV. Diffraction through the system optics also contributes to the transient response to a step change in the radiance pattern. Since the magnitude of the diffraction blur increases with longer wavelengths, this component of the minimum target size requirement is necessarily larger for longer wavelength infrared systems than for the typically short wavelength pyrometric instruments.

INFRAMETRICS 600 IMAGING INFRARED RADIOMETER SYSTEM

Performance Characteristics/Operational Capabilities: Introduced in 1985/1986, the Inframetrics 600 imaging infrared radiometer system is considered representative of a commercial state-of-the-art instrument. Other manufacturers, such as AGA, and Hughes, also produce a similar class of equipment, but with somewhat different operating characteristics. Ownership of an Inframetrics 600 system by the Applied Technologies Section of the Jet Propulsion Laboratory and resultant familiarity with it leads to representation of its operating characteristics in Table 1 as typical of a commercial state-of-the-art instrument.

Radiometric Equations for Temperature Calculation: Figure 1 schematically illustrates a scanner unit observing a target through an optical window within a chamber. A general formulation of the radiometric equation which may be written for

TABLE 1. INFRAMETRICS 600 IMAGING INFRARED RADIOMETER SYSTEM KEY OPERATING CHARACTERISTICS

Spectral Sensitivity	3-5, 8-12, or 3-12 microns
Detector Type	HgCdTe
Detector Operating Temperature	77K (liquid nitrogen cooled)
NETD	0.2C @ 30C (8-12 microns)
MDTD	0.1C @ 30C (8-12 microns)
Integrated NETD	0.05C @ 30C (8-12 microns)
Accuracy	Larger of +/- 2% of (T-25C) or 1C, for T<400C Larger of +/- 5% of (T-25C) or 2C, for T>400C
Output	RS-170 Video(30 Hz frame rate)
FOV	15 deg. vert. x 20 deg. horiz.
IFOV	2 mrad. x 2 mrad. (~0.1 mm x 0.1 mm, w/6 in. close up lens)
Chopper Temperature	Updated every 0.5 sec.
Calibration	I(T) stored in PROM for all installed filters, over the range of -20C<T<1500C
Radiometric Equation	Solved in real time for target temp. using window window transmittance, target emittance, background temp., and chopper temp.

TABLE 1. (CONTINUED)

Dynamic Range	8 bits, or 48 db w/16 frame integration option
Temperature Ranges	5, 10, 20, 50, 100, 200, 500, 1000, 2000C
Internal Filters	Any of 4 selectable on command
Display Modes	Black/white, false color, point readout, isotherms, horiz. line scan, fast (125 microsec.) line scan
Post Processing	Extensive IBM PC/AT based system, average up to 256 frames, statistical data, mult. display & parameter change options
Scanner Size/Weight	8 in. x 5 in. x 5 in., 6.5 lbs
Modes/Functions	Programmable through RS-232 computer interface

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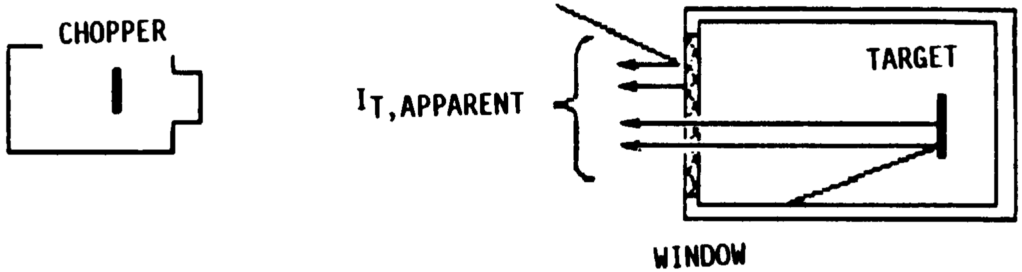
FIGURE 1

RADIOMETRIC EQNS. FOR GRAY, DIFFUSE TARGET IN A UNIFORM TEMP. ENVIRONMENT:



$$I_{T,APPARENT} - I_C = \tau_W\{\epsilon_T I_T + (1-\epsilon_T)I_{TB}\} + \epsilon_W I_W + (1-\epsilon_W-\tau_W)I_{WB} - I_C \quad (1)$$

$(\Delta I_{T,MEASURED})$

WHERE:

I = I(T) = INSTRUMENT RESPONSE TO BLACKBODY RADIANCE,

ϵ = EMITTANCE, τ = TRANSMITTANCE, T = TEMPERATURE

SUBSCRIPTS:

T = TARGET, W = WINDOW, C = CHOPPER, B = BACKGROUND

IF $\tau_W = \tau_{WB} = \tau_C$, THEN EQN. (1) REDUCES TO:

$$\Delta I_{T,MEASURED} = \tau_W\{\epsilon_T I_T + (1-\epsilon_T)I_{TB} - I_C\} \quad (2)$$

the target temperature is shown on that figure as equation (1). Key assumptions and simplifications used in this particular formulation include:

- the target surface is gray and diffuse, and its graybody emittance over the spectral measurement range of the instrument is known;
- the target is opaque;
- the target meets the minimum 5 IFOV size requirement;
- the entire surroundings (background) temperature is uniform and known;
- the window is diffuse, contains no internal fresnel reflections, and its transmittance, emittance, and temperature are known;
- the temperature outside the window, reflecting into the scanner, is uniform and known;
- the chopper is at approximately the same temperature as its immediate enclosed environment within the scanner, and is known.

The requirement for diffuse target and window may be relaxed if the radiance of the appropriate background directionally reflecting from those surfaces is known. As shown on Figure 1, under the further assumption that the window (and all other camera optics), the external window surroundings, and the chopper are all at the same temperature, equation 1 may be simplified and rewritten as shown in equation (2). Since the instrument response I(T) is assumed only a function of temperature, and is known from the system calibration curve, the target temperature may be solved if only the window transmittance, target emittance, and target background temperature is known. The Inframetrics 600 system continuously solves equation (2) over the entire scene for the target temperature, and displays the calculated temperatures on its display in real time. A useful feature of the instrument is its ability to record all necessary setting parameters along with the data on video tape, permitting further analysis by its minicomputer based post processor system in real time or off-line. This permits solution of more detailed equations if required.

POTENTIAL APPLICATIONS IN A SPACE LABORATORY ENVIRONMENT

Many potential applications exist for a broadband infrared radiometer in a space laboratory environment. This section includes a brief listing of some research applications, as well as non-destructive evaluation (NDE) and routine station maintenance functions. Thermographic results of some similar earthbased applications are included in the Figures.

Research Applications:

- Microgravity research experiments involving convective fluid flow;
- Sample temperature measurement in containerless processing experiments;
- Selective gas species identification through tunable wavelength active laser scanning. Several types of fluid mixing experiments could concievably be supported. Related work is being carried out by T. McRae at Lawrence Livermore National Laboratory;
- Medical experiments involving body or biological tissue temperature measurements. Several routine medical diagnostic uses for infrared radiometry already have been identified (see Figure 2);
- Non-contact temperature measurement of large structures/antennae, both deployable and fixed, for thermal modelling verification, and direct use in structural analysis and deflection prediction. Figure 3 illustrates an infrared examination of the Deep Space Net Echo antenna at Goldstone, Calif.;

Non-Destructive Evaluation, Station Maintenance Applications:

- Thermal evaluation of electronic circuit boards. Ground based thermographic inspection of circuit boards is known to be a powerful diagnostic tool. Figure 4 illustrates a single hot chip on an electronics board;
- Examination of solar cells and panel assemblies. Initial work performed at the Jet Propulsion Laboratory in support of the Flat Plate Solar Array (FSA) project confirmed the usefulness of infrared inspection of large photovoltaic assemblies for identification of damaged or severely back biased cells. Figure 5 illustrates a single back biased hot cell in a large photovoltaic panel;
- Composite panel crack detection, or delamination

Figure 2. Medical Applications of Thermal Imaging

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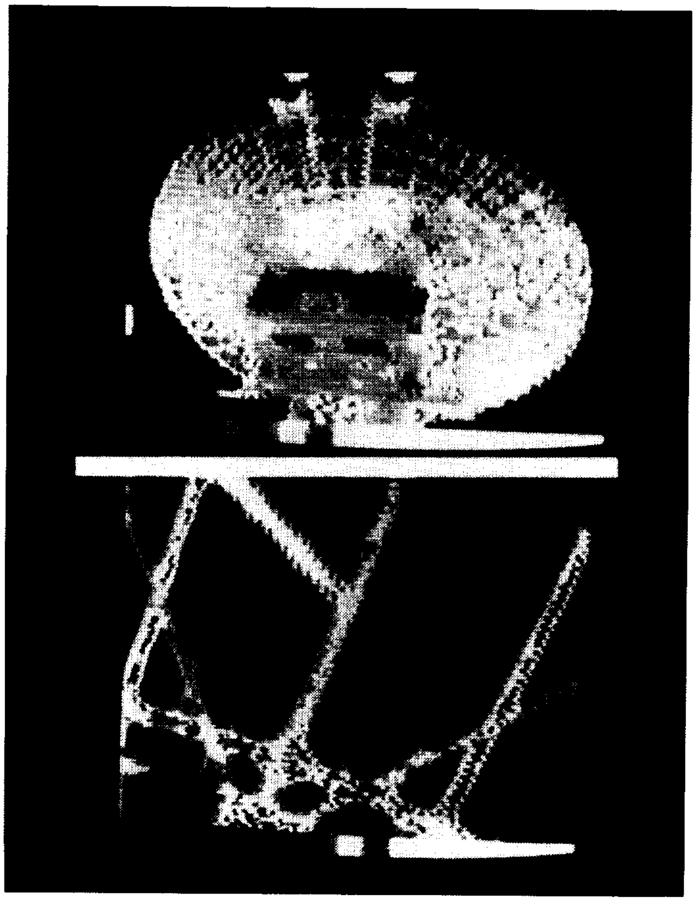

Figure 3. Thermal Image of Deep Space Net Echo Antenna at Goldstone, Calif.

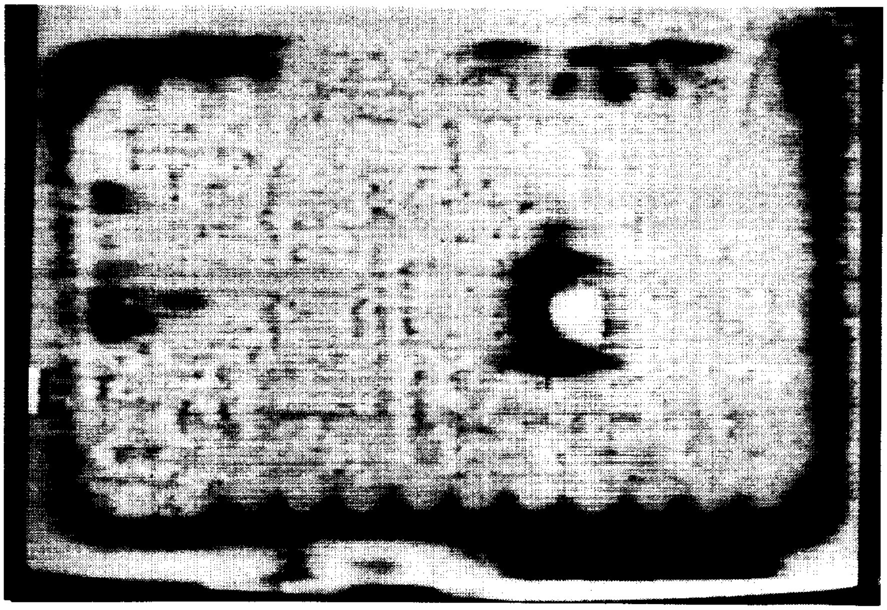

Figure 4. Non-Destructive Infrared Evaluation of Printed Circuit Board

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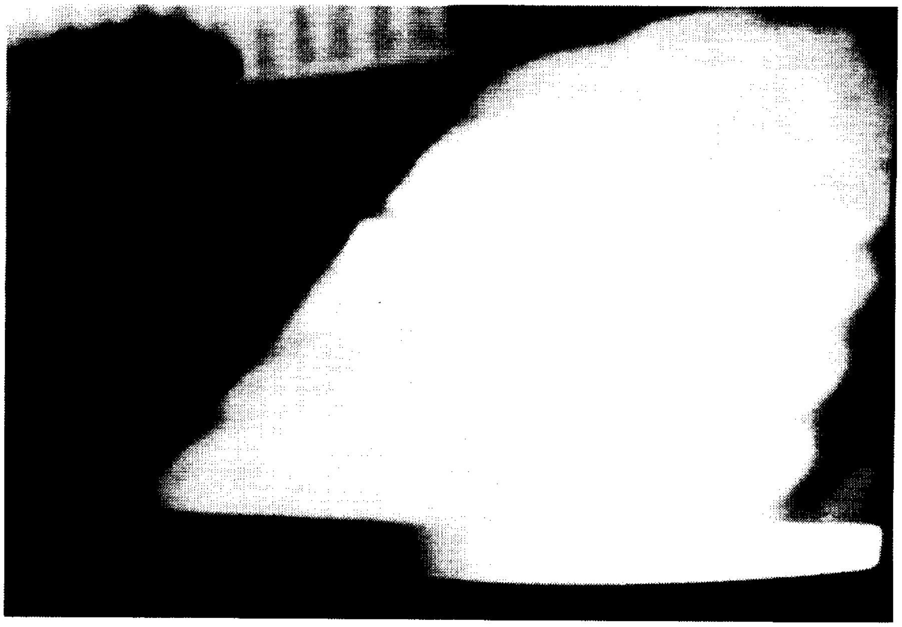

Figure 5. Infrared Examination of Photovoltaic Panel, with Hot (Back Biased) Cell

identification in composite or built-up structures. Figure 6 shows delamination in one of several heaters applied to the retro-propulsion module of the Galileo spacecraft. Actual local debonding of the film heater from the structure was confirmed.The heater was subsequently removed and rebonded;

- Thermal inspection of insulated panels, including multi-layer insulation blankets, to assist in thermal control;
- Infrared inspection of external surfaces, for the purpose of evaluating changes in emittance, and subsequent degradation of other thermal properties. Infrared radiometric equipment can be used to solve for target emittance under certain conditions;
- Thermal inspection of tanks containing liquids, to verify liquid/ullage levels. Figure 7 illustrates how the large heat capacity of liquefied natural gas in a tank translates to a large temperature difference during a transient heating event;
- spectral analysis of thruster plumes, and evaluation of contaminant spread to external surfaces.

FUTURE TRENDS IN INFRARED INSTRUMENTS/TEMPERATURE MEASUREMENT ALGORITHMS

Advances are being made in a number of areas relating to infrared instrument design and analysis algorithms. Practical results of these efforts promise simpler, more accurate, and more reliable instruments and data analysis. Some of the trends which would enhance the capabilities of instruments which may someday be qualified for spaceflight include:

- thermoelectric and closed cycle detector cooling. The use of stored cryogen for detector cooling is impractical for prolonged missions. Development of reliable closed cycle coolers will permit extended unattended operation, without mass or volume penalty associated with stored cryogens. AGA Corp. has already introduced a thermoelectric cooler in one of its commercially available radiometers.
- multielement (non-mechanical scanning) detector arrays. Although presently available in certain applications, high cost and difficulties in dynamic detector balancing and stability with time prevent their widespread use today.
- infrared optical fibers transparent in the 8-12 micron wavelength band. The availability of such fibers might provide weight and reliability improvements over a large

Figure 6. Non-Destructive Infrared Evaluation of Film Heater on Galileo Spacecraft, Showing Delamination

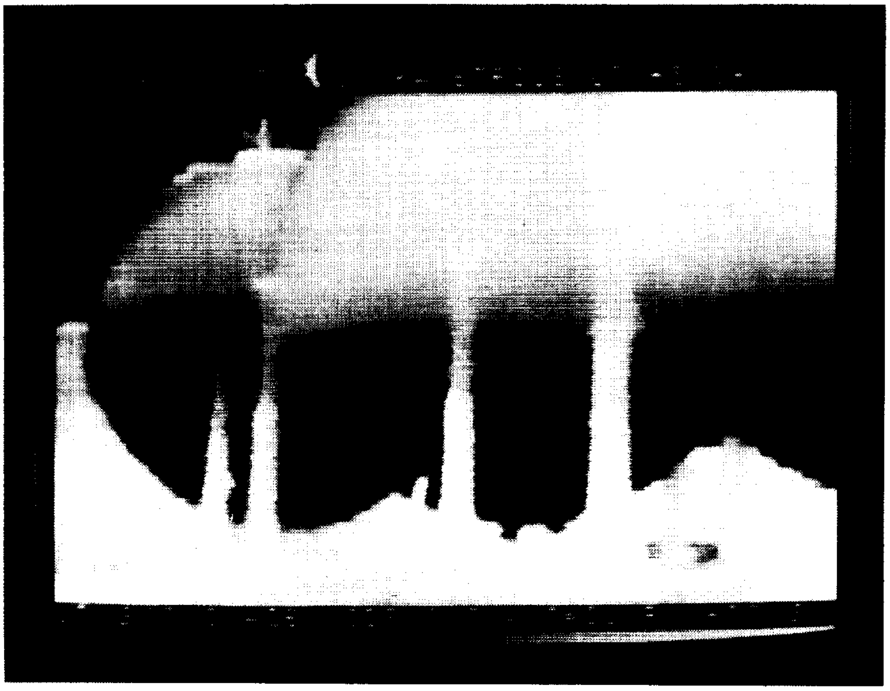

Figure 7. Thermal Image Showing Liquid Levels within LNG Tanks

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number of distributed conventional temperature sensors required in the Spacelab or aboard the Space Station. They may also permit more extensive use in areas where non-contact sensors are desireable, such as in certain electronics assemblies.

development of simple methods for spatial emittance measurement in specific situations. Techniques have already been developed for emittance mapping of electronic circuit boards under carefully controlled conditions during ground testing. The concurrent use of these two dimensional emittance maps with radiosity data promises to greatly enhance data accuracy.