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Temperature Calibration of Fast Infrared Scanners

Fast infrared scanners are highly sensitive to terrain surface temperatures, but their temperature dependence is fundamentally different from that of a slow infrared radiometer of identical bandwidth.

Introduction

The remote measurement of terrain surface temperatures by means of an airborne infrared radiometer or line scanner requires a method of calibrating the recorded electrical output of the device in degrees.† The resulting calibration curve relating output voltage to surface temperature is analogous to the characteristic curve used in the analysis of film imagery. For a linear detector of thermal radiation, the output voltage has the functional form

$$v = a\epsilon f(T) + v_0 \qquad (1)$$

where ϵ and T represent the emissivity and surface temperature of the terrain. Constants a and v_0 depend upon atmospheric transmissivity, collecting power of the scanner or radiometer optics, detector responsivity, and electrical amplification and offset, and are determined from the ground truth data for each flight.

If the emissivity ϵ and the calibration function $f(T)$ are known or assumed, Equation 1 can be solved for the surface temperature of the scanned terrain. In mapping thermal plumes, Scarpace, Madding, and Green (1975) adopted an empirical calibration function of the form

$$f(T) = AT^4 + B \qquad (2)$$

where A and B are determined by the method of least squares. They found that the simple power law set forth in Equation 2 provided an adequate least-squares fit to the temperatures of identifiable surface features scanned at 8 to 14 μm.

In this paper, the theoretical calibration function for an idealized infrared scanner with a fast, photon-sensitive detector is de-

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ABSTRACT: A theoretical calibration function relating the electrical output of an airborne infrared scanner to the surface temperature of the scanned terrain is derived from radiometric principles. The function is applicable to scanners employing fast, photon-sensitive detectors, such as InSb and HgCdTe. Computed values of the function are used to plot a calibration curve for an idealized scanner of 8 μm to 14 μm bandwidth. A simple fourth-power law of the form $AT^4 + B$ can be fitted to the plotted curve with errors of less than 0.05°C over a 25° temperature range. The assumption of a T^4 temperature dependence in thermal scanning at 8 μm to 14 μm is thereby justified on a theoretical basis. In addition, the temperature dependence of a fast infrared scanner is shown to be fundamentally different from that of a slow infrared radiometer of identical bandwidth.
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† Commercially available instrumentation usually includes a provision for internal calibration by means of temperature-controlled blackbody sources. This method, however, does not take into account atmospheric modification of the radiation emitted from the ground.

rived from radiometric principles. Computer-generated values of the function are used to plot a calibration curve applicable to a scanner with assumed flat response from 8 to 14 μm. The error involved in approximating the plotted curve by the simple fourth-power law (Equation 2) is evaluated. Finally, it is pointed out that an infrared radiometer employing a comparatively slow thermal detector does not obey the same power law as a fast infrared scanner.

Infrared Radiometers

Infrared radiometers were employed as early as 1944 for the airborne measurement of terrain surface temperatures. The term "radiometer," as used in this paper, refers to an energy-sensitive device which detects the heating effects of incident thermal radiation within a limited wavelength band. The theoretical basis for the radiometric measurement of surface temperature is Planck's Law. Expressed in a form applicable to energy-sensitive detectors, it states that

$$E_{e_\lambda}(\lambda,T) = \epsilon \frac{2\pi c^2 h \lambda^{-5}}{\exp(hc/\lambda kT) - 1} \qquad (3)$$

where $E_{e_\lambda}(\lambda,T)$ is the spectral exitance of radiant energy† at wavelength λ from a surface feature of emissivity ϵ and temperature T.

The output of an energy-sensitive airborne detector for input radiation of the form of Equation 3 can be expressed as $\int R_e(\lambda) E_{e_\lambda}(\lambda,T) d\lambda$, where $R_e(\lambda)$ is an overall response factor describing the detector characteristics, the filtering and collecting optics, and the transmissivity of the intervening atmosphere. If the variation of R_e with wavelength is known, the integration over λ can be carried out numerically, yielding the functional relationship between detector output and surface temperature. In particular, if the response is flat over the wavelength band of the instrument, the above expression reduces to an integral of the Planck distribution E_{e_λ}. The resulting dependence on temperature has been characterized by a number of published tables and formulas (Rohsenow, 1973; Dreyfus, 1963).

Analogous radiometric considerations can be extended to photon-sensitive detectors. The dependence of detector output on surface temperature in this case is obtained by integrating the photon distribution over λ. The result is a calibration function specifically applicable to fast infrared scanners.

Fast Infrared Scanners

In recent years, commercially available infrared scanners have found increasing use in the airborne monitoring of terrain surface temperatures. The term "scanner," in this context, refers to a photon-sensitive device which detects carrier pairs generated in a semiconducting crystal by incident thermal radiation. In operation, a photon detector is fundamentally different from an energy detector because it measures the number of infrared quanta rather than the amount of radiant energy absorbed by the detecting element (Petritz, 1959). Because the response time of a typical photon detector is in the submicrosecond range, infrared scanners are several orders of magnitude faster than infrared radiometers. It is this increased speed which allows the scanning of extensive areas of terrain from a rapidly moving airborne platform.

The distribution law applicable to photon-sensitive detectors is, dividing Equation 3 by the photon energy hc/λ,

$$E_{p_\lambda}(\lambda,T) = \epsilon \frac{2\pi c \lambda^{-4}}{\exp(hc/\lambda kT) - 1} \qquad (4)$$

where $E_{p_\lambda}(\lambda,T)$ is the spectral exitance of photons* at wavelength λ from a surface feature of emissivity ϵ and temperature T. The scanner output voltage can then be expressed as

$$v = \alpha \int R_p(\lambda) E_{p_\lambda}(\lambda,T) d\lambda + v_0 \qquad (5)$$

where $R_p(\lambda)$ is the response factor appropriate to photon transmission and detection, and α and v_0 are the electronic amplification and offset. The indicated integration can be carried out numerically if the variation of R_p with λ is known. Assuming for simplicity a flat response over the scanner wavelength band λ_1 to λ_2, the result is

$$v = \alpha R_p \gamma \epsilon i(T) T^3 + v_0 \qquad (6)$$

where $\gamma = 2\pi k^3/c^2h^3$ and, introducing the variable of integration $x = hc/\lambda kT$,

$$i(T) = \int_{hc/\lambda_2 kT}^{hc/\lambda_1 kT} \frac{x^2}{\exp(x) - 1} dx . \qquad (7)$$

Comparison of Equation 6 with Equation 1 yields the theoretical calibration function

† The symbol E_e denotes exitance of radiant energy in W/m^2.

* The exitance E_p is measured in photons/m^2 sec.

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C       CALIBRATION FUNCTION
C
        REAL T,K,I
        INTEGER L1, L2, PARITY
        DOUBLE PRECISION X, Y, K, C2, A, B, H, I, F
        Y(X) = X**2 / (DEXP(X)-1.0)
C       SPECIFY WAVELENGTH LIMITS IN MICRONS
        READ, L1, L2
C       SPECIFY CELSIUS TEMPERATURE
        READ, T
        K = T + 273.15
        C2 = 1.4388D4
        A = C2 / (FLOAT(L2)*K)
        B = C2 / (FLOAT(L1)*K)
        NMAX = 50
        H = (B-A) / FLOAT(NMAX)
        I = Y(A) + Y(B)
        DO 4 N=2,NMAX
1       PARITY = MOD(N,2)
2       IF( PARITY .EQ. 0 ) C=4.
3       IF( PARITY .EQ. 1 ) C=2.
4       I = I + C*Y( A+FLOAT(N-1)*H )
        I = I*H/3.
        F = I * K**3
        PRINT, T
        PRINT, F
        STOP
        END
```

FIG. 1. FORTRAN program to evaluate $f(T)$ at a specified temperature, T.

$$f(T) = i(T)\,T^3 \qquad (8)$$

for an idealized infrared scanner.

A FORTRAN routine which computes definite integral $i(T)$ using Simpson's rule is listed in Figure 1. This method is applicable to any given wavelength band and temperature. As a specific example, Figure 2 shows a calibration curve plotted for a scanner of 8-14 μm bandwidth. Over this particular wavelength range, $i(T)$ increases with T in almost linear fashion. Consequently, the calibration function $i(T)T^3$ may be approximated by the fourth-power law AT^4+B. The temperature deviation between the exact result (Equation 8) and the least-squares approximation (Equation 2) appears in Figure 3.

Due to the simplifying assumptions made in integrating over wavelength, the above result strictly applies to an idealized scanner with a flat response from λ_1 to λ_2. However, the detailed spectral characteristics

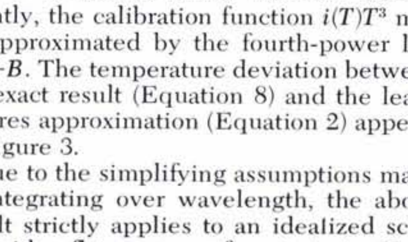

FIG. 2. Theoretical calibration function for a fast infrared scanner of 8-14 μm bandwidth. The temperature range shown is applicable to thermal scanning of rooftops during the winter heating season.

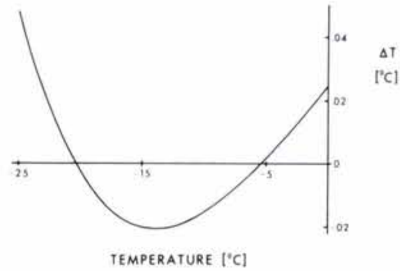

FIG. 3. Temperature deviation, ΔT, between $i(T)T^3$ and $AT^4 + B$.

of a commercial scanning system can, if known, be incorporated into the numerical integration routine of Figure 1 in a straightforward manner.

Calibration function $f(T)$ contains a factor, T^3. Thermodynamically, this factor arises because the number of photons emitted from a surface feature per unit time increases with the cube of the temperature. It is this sensitivity to slight variations in surface temperature which allows the thermal mapping of terrain using an airborne photon-sensitive detector. In the case of an energy-sensitive detector, the output depends not only on the rate at which photons are collected, but also on photon energy. Since the average energy of an individual photon is of order kT, a detector which measures radiant energy has a stronger temperature dependence than one which responds only to the number of electromagnetic quanta. Thus, an idealized infrared radiometer operating in the 8-14 μm region obeys a fifth- rather than a fourth-power law.

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