Infrared temperature sensing of snow covered terrain
by Bernard Allen Shafer

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Earth Science (Meteorology)
Montana State University

Abstract:
The feasibility of remotely monitoring snow surface temperatures with a Barnes IT-3 infrared thermometer was investigated. Much of the work concentrated on determining the vertical emissivity of dry snow in the atmospheric infrared "window" region between 8 and 14 microns.

The emissivity of various snow surface types was measured using an apparatus called an "emissivity box." An average emissivity for freshly fallen snow was found to be 0.975® For snow surfaces crusted by the effects of wind or melt phenomenon the average emissivity was 0.985. The mean emissivity for all snow surface types examined was 0.978. These high emissivity values substantiate the hypothesis that snow possesses approximately blackbody characteristics in the 8 to 14 micron spectral interval.

An analysis of errors in radiometrically obtained snow surface temperatures revealed that the IT-3 is capable of accurately measuring the true surface temperature to within two degrees Celsius for the temperature range experienced. Inversions in snow covered mountain valleys were successfully mapped during airborne case studies. Tops of inversions were located by measuring the snow surface temperature variation with elevation and noting the intersection of the inversion top with the mountain slope.

Remote radiometric temperature sensing of snow surfaces appears to offer a potentially useful tool for monitoring surface temperature gradients in arctic environments. Its application to meteorological investigations of surface temperature variation in otherwise inaccessible mountainous regions in winter may also prove valuable.

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Date 5/19/71

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Approved:

Head, Major Department

Chairman, Examining Committee

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DEFINITION OF SYMBOLS

Symbol	
a_{λ}	Absorptivity at wavelength λ.
$B^{*}(\lambda,T)$	Planck function for the radiant emittance of a blackbody.
$B(\lambda,T)$	Planck function for the radiance of a blackbody.
$B(T)$	Effective blackbody radiance sensed by a radiometer.
B_f	Effective blackbody radiance from the material forming the floor of the emissivity box.
B_r	Effective blackbody radiance from the roof of the emissivity box.
B_r^b	Effective blackbody radiance from the roof of the emissivity box with the black lid exposed.
B_r^m	Effective blackbody radiance from the roof of the emissivity box with the mirror lid exposed.
c	Velocity of light in a vacuum, 2.997925×10^{8} (m/sec).
C_1	First constant in Planck function for radiant emittance of a blackbody, 3.7105×10^{4} (watts-micron^4/cm^2).
C_2	Second constant in Planck function for radiant emittance of a blackbody, 1.43879 (microns-°K).
$E(\lambda,T_s)$	Spectral radiant emittance from a graybody.
$G(\lambda,T_a)$	Spectral radiant emittance from the sky.
h	Planck's constant, 6.6256×10^{-34} (joule-sec).
IRT	Infrared thermometer.
IT-3	Barnes Engineering Company's Infrared Thermometer.
k	Boltzmann constant, 1.38047×10^{-16} (erg/°K).

Symbol	
N	Total radiance from a graybody.
N_{bb}	Total radiance from a blackbody.
N_f	The radiance from the floor of the emissivity box upward.
N_r	The radiance from the roof of the emissivity box downward.
N_s	The radiance from a snow surface sensed by the IT-3, including the reflected component from the sky.
N_f^b	The radiance from the floor of the emissivity box when the black lid is exposed.
N_f^m	The radiance from the floor of the emissivity box when the mirror lid is exposed.
N_r^b	The radiance from the roof of the emissivity box with the black lid exposed.
PRT-5	Barnes Engineering Company's Portable Radiation Thermometer.
$q(\lambda)$	Filter response of radiometer which defines the spectral transmission characteristics of the radiometer.
r_λ	Reflectivity at wavelength λ.
r_s	Average reflectivity for a given spectral interval.
t_λ	Transmissivity at wavelength λ.
T	Temperature in degrees Kelvin.
T_s	Temperature of a given surface.
T_f	Temperature of material forming the floor of the emissivity box.
T_r	Temperature of the roof of the emissivity box.
T_a	Average temperature of the sky.
W	Total radiant emittance from a graybody.

Symbol	
W_{bb}	Total radiant emittance from a blackbody.
ϵ_λ	Emissivity at wavelength λ.
ϵ_f	Average spectral emissivity of the material forming the floor of the emissivity box.
ϵ_s	Average emissivity for a given spectral interval.
ϵ_t	Total average emissivity.
ϵ_r^m	Average spectral emissivity of the roof of the emissivity box with the mirror lid exposed.
ϵ_r^b	Average spectral emissivity of the roof of the emissivity box with the black lid exposed.
λ	Wavelength (microns).
λ_{max}	Wavelength of maximum emission from a blackbody at a given temperature.
π	3.1416
σ	Stefan-Boltzmann constant, 5.6698×10^{-12} (watts/cm^2-°K^4).

ABSTRACT

The feasibility of remotely monitoring snow surface temperatures with a Barnes IT-3 infrared thermometer was investigated. Much of the work concentrated on determining the vertical emissivity of dry snow in the atmospheric infrared "window" region between 8 and 14 microns.

The emissivity of various snow surface types was measured using an apparatus called an "emissivity box." An average emissivity for freshly fallen snow was found to be 0.975. For snow surfaces crusted by the effects of wind or melt phenomenon the average emissivity was 0.985. The mean emissivity for all snow surface types examined was 0.978. These high emissivity values substantiate the hypothesis that snow possesses approximately blackbody characteristics in the 8 to 14 micron spectral interval.

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Chapter 1

INTRODUCTION

1.1 General Remarks

Temperature in the zone from the surface of the earth to approximately two meters above the surface is important for many reasons. In this layer in which animal and plant life abound, temperature is one of the primary factors of their environment. Man is intimately affected by the temperature in this layer where he conducts nearly all of his daily activity. The type of clothing he wears, the crop he grows for food, and the transportation he utilizes to travel to his destination, all depend significantly on the temperature in this region.

To say that this zone is characterized by a unique temperature is, however, misleading and an oversimplification. In reality, the temperature of the surface may be substantially different than that at a height of one or two meters. The vertical temperature gradient which exists in the lowest two meters at any given location at a particular time is a function of many variables. The most important of these variables is wind speed (Geiger, 1966). Increased wind speeds tend to produce a well mixed layer of air in which temperature is relatively homogeneous except for perhaps a small layer of a few millimeters in depth immediately above the surface. The existence of this layer near the surface is attributed to frictional forces resulting from the motion of air over the surface. The distribution of temperature in the zone between the surface and a height of two meters represents a complex problem and is a major consideration in the science of microclimatology. Geiger (1966) presents a fine discussion of the difficulties involved in measuring temperatures from the surface to a height of two meters.

Most of the temperature data which are available within the lowest two meters are termed "surface temperature." These so called surface temperatures are usually the air temperatures obtained in weather shelters at about eye level (shelter height). This height was selected as the level at which the chance influences of position on meteorological measurements were largely eliminated. Most meteorological networks throughout the world have adopted the temperatures monitored at shelter height as a standard for forecasting and climatological purposes. Although it is known that the temperature at this height may not always give a true indication of the temperature of the earth's surface or very near the surface, it is not critical for many uses. Often the actual temperature of the surface will differ by only a few degrees from the air temperature at shelter height. However, in instances of intense solar heating at the surface such as are encountered in deserts, and in instances of severe radiation cooling on clear nights with low wind speeds, the temperature difference between the surface and shelter height may be substantial. With a basic knowledge of micrometeorological processes, and information on prevailing meteorological conditions, a reasonable estimate of the temperature differences between shelter height and the surface may be made. For example, if one were to measure the temperature distribution from a snow surface to a height of two meters on a cold clear night with no wind, a temperature inversion of from 2 to 6C might be found due to radiation cooling of the snow surface. If the same temperature structure were monitored during the day with a moderate wind the inversion would be much reduced or even absent. The temperature at the snow surface would very likely be almost the same as at a height of two meters.

Extensive portions of the earth exist, notably in polar and mountainous regions, which are snow covered. Often these regions have a pronounced lack of temperature data from the surface to shelter height. This paucity of temperature information in the layer in which most life exists could be substantially decreased if the actual snow surface temperature could be conveniently monitored and related to temperatures at shelter height. With the development of radiation detectors which are able to remotely measure infrared radiation (thermal radiation) given off by all surfaces, a new tool has been made available for surface temperature measurement. Application of infrared radiation detectors (radiometers) to the problem of sparse temperature data in remote arctic and alpine environments may offer a workable solution. They may be incorporated into data acquisition systems in airplanes or satellites capable of rapidly monitoring large areas. In this manner increased surface temperature information might be obtained in otherwise inaccessible regions. Surface temperature data obtained by a system employing infrared radiometers are valuable for a number of reasons.

Surface temperature information is important in the study of the heat flux at the land-air and sea-air interfaces, as well as in the investigation of infrared radiation flux in the lower atmosphere. Surface temperature data have also found application in economic and military fields. New areas on the earth's surface, especially in polar regions, have been exploited for their petroleum wealth. Large sections of these lands lack population and thus, surface and near surface (shelter height) temperature information. Now that man has extended his activities into these regions such information has become an important consideration for movement of men and materials.

Surface temperature information might be of significant worth from a military point of view. Our nation often finds itself immersed in conflicts over all parts of the globe. Our combat forces must be prepared to fight in all types of environments from the equatorial latitudes to polar regimes. Surface temperature information in such areas may be difficult to obtain by conventional means with the presence of an enemy to consider, and yet may be essential for planning of tactical maneuvers.

The thermal agitation of the molecules in all materials causes the emission of electromagnetic energy (Figure 1.1). For objects at temperatures between -100C and 1000C, 80 per cent of this energy is in the infrared region between 1.8 and 40 microns. Because the physical laws of radiation emission are well known, and because it is now possible to use electro-optical techniques to measure this radiation, reliable non-contact measurements of the temperature of distant objects can readily be made. Most infrared radiometers analyze only that portion of the thermal radiation falling in approximately the 8 to 14 micron spectral region (Figure 1.2). This region of the infrared spectrum is termed the atmospheric infrared "window" because it is a range with comparatively minor absorption of radiant energy by water vapor and carbon dioxide. Although other narrower windows exist, the 8 to 14 micron bandwidth is most often preferred in radiometry due to the relatively abundant radiant energy available to activate sensory equipment.

1.2 Definition of the Problem

The basic aim of the research was to explore the feasibility of using an airborne infrared thermometer to monitor snow surface temperatures. In order to accurately determine surface temperature using an infrared radiometer, the emissivity of the surface must be known. The

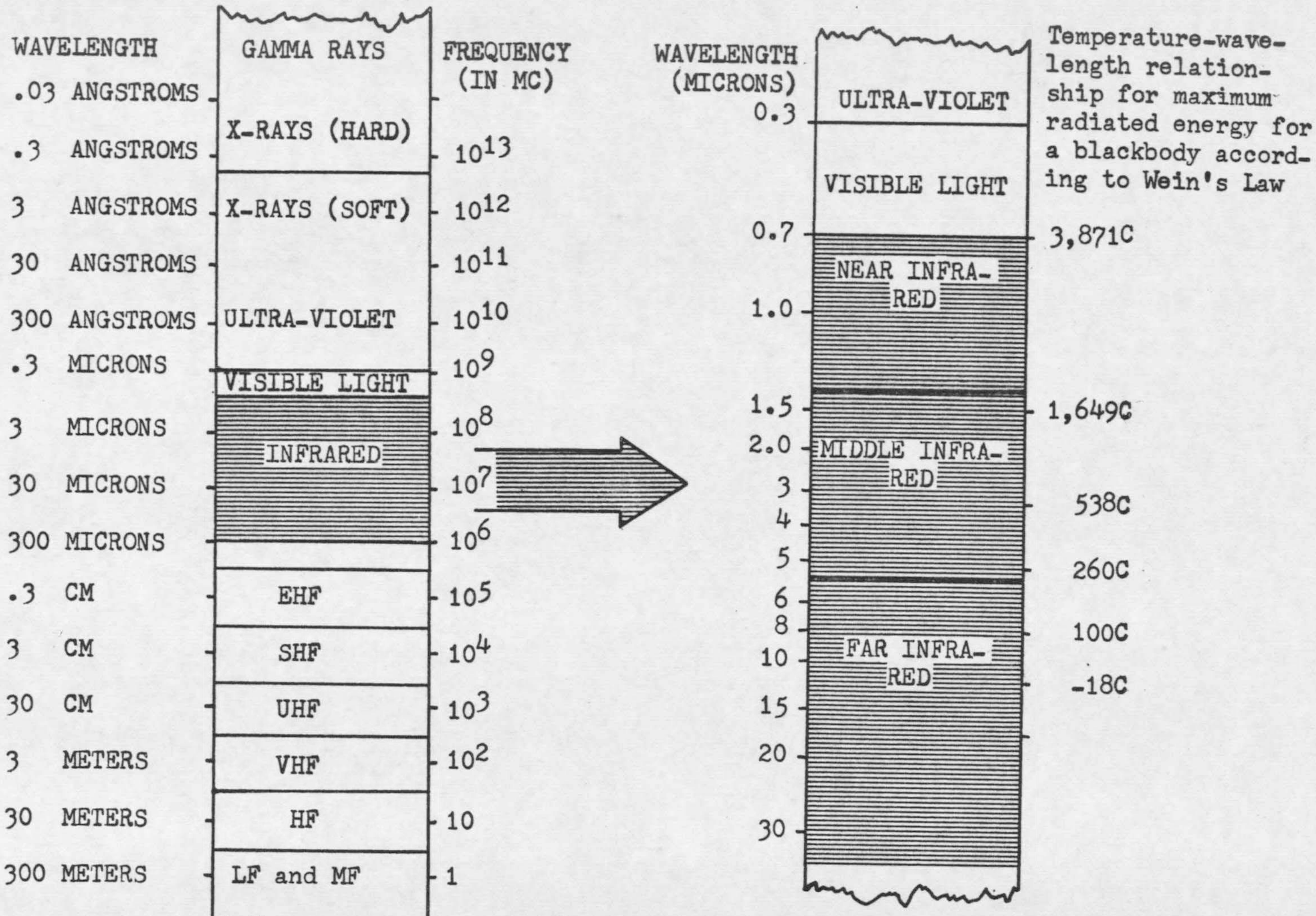

Figure 1.1 The electromagnetic spectrum and an expansion of the infrared region showing wavelength of maximum or peak emission for indicated temperatures.

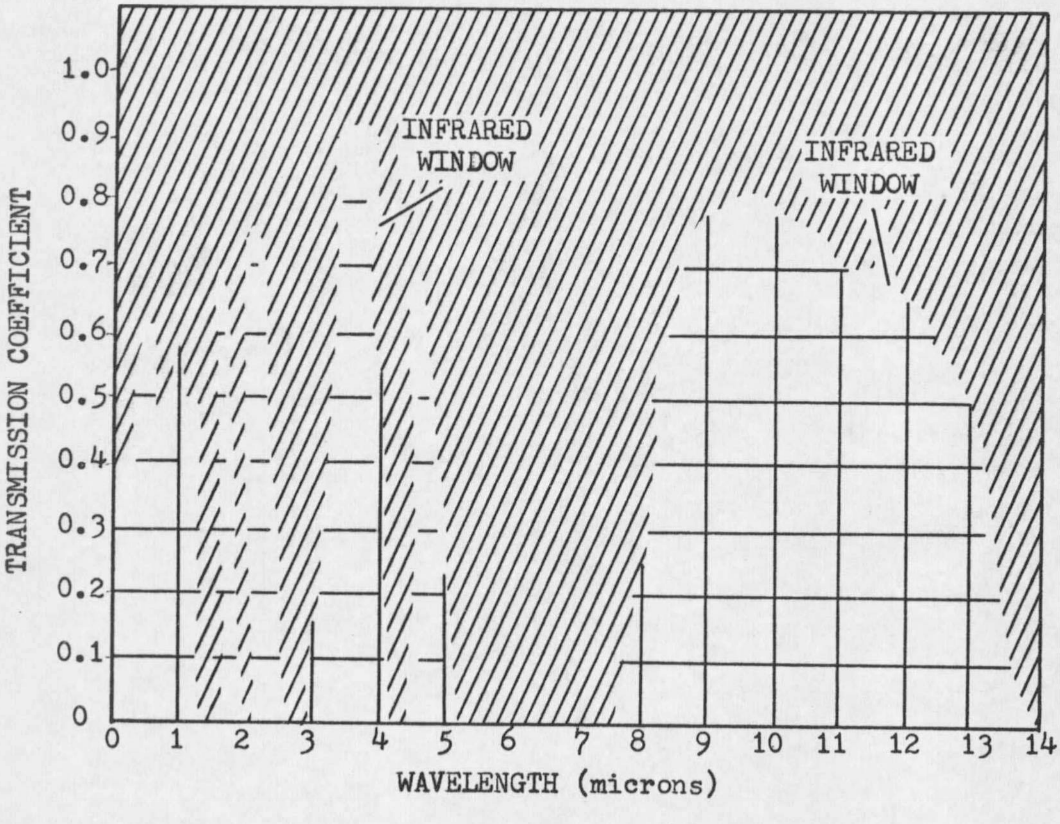

Figure 1.2 Spectral locations of atmospheric infrared "windows."

emissivity is defined as the ratio of the radiant power per unit area emitted by a surface to the radiant power emitted by a blackbody at the same temperature. A blackbody is a theoretical body which absorbs all radiation it intercepts, and emits the maximum radiation possible at every wavelength for its temperature. Some investigators, when analyzing infrared data, have assumed that earth surfaces radiate as a blackbody. In reality no naturally occurring surface is a perfect emitter in the 8 to 14 micron wavelength range. Emissivity is a function of both temperature and wavelength. Figure 1.3 demonstrates the effect of emissivity on surface temperature determinations using a radiometer which senses radiant energy in the 8 to 14 micron band. For any surface an emissivity over a portion of the spectrum (spectral emissivity) or over the entire spectrum (total emissivity) may be designated. For most natural surfaces the emissivity, whether it be total or spectral, remains relatively constant in the temperature range -40 to 100C (Kern, 1965). This is an important point for infrared thermometry, because the emissivity of a surface must remain invariant with respect to spatial and temporal variations in order that surface temperatures calculated from radiative measurements be accurate.

A search of the literature for a unique value of the emissivity of dry snow revealed conflicting and sometimes confusing data. Since the correct emissivity of snow is essential in determining actual snow

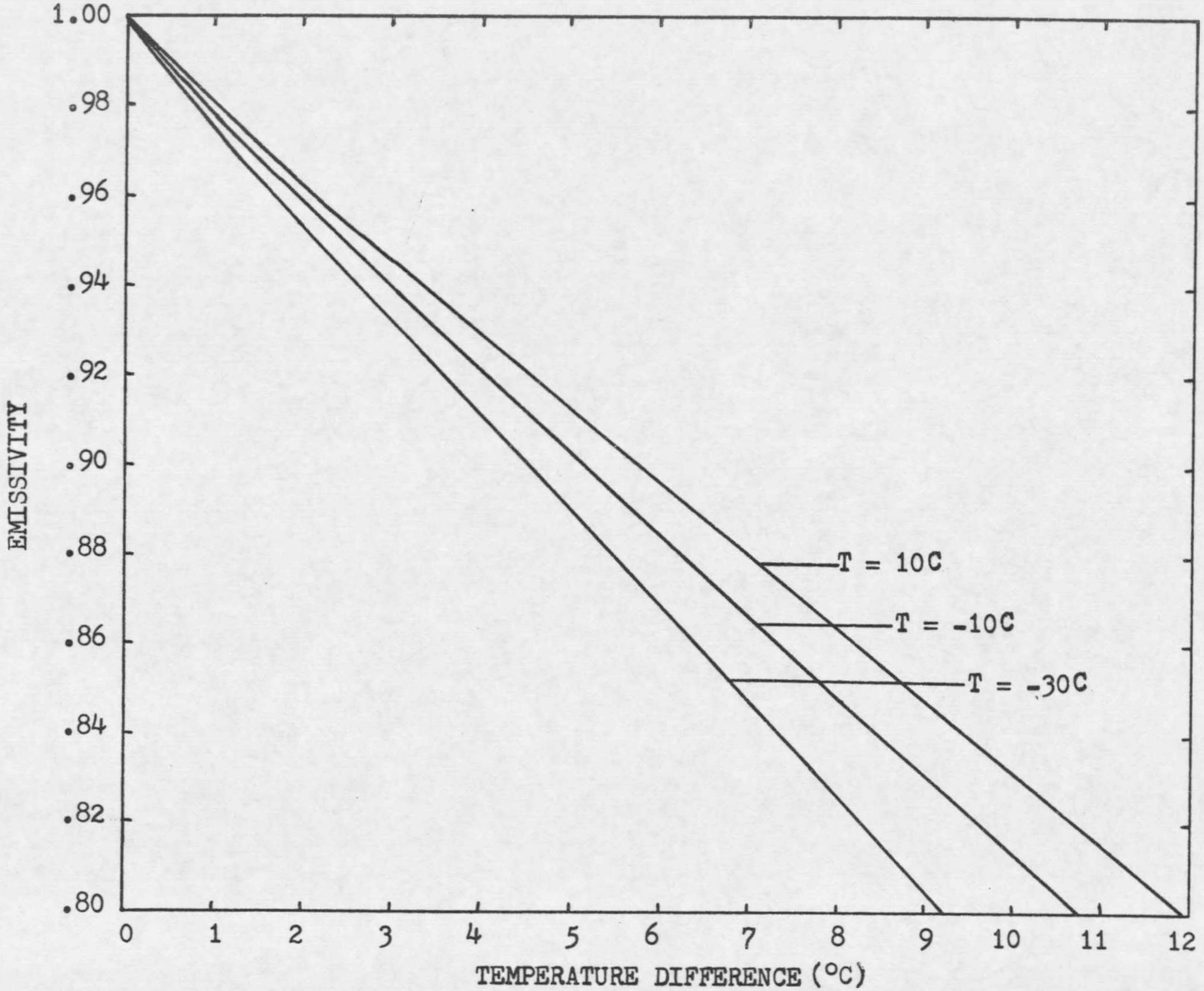

Figure 1.3 Temperature difference between the true surface temperature and the temperature indicated by a radiometer as a function of emissivity and surface temperature.

surface temperatures from radiometrically obtained data, it was decided that a basic goal of the research would be the determination of the emissivity of dry snow in the 8 to 14 micron wavelength region. To accomplish this an infrared radiometer manufactured by Barnes Engineering Company and an apparatus called an "emissivity box" were used.

Radiometric temperature measurements of surfaces having an emissivity near unity require little correction to obtain actual surface temperatures. Once snow and ice surfaces were found to possess a very high emissivity in the 8 to 14 micron interval, the study concentrated on determining the feasibility of using an airborne radiometer to monitor snow surface temperatures. Comparisons of radiometrically obtained snow surface temperatures and air temperatures at shelter level were made to determine if reliable estimates of shelter temperature could be derived from radiometric surface temperatures. Several case studies were made for varying meteorological conditions.

Radiometrically determined surface temperatures obtained from an aircraft are influenced by factors other than the temperature and the emissivity of the surface. The more important factors are reflected radiation from nearby objects, reflected sky radiation, reflected cloud radiation, and atmospheric attenuation in the intervening column of air between the sensor and the surface. Admittedly, these influences which are external to the surface under investigation are often assumed insignificant. However, if the magnitude of their effects is known, the error which they induce may be eliminated or at least estimated and the accuracy of the measurements thereby improved. For this reason the effect of reflected radiation and atmospheric absorption on radiometric temperature sensing was examined.

The primary goal of the research was to determine the feasibility of using an airborne radiometer to accurately monitor snow surface temperatures. In order to achieve this goal it was first necessary to determine the emissivity of snow in the 8 to 14 micron interval. Thus, field investigation was conducted in two stages. First, emissivity measurements were made of a large number of snow samples and an average emissivity computed. In the second stage several airborne flights were made over snowfields, and snow surface temperature gradients obtained with the radiometer were mapped. Radiometric snow surface temperatures obtained on these flights were compared with shelter level temperatures. The effect of reflected radiation and absorption on radiometric temperature sensing was also explored.

Chapter 2

SURVEY OF RECENT INFRARED TEMPERATURE SENSING INVESTIGATIONS AND ELEMENTARY RADIATION THEORY

2.1 General Remarks

During the early 1960s infrared technology for determining surface temperature advanced rapidly. This can be attributed largely to the wealth of infrared measurements which became available from the Tiros series of weather satellites.

Wark et al. (1962) analyzed the infrared data obtained from the Tiros II weather satellite. He arrived at a method for estimating infrared flux and surface temperatures from satellite infrared measurements. Corrections were made to account for filter characteristics of the radiometer and the absorption by water vapor and ozone in the atmosphere. The surface temperature which they correlated with the infrared radiation measured by the radiometer onboard the satellite was, in reality, the air temperature observed in instrument shelters.

Later, Kern (1963) discovered that the published surface temperatures derived from Tiros III infrared data were 10 to 20C too low. He found that the primary cause for the error was due to the variable emissivity of the surface. In order to better evaluate satellite infrared information Buettner and Kern (1965) designed and built a fieldworthy device to measure the infrared emissivities of natural surfaces. The emissivity values which they obtained have been largely verified by subsequent investigations: Lorenz (1966), Griggs (1968), and Dana (1969). For the purpose of illustrating the range of emissivities typically found, Table 2.1 presents some of the results obtained by Buettner and Kern and Lorenz.

The feasibility of using an airborne radiometer to measure surface temperature variation has been explored by several authors including Lenschow and Dutton (1964), Fujita et al. (1968), and Holmes (1968). In each case the emissivity of the surface was taken to be very near unity. Implicit in this is the assumption of a small range of emissivity values for natural surfaces. The error which this assumption produces was not critical for their purposes since relative temperature differences was the object of their efforts. The emissivity measurements made by Griggs (1968) of some natural surfaces were accomplished from an airborne platform. His treatment of the errors induced by the intervening atmosphere and for sunlight, skylight, and aircraft radiation are noteworthy.

Conway and Van Bavel (1967) and Idso and Jackson (1968) have probed the influence which fluctuations in sky radiant emittance exerts on radiometrically-determined surface temperatures. The conclusion reached by Idso and Jackson was that the error resulting from neglecting variations in sky radiant emittance is negligible except for very precise radiometry.

Infrared temperature sensing of ice and snow surfaces has received

Table 2.1 Normal emissivities of natural surfaces in the atmospheric infrared window between 8 and 14 microns.

Surface	Emissivity	Source
Granite, rough side	0.898	Buettner and Kern
Basalt, rough side, shiny	0.934	Buettner and Kern
Dunite, rough side	0.892	Buettner and Kern
Silicon sandstone, rough side	0.935	Buettner and Kern
Dolomite, rough side	0.958	Buettner and Kern
Dolomite gravel, 0.5 cm rocks	0.959	Buettner and Kern
Sand, quartz large grain	0.914	Buettner and Kern
Sand, quartz large grain, wet with water (nearly saturated)	0.936	Buettner and Kern
Sand, Monterey, quartz small grain	0.928	Buettner and Kern
Concrete walkway, dry	0.966	Buettner and Kern
Asphalt paving	0.956	Buettner and Kern
Water, pure	0.993	Buettner and Kern
Water plus thin film of petroleum oil	0.972	Buettner and Kern
Sand as used for mixing mortar	0.938	Lorenz
Slab of concrete	0.942	Lorenz
Coarse gravel, smooth round pebbles	0.943	Lorenz
Brick roof tile, old	0.950	Lorenz
Fine basaltic gravel with jagged edges	0.952	Lorenz
Asphalt, old road surface	0.955	Lorenz
Lawn, very dense and well kept	0.973	Lorenz

little attention. Miller (1963) reported results of a program which involved measuring the surface temperature of ice and snow surfaces over the Greenland ice cap by means of airborne radiometry. Combs et al. (1964) presents results of flights over Arctic terrain, some of which was covered by ice and snow. Griggs (1968) calculated the emissivity of a melting snow surface using an airborne radiometer. The air temperature over the snow surface was above freezing suggesting that the emissivity value obtained was probably for a thin film of liquid water on the snow surface.

To this writer's knowledge reports on infrared temperature sensing programs over snow and ice surfaces have not been widely published; inquiries to the Infrared Information Analysis Center at the University of Michigan, considered by many to be the clearing house for infrared sensing information, have revealed a definite lack of emissivity information for snow surfaces. Most investigations in this realm of radiometry have assumed very nearly unit emissivities for these types of surfaces. As will be shown, however, the validity of this assumption may seem questionable in light of the range of published values for the emissivity of snow and ice given in section 2.3.

Before commencing this discussion it is helpful to review some fundamental concepts in radiation theory applicable to the infrared wavelengths utilized.

2.2 Elementary Radiation Theory and Definition of Terms

In order to facilitate understanding of subsequent derivations, a number of terms frequently encountered are presented and defined in Table 2.2. For a more detailed account of infrared technology than will be given here, see Wolfe (1965).

Radiant energy is energy in transit. Radiant energy, when encountering a medium other than a vacuum, may be either transmitted, reflected, absorbed, or undergo a combination of these three processes. The degree to which any of the three occur is highly dependent on wavelength. This relationship may be expressed by

$$a_\lambda + r_\lambda + t_\lambda = 1 \qquad (2.1)$$

where a_λ is the absorptivity at wavelength λ, r_λ is the reflectivity at wavelength λ, and t_λ is the transmissivity at wavelength λ. A body which has an absorptivity equal to unity at all wavelengths is termed a blackbody. This stipulation of unit absorptivity requires that the reflectivity and the transmissivity equal zero. Perfect blackbodies do not exist in nature, but they are often closely approximated by natural surfaces at infrared wavelengths.

A further development of radiation theory asserts that under the condition of thermodynamic equilibrium, the emissivity for a given wavelength is equal to the absorptivity at the same wavelength. This law, known as Kirchoff's Law, can be stated in the form

Table 2.2 Definition of radiation terminology.

Term	Units	Definition
Radiant power	watts	The radiant energy emitted by a surface per unit time.
Spectral radiant power	watts/micron	The radiant power emitted by a surface within a given spectral range.
Radiant intensity	watts/steradian	The radiant power emitted by a source per unit solid angle.
Spectral radiant intensity	watts/ster./micron	The radiant intensity considered over a given spectral range.
Radiant emittance	watts/m^2	The radiant power emitted per unit area by a source into a hemisphere.
Spectral radiant emittance	watts/m^2/micron	The radiant emittance over a given spectral range.
Radiance	watts/m^2/steradian	The radiant power emitted by a source per unit solid angle per unit projected area.
Spectral radiance	watts/m^2/ster./micron	The radiance considered over a given spectral range.
Reflectivity	dimensionless	The fraction of radiant power incident on a surface which is reflected or back scattered.
Absorptivity	dimensionless	The fraction of radiant power absorbed by a medium.
Transmissivity	dimensionless	The fraction of radiant power transmitted by a medium.
Emissivity	dimensionless	The ratio of the radiant emittance of a source to the radiant emittance of an ideal blackbody radiator at the same temperature.
Spectral emissivity	dimensionless	The emissivity of a source considered over a given spectral range.

$$a_\lambda = \epsilon_\lambda \tag{2.2}$$

If we now consider the body to have zero transmissivity (i.e. it is opaque to radiation of a given wavelength and substitute Eq. 2.2 into Eq. 2.1), we arrive at

$$\epsilon_\lambda = 1 - r_\lambda = a_\lambda \tag{2.3}$$

which declares that the emissivity at a specified wavelength is equal to one minus the reflectivity at the same wavelength. It should be remembered that this relationship is true only for opaque bodies. The restriction to opaque bodies is not as severe as it might seem. Gubareff et al. (1960) states that most materials are opaque at infrared wavelengths.

The spectral radiant emittance, $B^*(\lambda,T)$, of a body at temperature T is given by Planck's Law of blackbody radiation

$$B^*(\lambda,T) = C_1 \lambda^{-5}(\exp(C_2/\lambda T) - 1)^{-1} \quad \text{(watts/cm}^2\text{/micron)} \tag{2.4}$$

where $C_1 = 3.7405 \times 10^4$ (watts-micron^4/cm^2)

$C_2 = 1.43879$ (microns-°K)

λ = wavelength (microns)

Figure 2.1 presents several representative curves of spectral radiant emittance into a hemisphere versus wavelength derived by evaluating the Planck function for the indicated temperatures which are typical of

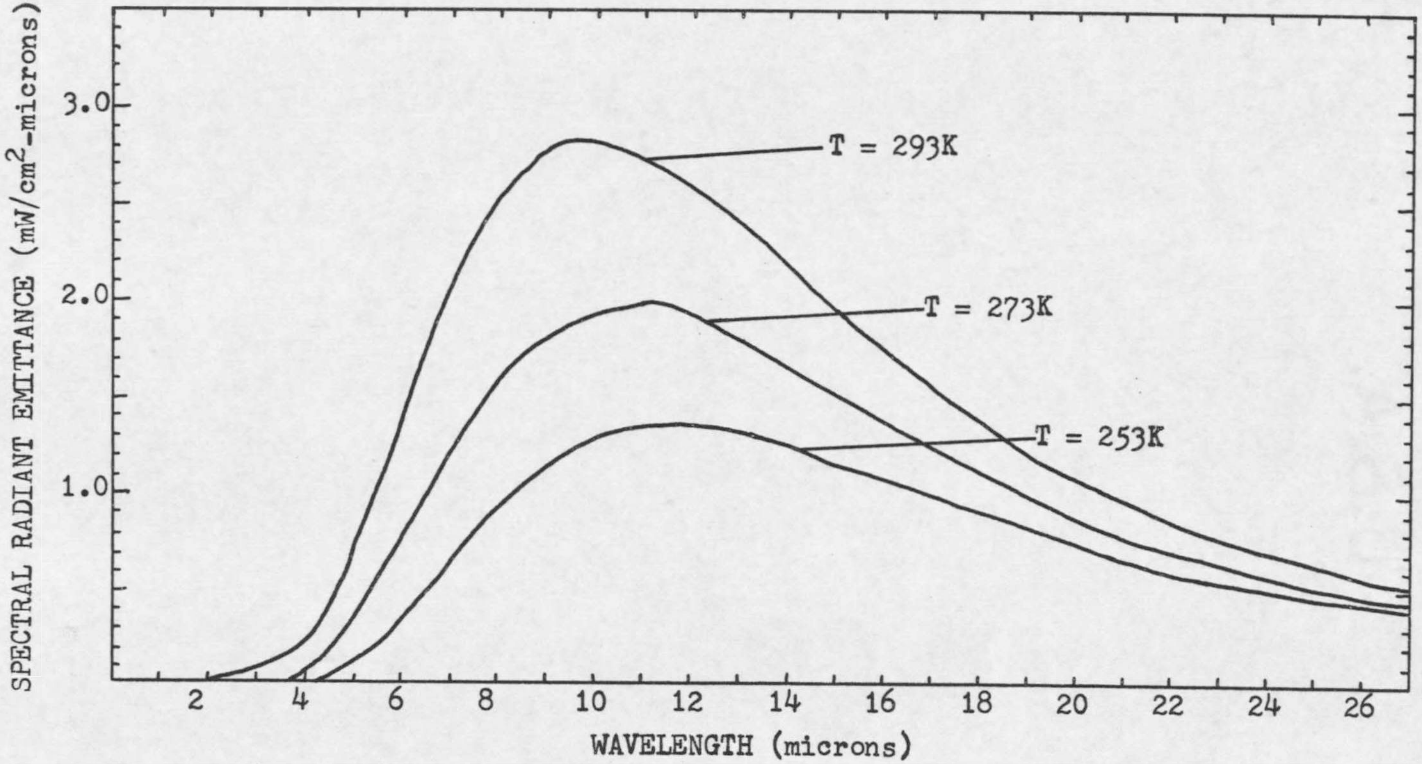

Figure 2.1 Blackbody radiation curves for the temperature range commonly experienced by natural surfaces.

terrestrial surfaces.

If the spectral radiant emittance of Planck's Law is integrated over all wavelengths, the Stefan-Boltzmann Law results. This law relates the total radiant emittance for a blackbody, W_{bb}, to the fourth power of the absolute temperature. In mathematical notation this law is expressed as

$$W_{bb} = \sigma T^4 \tag{2.5}$$

where σ is the Stefan-Boltzmann constant having a value of 5.6698×10^{-12} watts cm^{-2} $^{o}K^{-4}$ as established by the U.S. National Academy of Sciences and the Canadian National Research Council (Landsberg et al., 1970).

To obtain the wavelength of maximum intensity for blackbody radiation, Planck's Law is differentiated with respect to wavelength and solved for wavelength. This produces Wein's Displacement Law

$$\lambda_{max} = \frac{2897}{T} \quad \text{(microns-}^{o}\text{K)} \tag{2.6}$$

From this law it is obvious that the wavelength of maximum intensity, λ_{max}, increases with decreasing temperature. In the range of temperatures commonly experienced by terrestrial surfaces, the wavelength of maximum intensity lies within the atmospheric infrared window between 8 and 14 microns.

If the source is not a perfect blackbody (a "graybody") the total radiant emittance, W, from that source is described by

$$W = \epsilon_t \sigma T^4 \tag{2.7}$$

where ϵ_t now becomes the emissivity averaged over all wavelengths. Equation 2.7 is a more accurate representation of the condition which exists in nature than Eq. 2.5, since all natural surfaces can be considered graybodies to varying extents. The total radiant emittance from natural surfaces must necessarily be less than the total radiant emittance of a blackbody at the same absolute temperature because the value of ϵ_t is less than or equal to 1.0.

To obtain the radiance from a surface, Lambert's Law is applied. This law states that the radiant intensity (flux per unit solid angle) emitted in any direction from a unit radiating surface varies as the cosine of the angle between the normal to the surface and the direction of radiation. Expressed another way, the emitted radiation from a blackbody has no preferred direction of propagation. If, however, the surface acts approximately as a perfectly diffuse radiator, Lambert's Law is also valid. Such is the case for many natural surfaces, and in particular snow surfaces. The radiance, N_{bb}, for a perfect blackbody is given by

$$N_{bb} = \frac{W_{bb}}{\pi} = \frac{\sigma T^4}{\pi} \tag{2.8}$$

and the radiance, N, for a graybody by

$$N = \frac{W}{\pi} = \frac{\epsilon_t \sigma T^4}{\pi} \tag{2.9}$$

At this point the total average emissivity, ϵ_t, can be defined as

$$\epsilon_t = \frac{N}{N_{bb}} \tag{2.10}$$

where both the blackbody radiation source and the graybody radiation source are at the same temperature.

With the preceding radiation theory in mind, the emissivity of a snow surface can be developed.

2.3 Spectral Emissivity and Total Emissivity of Snow

Many commercially available infrared radiometers do not measure radiation over all infrared wavelengths. Rather, through an optical filtering system, the radiation accepted by the radiometer is confined to a limited spectral region coincident with the atmospheric window portion of the spectrum. Emissivities of surfaces determined by employing such radiometers are thus spectral emissivities. Further, reported emissivities frequently are restricted to orientations normal to the surface giving rise to what is termed the spectral normal emissivity of the surface, ϵ_s, weighted by the filer response of the radiometer, $q(\lambda)$. ϵ_s is defined through the use of an equation

$$\epsilon_s = \frac{\int_0^\infty q(\lambda)\, E(\lambda, T_s)\, d\lambda}{\int_0^\infty q(\lambda) B^*(\lambda, T_s)\, d\lambda} \tag{2.11}$$

where $E(\lambda,T_s)$ is the spectral radiant emittance of the gray surface at temperature T_s, $B^*(\lambda,T_s)$ is the spectral radiant emittance of a black-body at temperature T_s, and $q(\lambda)$ is the filter function of the radiometer specifying the spectral range of the radiometer.

The spectral emissivity, ϵ_s, of Eq.2.11, may be less than, equal to, or greater than the total emissivity, ϵ_t, of Eq. 2.10. This may happen because emissivity is a function of wavelength as well as temperature and is not constant over the entire infrared region of the spectrum.

Both spectral and total emissivities have been published for snow and ice surfaces, although at times the distinction as to which was meant is not made clear. Unless otherwise noted, all emissivities mentioned in this work are spectral emissivities valid in the 8 to 14 micron bandwidth.

Buettner and Kern (1965) reported that Falckenberg (1928) arrived at an emissivity for snow equal to 0.995 which was very nearly the same as the emissivity calculated by Griggs (1968) for a melting snow surface. As previously noted, emissivity values for melting snow are, in all likelihood, emissivities calculated for a thin film of liquid water on the snow surface. McAlister (1964) has shown that when a substance such as water covers a surface to depths of 0.02 mm an essentially new radiating surface is apparent. The new effective surface may mask the true radiative properties of the underlying surface.

Weingeroff (1931) conducted a study of the infrared reflectivity of water and ice. His results, as reported by Buettner and Kern (1965), are presented in the curves of Figure 2.2.

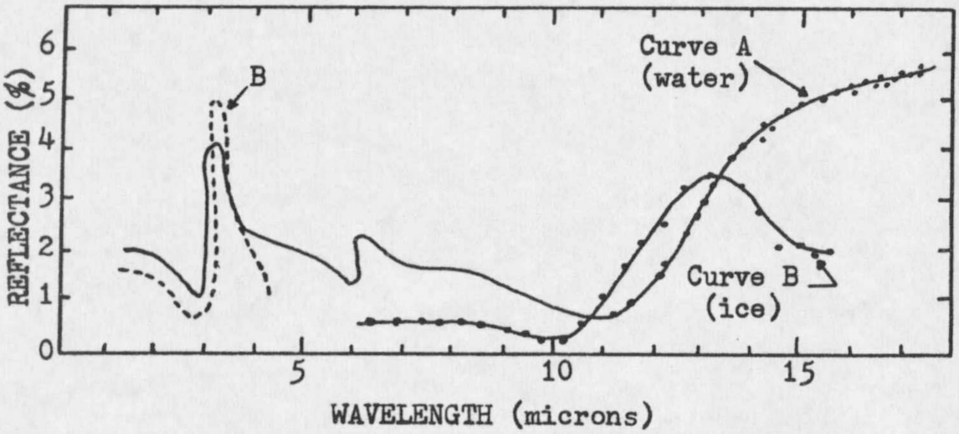

Figure 2.2 Vertical reflectance curves for water (Curve A), and for a smooth ice surface (Curve B) due to Weingeroff (1931) as reported by Buettner and Kern (1965). Curve B is only relative due to the formation of frost on the surface.

Applying the results of Eq. 2.3 and extending the emissivity and reflectivity terms to denote an average over the interval 8 to 14 microns, we arrive at $\epsilon_s = 1 - r_s$. The emissivity for ice which is shown by Weingeroff's data according to this relation is approximately 0.98 for the 8 to 14 micron window region. The peak in reflectivity seen at 13 microns makes it difficult to estimate the emissivity of dry snow in the window region without actual measurements.

Dunkle _et al_. (1955) presents a total longwave emissivity of 0.82 for new snow, similar in size to frost crystals, for a temperature range of 15.0 to 19.5F. This value is often quoted in the literature. In the same report by Dunkle, a total emissivity for granular snow (approximately 1/32 of an inch in diameter) is listed as 0.89 for a temperature range of 13.0 to 21.0F, while an emissivity of 0.95 is reported for ice crushed into crystals slightly larger than the granular snow. Ice ground in a blender was found to exhibit a total emissivity of 0.81. The total emissivity of a crushed ice sample was found to be a function of temperature as the sample was warmed to the melting point from 22.5F. The emissivity varied from 0.87 at the lower temperature to 0.95 at 32F. Dunkle concluded that the emissivity variation between snow and ice surfaces is a function of particle size and surface roughness and is imperfectly understood.

The emissivity for a snow surface in Greenland, determined from data presented by Miller (1963), is calculated to be between 0.43 and 0.66. Cirrus clouds composed of ice crystals have been found to have emissivities in the 8 to 13 micron region which vary from 0.05 to 1.00 (Valovcin, 1968). Gubareff <u>et al</u>. (1960) presents a total emissivity for rime ice equal to 0.985. Geiger (1966), Gates (1961), and the U.S. Army Corps of Engineers <u>Snow Hydrology</u> report (1956) suggest that snow and ice are nearly perfect blackbody radiators at infrared wavelengths.

From the previously cited literature it is evident that significant discrepancies exist concerning the emissivity of snow in its diverse forms. Clarification of these conflicting data, at least for the spectral band 8 to 14 microns, is attempted in Chapter 4.

Before proceeding to report on the emissivity investigations undertaken by the writer, the characteristics of the radiometer which was utilized for the investigation are discussed.

Chapter 3

DESCRIPTION OF RADIOMETER

3.1 General Description of Radiometer and Recorder

The instrument used for all radiometric measurements in this investigation was a Model-A Barnes IT-3 Infrared Thermometer manufactured by the instrument division of Barnes Engineering Company. This model has a capacity for measurements in the temperature range -40 to 60C. It consists of a thermistor-bolometer detector, chopper, and preamplifier in a sensing head which is connected to a compact, portable electronic console containing a post amplifier and the power supply.

The radiant energy is collected and filtered by the optical system in the sensing head. A germanium filter focuses the radiation on the thermistor-bolometer detector. Indium antimonide provides the filter material for the short wavelength cutoff at eight microns and a Kodak Irtran-2 filter provides the long wavelength cutoff at 14 microns. The incoming radiation from the target is modulated at a frequency of 90 cps by a gold plated chopper. As the chopper rotates, the detector alternately compares the target radiation to radiation from an internal, temperature controlled blackbody reference cavity. The result is the generation of an a.c. signal proportional to the energy difference between the target radiance and the radiance from the internal cavity. The a.c. signal is preamplified and transmitted to an electronic console where it is further amplified, demodulated, and rectified to provide a d.c. output which drives a meter circuit and recorder output circuit. Since the radiance from the target is determined by its temperature, the radiometer output can be calibrated in terms of target temperature if the target is radiating as a blackbody.

The field of view of the radiometer is three degrees focused at infinity. The size of the viewing area is reported by the manufacturer to be a one inch square at one foot and a 57 foot square at 1000 feet. Investigations by Dana (1969) for a Barnes model PRT-5 with similar sensing head revealed that the radiometer actually "saw" radially outward a considerably greater distance than advertised by the marketing firm. From his evidence it might be concluded that where knowledge of the area viewed by the radiometer is critical, tests should be conducted to verify the dimensions of the effective viewing area.

The absolute accuracy as stated by the manufacturer of the infrared thermometer is ±2C above 0C and ±4C below 0C. The advertised resolution is 0.5C above 0C and 1C below 0C. These accuracy figures are specified for a target of unit emissivity in the spectral range of the radiometer. During the calibration procedures for the radiometer reported later in this chapter, the accuracy figures stated above were substantiated by actual measurements.

The IT-3 is equipped with a selector switch which provides the user access to either a "fast" response or a "slow" response. In the "fast" position, 50 milliseconds are required to achieve 63 per cent of full response to a step change in input signal, while in the "slow" position the response time is 500 milliseconds. The slow mode has the advantage of reduced noise and greater resolution. For the purposes of this research the slow mode was found to result in a superior quality of data obtained on a recorder.

A Leeds and Northrup Speedomax H strip chart recorder was utilized with a full scale range of ten millivolts. Advertised accuracy for this recorder is ±0.3 per cent of electrical span. The span step-response-time rating is one second for a full scale deflection. A record is obtained using a multi-point print wheel rather than a continually recording pen with the print time per point equal to 1.2 seconds. The 1.2 second print cycle permits an accurate record well within the response time of the recorder for instantaneous fluctuations in signal.

The d.c. output of the infrared thermometer (IRT) is 50 millivolts full scale adjustable. Since the 50 millivolt output for which the IRT was factory-calibrated against blackbody reference sources was not commensurate with the Leeds and Northrup recorder's capability, it was adjusted to output a signal in the range 0 to 10 millivolts full scale. This adjustment necessitated a new calibration to correct for the change in the range of the IRT output. To accomplish this a blackbody calibration chamber was designed and built. Calibration procedures and results are given in section 3.3.

3.2 Spectral Response of the IT-3

The precise filter transmission characteristics for the radiometer were not available from the manufacturer at the time data compilation and synthesis for this study was done. Figure 3.1 gives a transmission curve reported by Dana (1969) for a Barnes PRT-5 which is believed to be the same as for the IT-3 Model-A. It is presented here to provide an example of the mechanics involved in computing the radiance effective at the sensor. As is readily seen from Figure 3.1 the filters actually allow infrared radiation outside of the advertised 8 to 14 micron band-pass. The total spectral response, $q(\lambda)$, is thus the transmission over the range from about 7.4 to 16.7 microns with a minor response near 19 microns. Therefore, to describe the radiant energy which the IT-3 senses, the blackbody spectral emittance curve for a particular temperature is multiplied point by point by the transmission curve of Figure 3.1. In Figure 3.2 this process has been done for a temperature of 253K. The area under the dashed line represents that portion of the radiant emittance from a blackbody sensed by the IT-3.

Radiant energy emitted by a graybody is often referred to as blackbody radiance. The concept of blackbody radiance of a graybody is interpreted to mean the temperature at which a blackbody would radiate in order to produce the same amount of radiant energy as the graybody. An expression for this quantity may be derived by integrating a form of Planck's Law which is slightly different than Eq. 2.4. The altered form

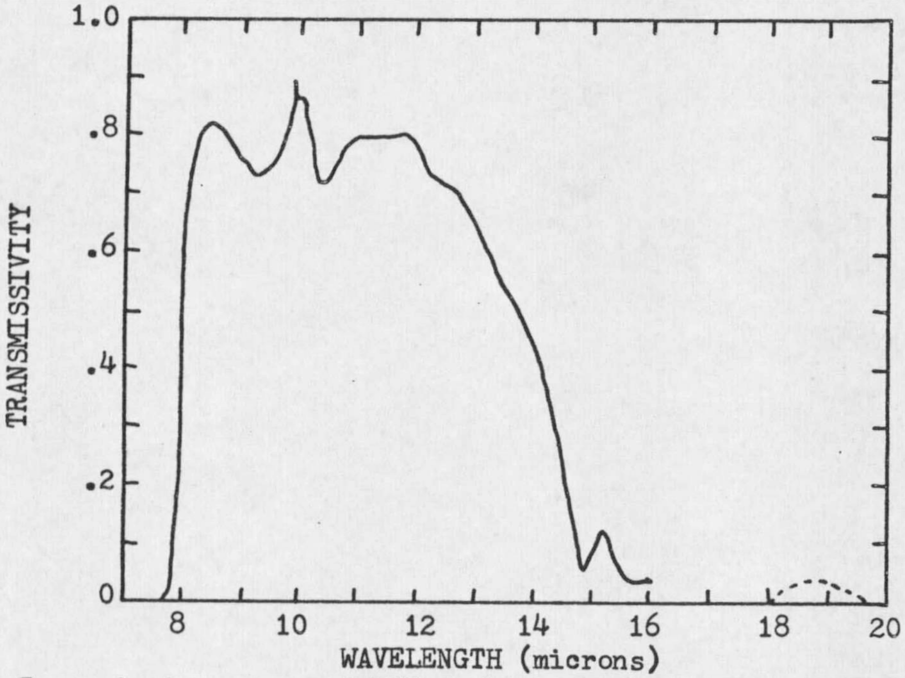

Figure 3.1 Transmission curve of PRT-5 which is similar to that of the IT-3 (after Dana, 1969).

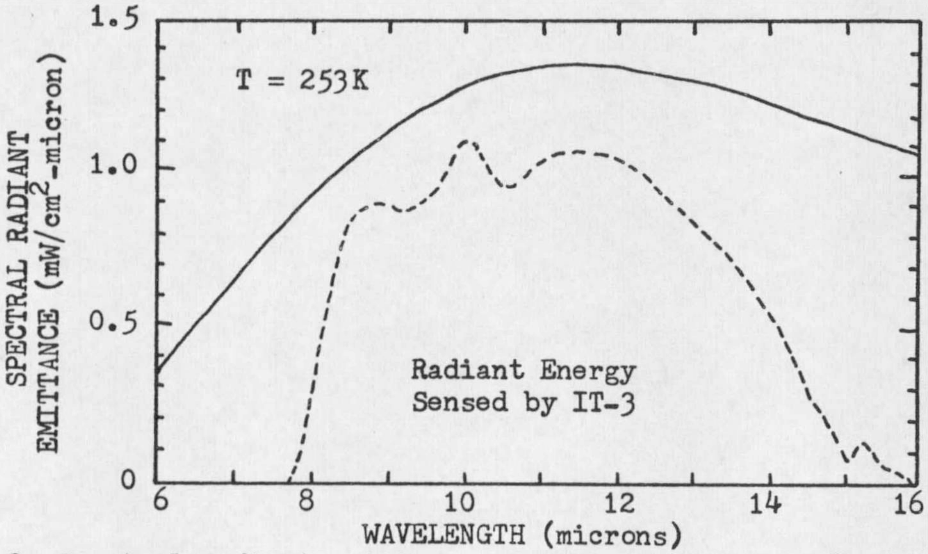

Figure 3.2 Spectral radiant emittance of a blackbody at 253K sensed by IT-3. Dashed curve is formed by multiplying the blackbody curve by the transmission curve of Figure 3.1.

of Planck's Law to be integrated is

$$B(\lambda,T) = 2hc^2 \lambda^{-5} (\exp(hc/k\lambda T) - 1)^{-1} \quad \text{(watts/micron/cm}^2\text{/steradian)} \tag{3.1}$$

where h = Planck's constant
c = velocity of light
λ = wavelength
k = Boltzmann constant
T = temperature in degrees Kelvin

The total radiance of a blackbody at temperature T can now be expressed by integrating Eq. 3.1 over all wavelengths

$$\int_0^\infty B(\lambda,T)\, d\lambda \qquad \text{(watts/cm}^2\text{/steradian)} \tag{3.2}$$

The effective blackbody radiance, B(T), of a blackbody entirely filling the field of view of the IRT is the blackbody radiance weighted by the spectral response $q(\lambda)$ of the IRT. It is given by

$$B(T) = \int_0^\infty q(\lambda)\, B(\lambda,T)\, d\lambda \quad \text{(watts/cm}^2\text{/steradian)} \tag{3.3}$$

Numerical integration of Eq. 3.3 was done using a computer, and the results were furnished by the manufacturer. Figure 3.3 is a curve of B(T) versus temperature for the IT-3 plotted from data supplied by the Barnes Engineering Company. Emissivity calculations for snow surfaces were computed using radiance values from this curve.

The IT-3 was designed for extensive use in the field of earth sciences, and the Model-A version was designed for measurements at relatively low terrestrial temperatures. The environment in which many

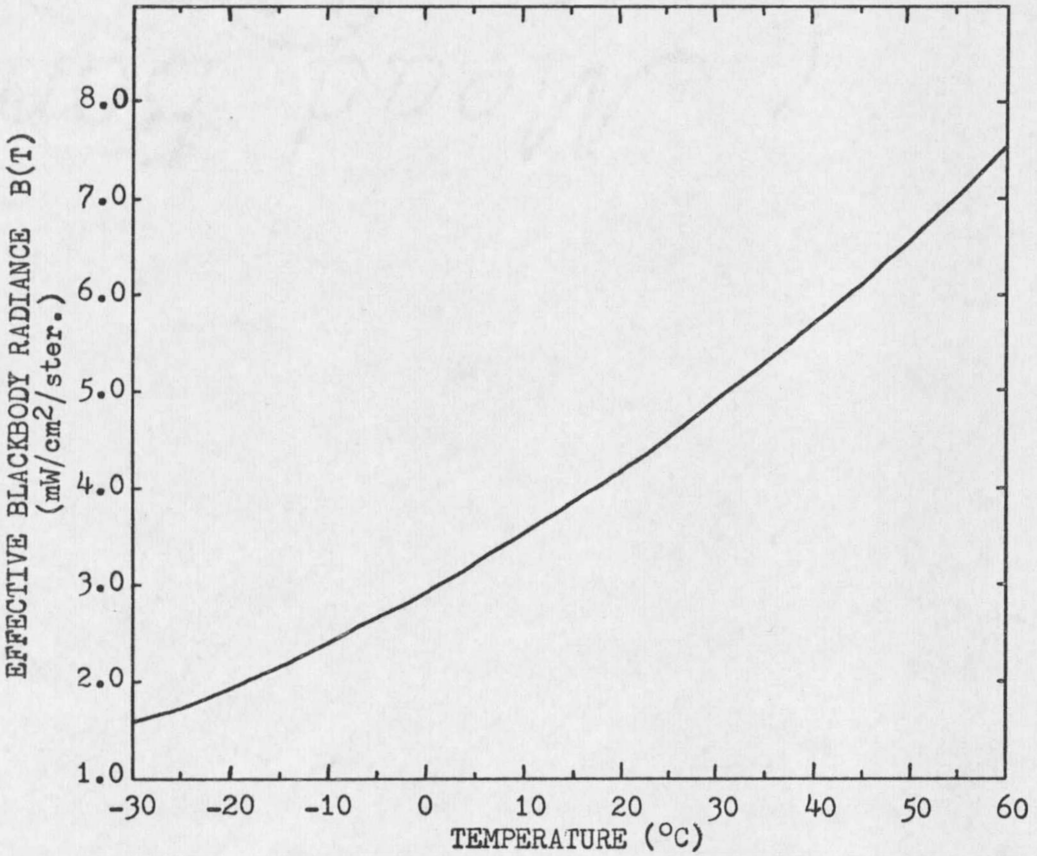

Figure 3.3 Effective blackbody radiance B(T) versus temperature for the Barnes IT-3.

measurements are made makes it imperative to be able to "look" through an intervening column of atmospheric constituents, both horizontally and vertically. If there were strong absorption (and correspondingly, strong emission) bands in the atmosphere, serious errors would be expected in radiometric measurements. However, as mentioned earlier, the existence of an infrared window in which there is relatively little absorption provides a solution to this problem. By designing the filter system of the radiometer to coincide with the infrared window region, absorption effects are minimized.

Figure 3.4 presents the infrared transmission characteristics of the earth's atmosphere looking vertically for typical concentrations of water vapor, carbon dioxide, and ozone--the three gases which primarily affect the absorption spectra at infrared wavelengths. It is easily seen that in the 8 to 14 micron spectral region of the IT-3, there is relatively little absorption except at 9.6 and 9.9 microns. Here, strong absorption exists due to the influence of the ozone vibrational band. If measurements are made at low levels in the atmosphere, the influence of the absorption band of ozone is of minor importance. In conjunction with the highly transparent regions from 8 to 14 microns it may be noted from Figure 2.1 that this particular range is also the region of peak thermal radiation.

The preceding discussion shows that the spectral bandpass of the IT-3 represents an optimum viewing interval for radiometric measurements,

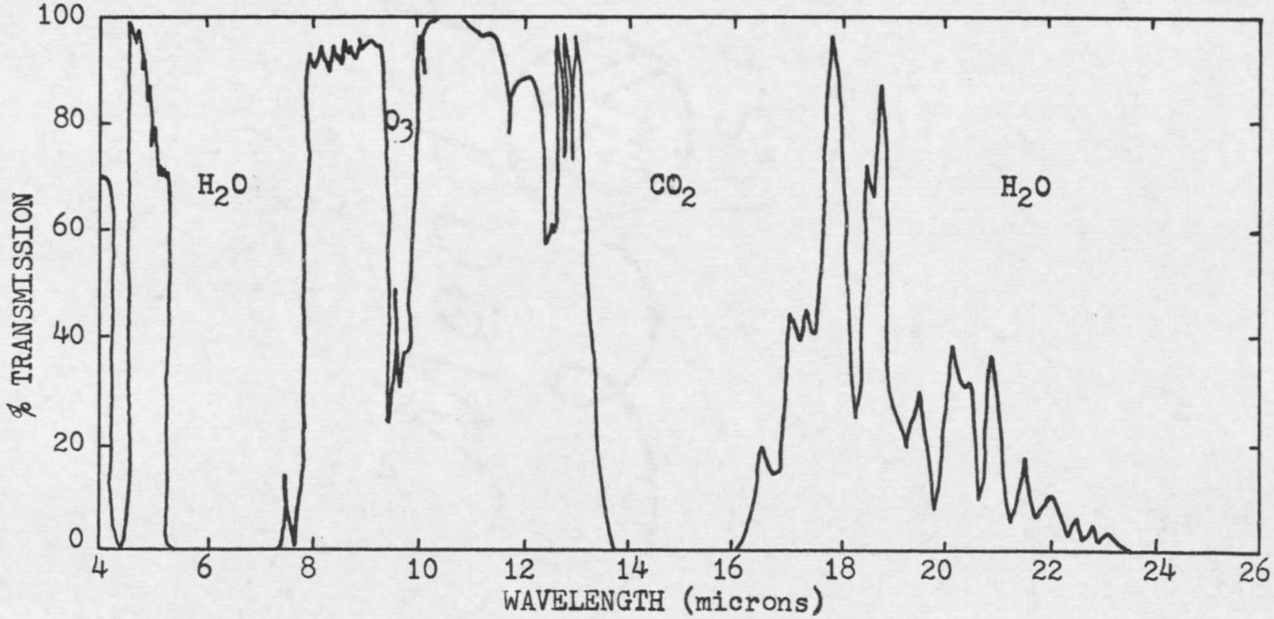

Figure 3.4 Transmission characteristics of the atmosphere for typical concentrations of water vapor, carbon dioxide, and ozone (after Gates, 1962).

especially for low temperature environments near the earth's surface.

3.3 Calibration of the Radiometer

Calibration procedures were carried out in an effort to obtain a stable curve of blackbody temperature versus millivolts output on the Leeds and Northrup recorder. At the same time the accuracy of the instrument was investigated and compared against factory specifications.

The basic technique in calibrating the infrared thermometer was to construct a blackbody and vary its temperature while tabulating the recorder output. The temperature of the blackbody needed to be uniform at the time readings were taken. This necessitated a calibration chamber with considerable thermal mass. To further complicate matters, temperatures below freezing were required.

The calibration chamber which was designed and built consisted of a high quality blackbody cavity housed in a cylindrical aluminum container (Figure 3.5) around which a liquid could be circulated to produce the variable temperatures needed. The blackbody cavity was constructed of two aluminum cones fastened base to base. One end was cut away to provide an aperture for viewing with the IRT. The interior of the cones was painted with Parsons Black Optical Paint. This is a special paint which possesses the property of an emissivity of 0.985 at infrared wavelengths.

The blackbody cavity was placed in a stirred bath of either ethylene glycol and water or water alone depending on the temperature