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SUMMARY OF RESULTS OF SPECTRAL AND ANGULAR SKY RADIATION MEASUREMENT PROGRAM*

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Abstract

Results are analyzed and plotted for a series of more than 50 thousand spectral infrared sky radiation measurements made in 6 U.S. cities. An empirical equation is developed to disaggregate the total sky emissivity into its spectral and angular components. This information is of special relevance to the performance of radiative cooling systems.

1. Introduction

Infrared transfer between the building envelope and the environment is typically treated in a very approximate manner in calculations of building thermal performance. Corrections to the skin temperature of building walls and windows due to this phenomenon are required since half the field of view "seen" by these surfaces is at the "sky temperature." Reductions in the skin temperature of roof surfaces can be more significant since roofs are completely exposed to the radiatively cooler sky dome. It is desirable to be able to estimate these effects accurately in order to properly model the thermal performance of buildings. It has also been demonstrated that with a roof system designed to take advantage of infrared heat rejection to the sky, it is possible to achieve cooling rates of the same order of magnitude as the cooling loads for single story buildings. The degree to which this can be done depends on the effectiveness of the radiative and convective coupling of the radiator surface to the sky and to the interior space being cooled. It also depends on the amount of downward infrared radiation received from the sky dome.

Previous studies have concentrated on measurements and evaluation of the total downward radiative flux, which is usually expressed in terms of an effective "sky temperature," or a total sky emissivity [1]. It now appears, however, that the development of spectrally selective radiator and glazing materials could permit increased cooling rates to be achieved, thus requiring knowledge of spectral sky radiation properties.

A blackbody emitter radiates according to the relationship

$$R_r = \epsilon_r \sigma T_r^4 \quad (1)$$

where ϵ_r is a constant emissivity having a value near unity for radiator surfaces ($\epsilon_r=1$ for a true blackbody emitter); $\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$, and T_r is the radiator temperature in degrees Kelvin. For a spectrally selective radiator the surface material is chosen to make the emissivity large in one portion of the infrared spectrum and small over the remainder.

The calculated spectral and angular behavior of typical midlatitude clear sky radiance is shown in Figure 1. The plotted curves are most sensitive to variations in the moisture content and temperature profile of the atmosphere, and especially to the presence of cloud cover. The region between approximately 8 and 14 micrometers is the part of the infrared spectrum through which most heat can be rejected to the sky, since the incident radiation from the sky is at a low level. This region is often referred to as the infrared "atmospheric window". A selective radiator would be designed to emit and receive radiation strongly only within this window region. The measurements presented here are the result of a multiyear program to investigate the specular and angular sky radiation properties over a range of climates in the southern continental United States.

Detailed spectral measurements of the sky radiation are reported for six U.S. locations; Tucson, AZ, San Antonio, TX, St. Louis, MO, Gaithersburg, MD, West Palm Beach, FL, and Boulder City, NV. The radiometers used in this study were developed at Lawrence Berkeley Laboratory to measure the incident sky radiation through a 2° field of view at five zenith angles (0° , 20° , 40° , 60° , 80°). At each angular position, the incident radiation was recorded through seven infrared filters for which the transmission characteristics are presented in Figure 2. The "no filter" channel actually represents the spectral radiation passing through a coated germanium lens. The remaining six channels will be referred to in terms of their central wavelengths or their pass bands: 8.8 μm , 9.6 μm , 11 μm , 8-14 μm , 15 μm , and 17-22 μm .

During the course of approximately 1 1/2 years of measurements, readings were taken at half hour intervals. Analysis of the resulting data base yielded a total of 57 months of good data from among the six locations. Radiation measurements were averaged over each month for all seven filter channels and for each

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of the five zenith angles. The data for no filter and the 8-14 micrometer filter is plotted as a function of the total sky emissivity in a series of graphs presented in section 7.

2. Apparent Sky Emissivity

Sky radiation data can be expressed in a number of ways which are essentially equivalent, but differ in their ease of interpretation. The sky radiance $R_S(\lambda, \theta)$ which is a function of wavelength λ and zenith angle θ is the quantity most directly related to the net radiative heat flux at any time. This quantity is not expressed by means of an equation similar to Eq.(1) because the sky does not radiate as a blackbody, as can be seen from the typical radiation profiles of Figure 1. An effective "sky temperature" T_S can be defined as being the temperature of a blackbody for which the emitted radiative flux is the same as for the sky:

$$R_S = \sigma T_S^4 \quad (2)$$

where R_S is the measured incident flux containing all thermal wavelengths at all angles from the sky. The objections to using an effective sky temperature are twofold; first, the concept of temperature refers to a body in thermal equilibrium in a well defined state, whereas the atmosphere consists of a gradation of layers at different temperatures, whose spectral emissivity changes as a function of altitude. Due to the partial transparency of the air layers, the observer in reality "sees" a weighted average of temperatures from each layer which is a function of the wavelength. The second objection is more pragmatic in nature. The "sky temperature" as defined in Equation 2 fluctuates strongly with the ambient air temperature T_a throughout the day [1]. The changes in apparent emissivity of the sky can thus be masked to a great extent by ambient air temperature changes. In this report we choose to express the sky radiation data in terms of the spectral and angular sky emissivity $\epsilon_S(\lambda, \theta)$ which is defined to yield the spectral sky radiance:

$$R_S(\lambda, \theta) = \epsilon_S(\lambda, \theta) B_a(\lambda). \quad (3)$$

Here $B_a(\lambda)$ is the Planck function evaluated with the ambient air temperature T_a ($^{\circ}\text{K}$). The temperature T_a is to be measured in the conventional meteorological fashion at a height of 1 to 2 meters above the ground. The Planck function is given explicitly by

$$B_a(\lambda) = 2hc^2\lambda^{-5} \left[\exp\left(\frac{hc}{\lambda k_B T_a}\right) - 1 \right]^{-1}, \quad (4)$$

where h is Planck's constant (6.626×10^{-34} Js), k_B is Boltzmann's constant (1.381×10^{-23} J K^{-1}), and c is the speed of light (2.998×10^8 m s^{-1}).

Under clear sky conditions, the value $\epsilon_S(\lambda, \theta)$ remains practically constant throughout the day. Multiplication by the factor containing T_a allows the incident radiance to be calculated readily, since air temperatures are available for most locations. The total incident sky radiation received by a horizontal surface is obtained by integration of equation (3) over all wavelengths and zenith angles.

$$R_S = 2\pi \int_0^\infty d\lambda B_a(\lambda) \int_0^1 \cos\theta \, d\cos\theta \epsilon_S(\lambda, \theta). \quad (5)$$

The total sky emissivity ϵ_S may be defined by

$$R_S = \epsilon_S \sigma T_a^4, \quad (6)$$

analogous to Eq.(3). Equations (5) and (6) can be used to express the total sky emissivity in the form

$$\epsilon_S = \frac{\int_0^\infty d\lambda B_a(\lambda) \int_0^1 \cos\theta \, d\cos\theta \epsilon_S(\lambda, \theta)}{\left[\int_0^\infty d\lambda B_a(\lambda) \int_0^1 \cos\theta \, d\cos\theta \right]^{-1}} \quad (7)$$

which shows that ϵ_S is a weighted average of $\epsilon_S(\lambda, \theta)$.

3. The Sky Radiance Equation

An empirical equation has been developed to describe the spectral sky emissivity $\epsilon_S(\lambda, \theta)$ as a function of zenith angle θ and total sky emissivity ϵ_S . The spectral emissivity of the sky can be written in terms of the apparent sky transmissivity:

$$\epsilon_S(\lambda, \theta) = 1 - \tau(\lambda, \theta) \quad (8)$$

We make the assumption that the wavelength and angular dependences can be separated, and that the angle enters in the form

$$\epsilon_S(\lambda, \theta) = 1 - A\tau(\lambda)e^{-b/\cos\theta} \quad (9)$$

where $1/\cos\theta$ is the air mass. The constant A can be determined by the condition that $\epsilon_S(\lambda, \theta)$ averaged over all wavelengths and over the angles 0 to 90° corresponding to the sky dome must equal the total sky emissivity ϵ_S (Eq.7):

$$\epsilon_s = 1 - 2A\bar{\tau} \int_0^1 e^{-b/\cos\theta} \cos\theta \, d\cos\theta$$

$$\text{where } \bar{\tau} = \int_0^\infty d\lambda t(\lambda) B_a(\lambda) / \int_0^\infty d\lambda B_a(\lambda),$$

The integral over $d\cos\theta$ in Equation (10) is equal to twice the third exponential integral [2], $2E_3(b)$, which can be well approximated over the range of interest ($0 < b < 0.6$) by the exponential function $e^{-1.7b}$. We can thus write Equation (10) as:

$$\epsilon_s = 1 - \bar{\tau} A e^{-1.7b}$$

which yields an expression for A,

$$A = (1 - \epsilon_s) e^{1.7b} / \bar{\tau}$$

Substitution in Equation (9) results in the sky radiance equation:

$$\epsilon_s(\lambda, \theta) = 1 - (1 - \epsilon_s) \left[t(\lambda) / \bar{\tau} \right] e^{b(1.7 - 1/\cos\theta)} \quad (11)$$

The expressions $t(\lambda)/\bar{\tau}$ and b implicitly contain a dependence on the total sky emissivity ϵ_s , which will be determined by analysis of the experimental data.

4. Determination of Total Sky Emissivity

The spectral radiometer used to make the sky radiation measurements was considered to be a more accurate instrument than the pyrgeometer. After each set of measurements (every half hour) the sensor was directed into a blackbody reference cavity of known temperature. Once a day the cavity was caused to pass through a fixed temperature range allowing an absolute calibration of the radiometer to be carried out. The pyrgeometer cannot be calibrated as readily, and is thus considered to be less accurate. Furthermore, the radiometer readings are not affected by the sun, whereas a correction must be applied to pyrgeometer readings due to heating of the silicon dome by shortwave solar radiation.

For these reasons, a quantity called the "pseudo pyrgeometer" was derived from the recorded data. The emissivities measured at each zenith angle with the "no filter" channel are weighted by the solid angle subtended by them in the sky dome, and by the cosine of the zenith angle to account for their projection onto a horizontal surface. The quantity thus constructed behaves like a pyrgeometer reading, if the pyrgeometer is averaged over a sufficient interval to smooth out fluctuations due to cloud asymmetry. A plot showing the pseudo pyrgeometer as a function of dewpoint temperature is presented in Figure 3. The straight line in the figure is a least square fit to the 57 monthly average pseudo pyrgeometer values:

$$\epsilon_{ps} = 0.00831 T_{dp} + 0.6033, \quad (12)$$

where T_{dp} is the dewpoint temperature in degrees Celsius. Each of the measured average monthly spectral sky emissivities $\epsilon_s(\lambda, \theta)$ can be plotted against the pseudo pyrgeometer reading, where ϵ_{ps} replaces ϵ_s in Equation (11). The advantage of doing so is that this equation provides a good fit to the data points taken under all sky conditions, as well as under the clear sky conditions used to empirically establish the constants in the equation. However, since the pseudo pyrgeometer is not a readily available instrument, it is more desirable to express the equation in terms of the true total sky emissivity as would be measured by a properly calibrated pyrgeometer.

A relationship can be derived between the pseudo pyrgeometer (Equation 12) and the pyrgeometer reading based on the correlation developed by Berdahl and Fromberg [1], which can be expressed as

$$\epsilon_s = 0.00614 T_{dp} + 0.734. \quad (13)$$

This equation was originally developed by analyzing 11 months of clear sky data, and applying correction factors to account for daytime solar heating of the pyrgeometer and small calibration corrections. In applying this equation to the data based on 57 months of clear sky data it was found necessary to adjust the relationship given in Equation (13) to read

$$\epsilon_s = 0.00696 T_{dp} + 0.709 \quad (14)$$

The reason for this adjustment is that the mean clear sky conditions for the original 11 month data set were systematically (if slightly) different from conditions for the full 57 month data set. The full data set indicates slightly lower emissivities for a given dewpoint temperature. To maintain consistency in our analysis we require a relationship between ϵ_s and T_{dp} based on the entire 57 month data set. The adjustment of Equation 13 to produce Equation 14 was determined by evaluating the difference between the two data sets using the pseudo pyrgeometer and then using the approximate relation

$$\Delta \epsilon_s = 0.84 \Delta \epsilon_{ps}$$

to determine the adjustment required. In principle Equation 14 is an improvement over Equation 13 because it is based on more data. However, the difference is small, especially at dewpoint temperatures above 0°C, and the current derivation is somewhat indirect. The utility of Equation 14 in the present context is that it is consistent with Equation 12, especially since it is based on the same data set. Eliminating the dewpoint temperature between equations (12) and (14), one arrives at the desired expression for total sky emissivity ϵ_s as a function of the pseudo pyrgeometer value ϵ_{ps} .

$$\epsilon_s = 0.838 \epsilon_{ps} + 0.204 \quad (15)$$

This relationship is plotted in Figure 4, along with the data points which display measured pseudo pyrgeometer values versus the measured pyrgeometer values for clear skies. The small systematic difference between the derived line and the data is due to the effect of sunlight on the pyrgeometer. If it were possible to correct the pyrgeometer observations for this error, agreement would be better. The same relationship is presented in Figure 5, which shows the corresponding plot for all sky conditions. For the purposes of this paper the pyrgeometer values ϵ_s are always obtained from measured pseudo pyrgeometer values by the use of Equation 15.

5. Determination of Parameters in the Sky Emissivity Equation

Equation (11) is of a form suggested by the physical phenomena taking place within the atmosphere. However, it is not a rigorously derived equation, and the primary purpose for introducing it at this time is to provide a concise analytical expression which adequately embodies the results of tens of thousands of individual spectral sky emissivity measurements. The nature of the transmissivity function $t(\lambda)$ has as yet been left undefined, except to state that it is related to the atmospheric spectral transmissivity (in the zenith direction). It is expected to be a function dependent on the total sky emissivity ϵ_s .

In order to fit the experimental data measured through seven infrared filters at five zenith angles, we consider the quantities $t(\lambda)/\bar{t}$ and b to be linear function of ϵ_s . In all four filter regions included in the atmospheric window (8-14 micrometers), and for the "no filter" case, the parameter b is a well defined linear function of ϵ_s . In the 15 micrometer channel there is only a slight dependence of either parameter on the total emissivity, since the atmosphere is optically dense at this wavelength. In other words, due to the fact that most 15 micrometer radiation reaching the detector originates within a few tens of meters from the instrument, the angular dependence described by the air mass term ($1/\cos\theta$) is no longer of relevance. This is borne out by the fact that the average value of the parameter $t(\lambda)/\bar{t}$ approaches zero (approx 0.02), and each spectral emissivity, as well as the total emissivity approaches unity.

The other anomalous channel is the 17-22 micrometer region. Here the clear sky data can be used to determine a least squares fit for the b -parameter, but a large amount of scatter exists. Again, as in the 15 micrometer case, the value of $t(\lambda)/\bar{t}$ is small (≤ 0.2 for $\epsilon_s > 0.7$) indicating a situation where all emissivities approach unity. The unique feature in this spectral region is that a secondary "window" begins to open at low values of ϵ_s (low dewpoint temperatures).

The results of performing least squares fits for the two parameters b and $t(\lambda)/\bar{t}$ to straight lines as a function of the total sky emissivity ϵ_s are presented in Table (2).

Table 2
Values of least squares fit parameters for use in Equation 11 to predict spectral sky emissivity.

	$b = A \epsilon_s + B$		$t(\lambda)/\bar{t} = C \epsilon_s + D$	
	A	B	C	D
"no filter"	1.4929	-0.8668	1.1243	0.5997
8-14 μ m	1.7915	-1.1127	1.8068	1.0340
8.8 μ m	1.2809	-0.7710	5.1191	-1.1922
9.6 μ m	1.3046	-0.7153	5.3211	-1.6090
11.0 μ m	1.7784	-1.1592	3.1744	0.4515
15.0 μ m	-5.7780	5.2576	0.0410	-0.0066
17-22 μ m	-0.6914	1.6528	-1.5486	1.2975

These values are substituted into the sky radiance equation (Equation 11) in order to produce the curved lines through the data points in the graphs presented in section 4 (Figures 6-9). Clear sky data has been used to generate the parameters in Table 2, which have not been altered for presentation of the data from all sky conditions. In obtaining the values for these parameters, the b -coefficient is determined by fitting the data points at the zenith and 60° angles. Measurements at a zenith angle of 80° were judged to be of less practical importance for radiative cooling purposes due to the small projected area of a horizontal surface in that direction (cosine effect).

6. Estimation of Total Sky Emissivity

The most straightforward way to obtain a value for the total sky emissivity ϵ_s for use in Eq.(11) is to measure it directly with a pyrgeometer. A correction to the reading is required to account for heating of the silicon dome whenever the instrument is located in direct sunlight. Unfortunately, pyrgeometers are not common instruments, and little data from them is available on a long-term basis. Even weather stations operated by the National Oceanic and Atmospheric Administration (NOAA) do not use such an instrument for routine measurements.

A correlation has been documented by Berdahl and Fromberg [1] for the total emissivity as a function of dewpoint temperature ($^{\circ}\text{C}$). This correlation has been developed from clear sky pyrgeometer data which was subjected to corrections to account for solar heating of the instrument. Berdahl and Fromberg report two linear relationships for this function; one is a nighttime correlation; and the other is valid during the daytime:

$$(16a) \quad \text{daytime} \quad \epsilon_s = 0.0060 T_{dp} + 0.727 \quad \text{nighttime} \quad \epsilon_s = 0.0062 T_{dp} + 0.741 \quad (16b)$$

A third relationship, valid for 24 hour average emissivities, can be obtained by simply averaging the coefficients of these two equations, and has been given as Equation 13.

Use of the linear fit which best describes the day/night conditions of interest in a given situation will yield total sky emissivities nearly as accurate as pyrgeometer readings if the clear sky condition is satisfied.

When clouds are present, a number of complexities are introduced into the estimation of the total sky emissivity. The temperature of the cloud base as well as its zenith angle and angular extent must properly be taken into consideration to produce accurate results. In practice this detailed analysis is not usually feasible. One must be content with estimating the fraction of the sky vault covered by clouds, and the cloud base temperature must be roughly inferred from its altitude and the atmospheric lapse rate. The assumption is made that over a period of time the angular distribution of clouds as seen by an observer is uniform over the sky dome.

The method recommended here is that in the presence of clouds, the total sky emissivity be assigned a value [3]:

$$\epsilon_s = \epsilon_s^{\text{clear}} (1 - \Gamma_n) + \Gamma_n, \quad (17)$$

where $\epsilon_s^{\text{clear}}$ is the clear sky emissivity calculated from Equation 13 or 16, n is the estimated fraction of sky covered by clouds, and Γ is a parameter which depends on the cloud height and type. Values for Γ range over 0.16 for cirrus clouds (height 12.2 km), 0.66 for altocumulus clouds (height 3.7 km), and 0.88 for stratocumulus clouds (height 1.2 km). Measurements in Atlanta, GA [4] and San Antonio, TX [5] indicate that a value of $\Gamma = 0.55$ to 0.6 can be used as an average for opaque clouds at these locations. Further information is available in the monographs by Sellers [6] and Kondratyev [7].

Once the total sky emissivity has been determined by the above means, it can be used directly in the sky radiance equation, or one can use it to find the desired spectral emissivity from one of the graphs presented in section 4.

7. Discussion of Results

A total of 12 graphs are used to plot the spectral sky emissivities as a function of the total sky emissivity for each measurement channel. Half of these graphs are used to plot monthly averaged emissivities over clear sky conditions only, and the other half plot the same quantities using data from all sky conditions. Each set of graphs represents measurements made through six zenith angles (actually five angles and one composite channel referred to as the "global" measurement).

Due to the importance of blackbody emitters and radiators which emit strongly between 8 and 14 micrometers, we present detailed results for these two cases in Figures 6-9.

Both the clear sky conditions and all sky conditions are well described by equation (11) using the parameters provided in Table 2. At a zenith angle of 80° (10° above the horizon) the equation consistently predicts larger emissivity values than are observed. In all cases it will be noted that the angular-weighted global measurement closely approximates the emissivity at a zenith angle of 50° . For smaller zenith angles the sky emissivity varies only slightly, achieving its lowest value in the overhead direction. As one approaches within 30° of the horizon all the measured emissivities increase rapidly, confirming the known fact that a cooling surface should be in radiative contact with the upper portion of the sky dome. However, little is to be gained by focusing a radiator sharply toward the zenith, since the emissivity values do not begin to increase rapidly until within 30° of the horizon.

The potential advantage of using a selective radiator which is highly emissive only within the 8-14 micrometer region is shown by an examination of the 8-14 micrometer global results (Figs 8,9). The maximum

temperature depression (below air temperature) which can be produced by a non-selective (blackbody) radiator is roughly proportional to $(1 - \epsilon_s)$, the deviation of the total sky emissivity from unity. The maximum temperature depression which can be produced by an 8-14 micrometer selective radiator is proportional to the deviation of the corresponding emissivity from 1, with approximately the same constant of proportionality. Since the slope of the curve in Figure 8a is greater than 2, the maximum temperature depression achievable with an 8-14 micrometer selective surface is more than twice the value achievable with an ordinary blackbody radiator. This can be particularly beneficial under overheated conditions where the dewpoint temperature, and hence the total sky emissivity ϵ_s , is relatively high.

8. Acknowledgment

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9. References

1. P. Berdahl and R. Fromberg, "The Thermal Radiance of Clear Skies," to be published in Solar Energy, 1982.
2. M. Abramowitz and I. Stegun, eds., Handbook of Mathematical Functions, National Bureau of Standards Applied Mathematics Series, published by the U.S. Gov't. Printing Office, p.228, formula 5.1.4 (1964).
3. P. Berdahl and R. Fromberg, "An Empirical Method for Estimating the Thermal Radiance of Clear Skies," Lawrence Berkeley Laboratory Report LBL-12720, (May 1981). This report is a slightly more comprehensive version of Ref.3.
4. K.G. Picha and J. Villanueva, "Nocturnal radiation measurements," Atlanta, Georgia, Solar Energy 6, 151 (1962).
5. G. Clark and C.P. Allen, "The Estimation of Atmospheric Radiation for Clear and Cloudy Skies," Proceedings Second National Passive Solar Conference, Vol. 2, p.676, Philadelphia (1978).
6. W. Sellers, Physical Climatology, p.58, Univ. of Chicago Press, Chicago (1965).
7. K. Kondratyev, Radiation in the Atmosphere p.576, Academic Press, New York (1969).

Spectral Radiance of Clear Skies Midlatitude Summer Atmosphere

XBL 813-520

FIGURE 1

NOTATION: In all the subsequent graphs each letter symbol represents a full month of averaged data from one of the six U.S. cities at which radiometer measurements were taken. The key to interpreting these symbols is:

- A = San Antonio, TX
- B = Boulder City, NV.
- G = Gaithersburg, MD
- L = St. Louis, MO
- T = Tucson, AZ
- W = West Palm Beach, FL

RADIOMETER SPECTRAL RESPONSE FOR EACH FILTER CHANNEL

FIGURE 2

FIGURE 3

FIGURE 5

FIGURE 4

Figure 6

Figure 9

8
6
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