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# Atmospheric Transmittance Determination from a Two-Angle Measurement of Radiance Change

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## INTRODUCTION

Space-based systems which sense the earth's surface remotely could benefit from ground-truth measurements that can provide needed corrections due to the effects of atmospheric radiance. In addition, a ground-based measurement of atmospheric transmittance would affect the predictions of the probability of detection by a space-based vehicle. In this report, an experimental technique is described for estimating infrared atmospheric transmittance to space from the ground. Using an idealized model for atmospheric absorption, it is shown that the measurement of the ratio of radiance gradients at two different zenith angles can be used to estimate the clear-sky transmittance. Transmittances obtained with this technique were compared with LOWTRAN 6 (Kneizys et al., 1983) calculations using measured profiles of meteorological parameters. The results showed the modeled transmittances to be in agreement within 10 percent for zenith angles above the horizon.

## MATHEMATICAL FORMULATION

The starting point for the model development is the general radiative transfer equation. The apparent temperature,  $T_{ap}$ , observed from and above and at a distance,  $r$ , from a source can be expressed as

$$T_{ap}(r) = T_{ap}(0)e^{-\tau'(0,r)} + \int \sigma_e(r')[(1-a)T(r') + aT_{sc}(r')]e^{-\tau'(r',r)}dr', \quad (1)$$

where  $\sigma_e$  is the extinction coefficient at  $r'$ , and  $T$  is the temperature of the atmosphere at  $r'$ .  $T_{sc}$  is a temperature corresponding to the radiation scattered into the volume element at  $r'$ ,  $a$  is the albedo,  $\sigma_s/\sigma_e$ , and

$$\tau'(0,r) = \int \sigma_e(r')dr'. \quad (2)$$

For a ground-based radiometer looking at the clear sky, i.e., no cloud reflectors or contributors from scatters,  $T_{sc} = 0$ , and  $T_{ap}(0) = 0$ . This yields

$$T_{ap} = \int \sigma_a(r')T(r')e^{-\tau(0,r')}dr'. \quad (3)$$

Expressing the above equation in terms of altitude,  $z$ , and zenith angle,  $\theta$ , yields

$$T(\theta)_{ap} = \int_0^H \sigma_a(z')T(z')e^{-\tau(0,z')\sec\theta}(\sec\theta)dz'. \quad (4)$$

If  $T(z')$  and  $\sigma_a(z')$  are taken as average values over the height interval then,

$$T(\theta)_{ap} = T_o \sigma_a \sec\theta \int_0^H e^{-\sigma_a z' \sec\theta} dz' \quad (5)$$

and integration yields

$$T(\theta)_{ap} = T_o[1 - \tau^{\sec \theta}] \quad (6)$$

where

$$\tau = e^{-\sigma_a H}.$$

The ratio of the temperature (radiance) change made at two different zenith angles can be used to obtain an estimate of  $\tau$ . This is demonstrated using the derivative of equation (6)

$$[dT(\theta)_{ap}/d\theta]_{\theta} = T_o(-\sigma_a H)\tau^{\sec \theta}[d(\sec \theta)/d\theta]_{\theta}. \quad (7)$$

The derivative of  $T_{ap}(\theta)$  is equivalent to the angular derivative of radiance. The ratio,  $R$ , of  $dT(\theta)_{ap}/d\theta$  made at two angles is

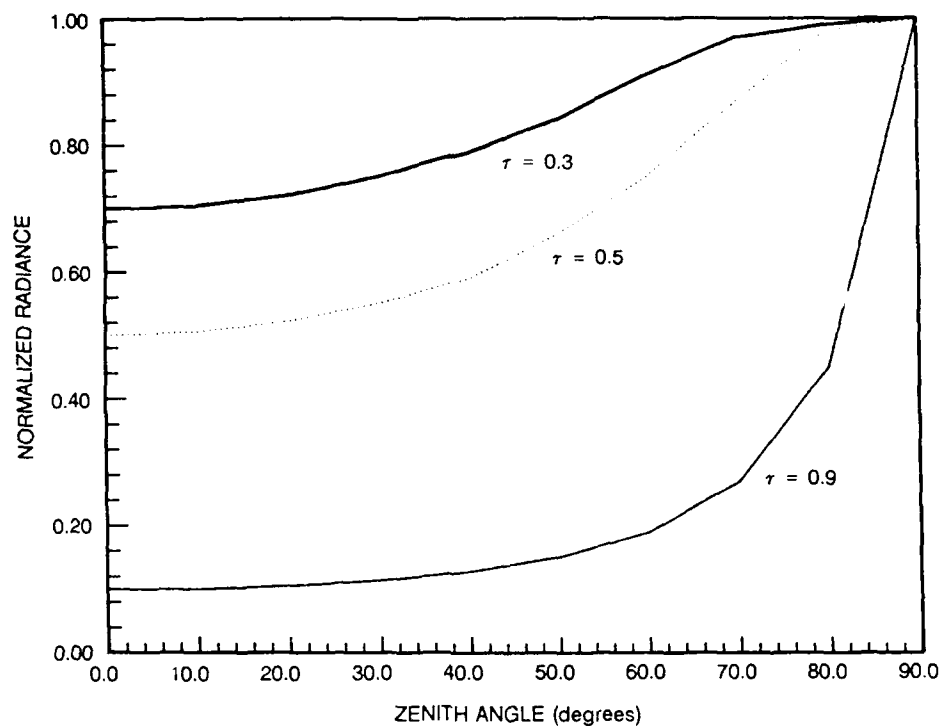
$$R = \tau^{(\sec \theta_1 - \sec \theta_2)} [d(\sec \theta_1)/d\theta_1] / [d(\sec \theta_2)/d\theta_2]. \quad (8)$$

The solution for  $\tau$  becomes,

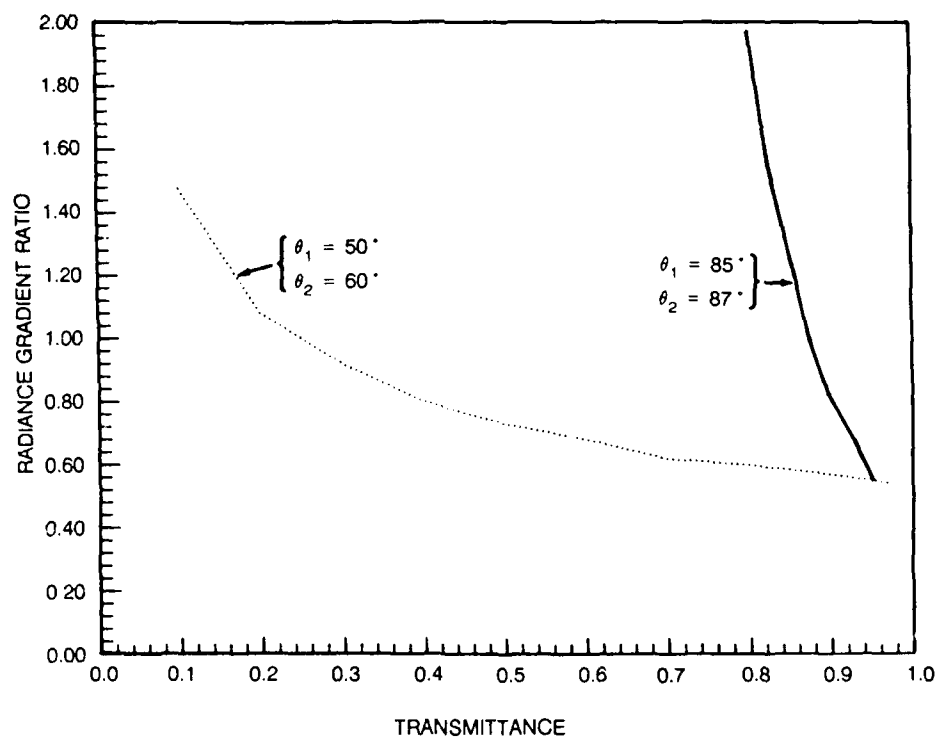
$$\tau = [R(\sec \theta_2 \tan \theta_2 / (\sec \theta_1 \tan \theta_1))^{1/(\sec \theta_1 - \sec \theta_2)}]. \quad (9)$$

Figure 1 is a plot of equation (6) for several values of  $\tau$ . The figure indicates that at a given zenith angle, the slope of the radiance is a measure of  $\tau$ . Greater slopes correspond to higher transmission. The figure also indicates that the range of zenith angles 50 degrees  $< \theta < 80$  degrees offers the largest gradient differences over a wide range of  $\tau$ . Figure 2 illustrates the expected values of  $R$  versus transmittance obtained for two differing pairs of angles. Measurements made at the large zenith angles can be expected to have higher resolution.

Replacing  $T(z')$  and  $\sigma_a(z')$  by constants is a gross approximation and intuitively unsatisfactory. However, as shown in the following section, transmittances obtained when using uniform conditions are quite close in value to those obtained from a model which accounts for the altitude profiles of  $T$  and  $\sigma$ . The extent to which the simple model can be used in a real environment was examined over a limited number of cases. The results, while encouraging, are far from conclusive. This subject is covered in the next section.



**Figure 1.** Uniform model radiance versus zenith angle for different transmittances.



**Figure 2.** Ratio of radiance gradients versus transmittance for zenith angles of between (a) 50 and 60 degrees and (b) 85 and 87 degrees.



## TEST OF CONCEPT

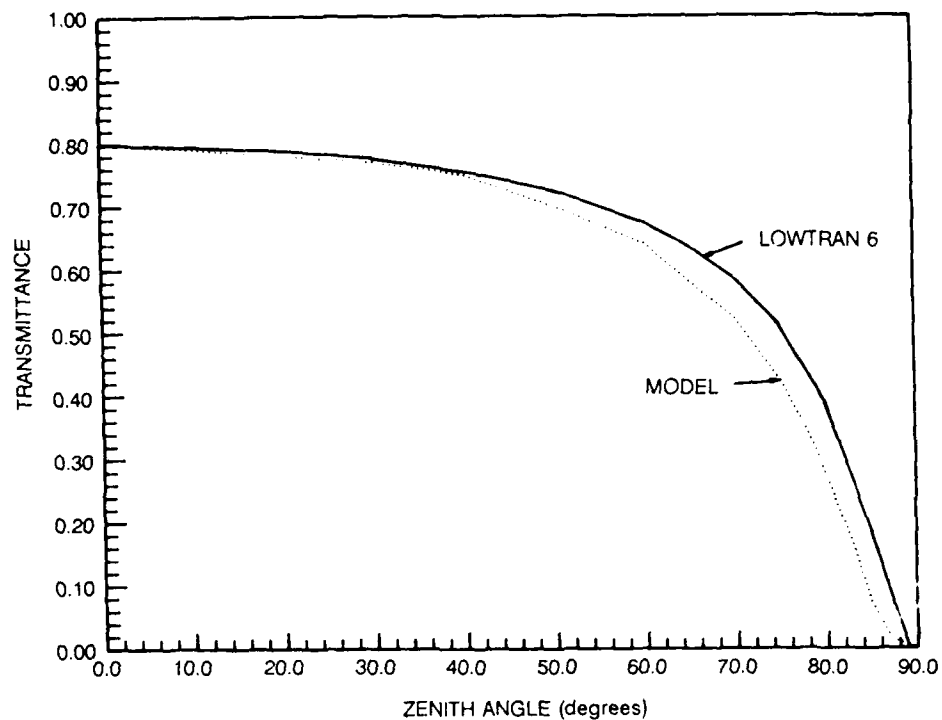
The assumptions regarding constant  $T$  and  $\sigma$  with altitude cast doubt on applying the model in a real environment. To test the model, the transmittances obtained with the model were compared with those calculated using measured profiles of air temperature, relative humidity, and pressure as inputs to the atmospheric transmittance radiance computer code LOWTRAN 6. In these calculations the Navy Maritime Aerosol Model was used to include the effects of aerosol scattering and absorption. Calculations were made which yielded radiances and transmissivities versus zenith angle. Figures 3 through 6 compare the results obtained from the uniform model with the LOWTRAN 6 calculations using measured profiles of meteorological parameters. Figure 3 (10 November 1988) compares the results of the transmittance calculations resulting from the use of the two models. A match is forced at  $\theta = 0$  degree. Figure 4 compares the results of the models for a different day (30 June 1987), but in this case the match is chosen at  $\theta = 60$  degrees. This minimized the larger errors.

Figure 5 compares the radiance obtained on 10 November 1987 from the two models with a match forced at  $\theta = 0$  degree. The radiance calculated with a variable atmosphere (solid line) was made to match the radiance measured at the horizon using a calibrated AGA THERMOVISION thermal imaging system. Figure 6 gives a similar comparison of the radiance results obtained on 30 June 1987. The transmittance curves and radiance curves show a fair match. However, the differences in the radiance values shown would translate into larger effective blackbody temperature differences in the 8- to 12- $\mu\text{m}$  wavelength band.

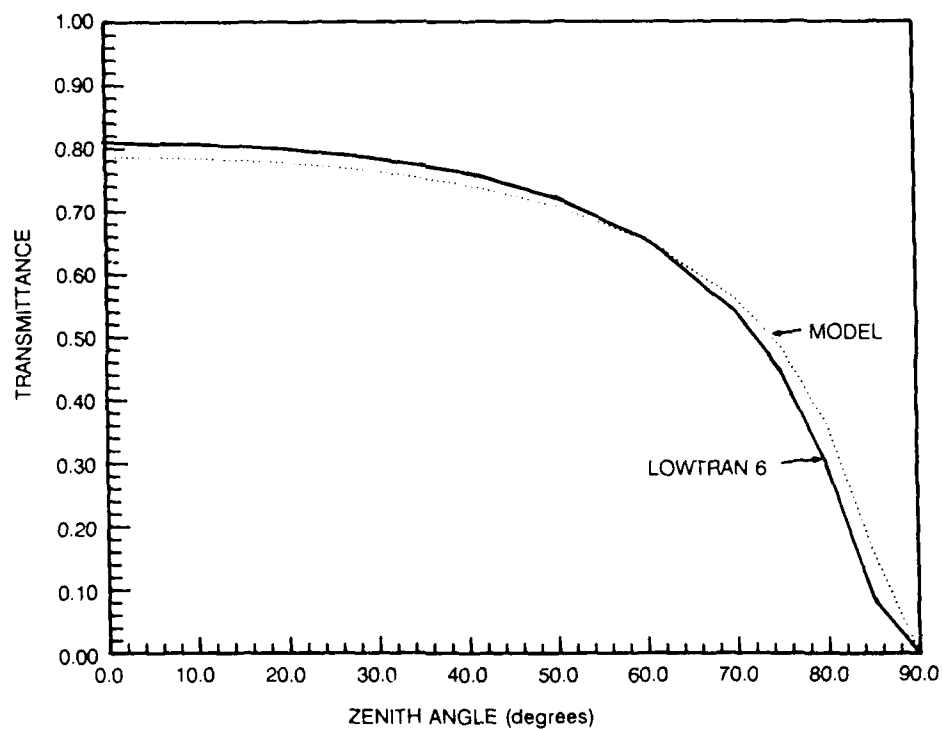
Further comparisons of the transmittance results obtained from the two models are given in table 1.

**Table 1.** Calculated transmittances at  $\theta = 0$  degree.

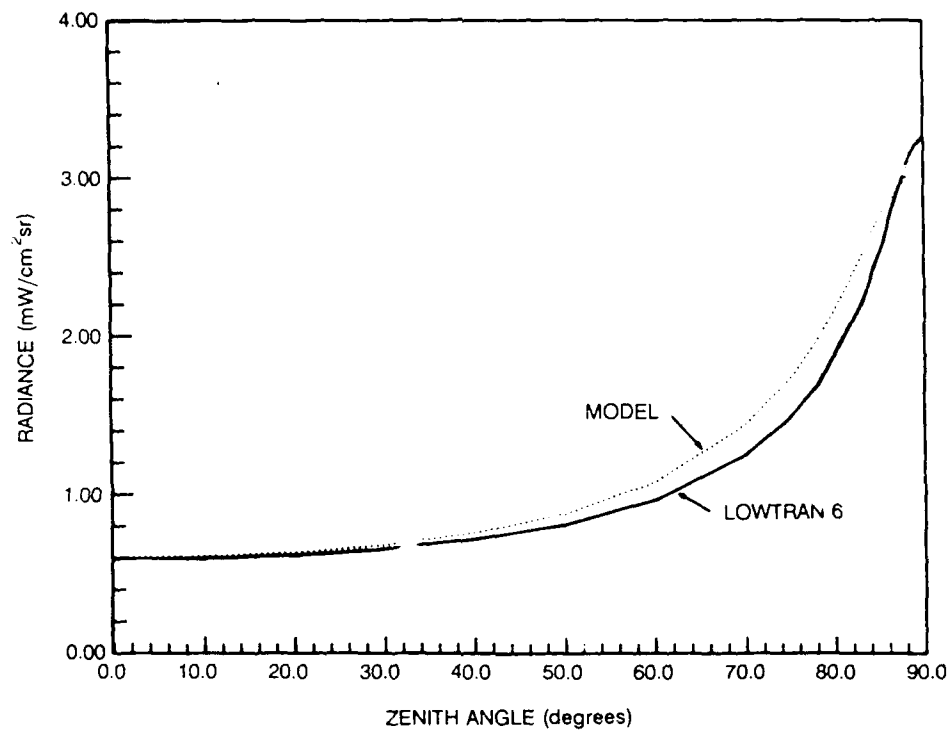
| Date        | Uniform Model | LOWTRAN 6<br>Calculations |
|-------------|---------------|---------------------------|
| 24 Nov 1987 | 0.91          | 0.87                      |
| 29 Sep 1987 | 0.84          | 0.78                      |
| 3 Nov 1987  | 0.84          | 0.76                      |



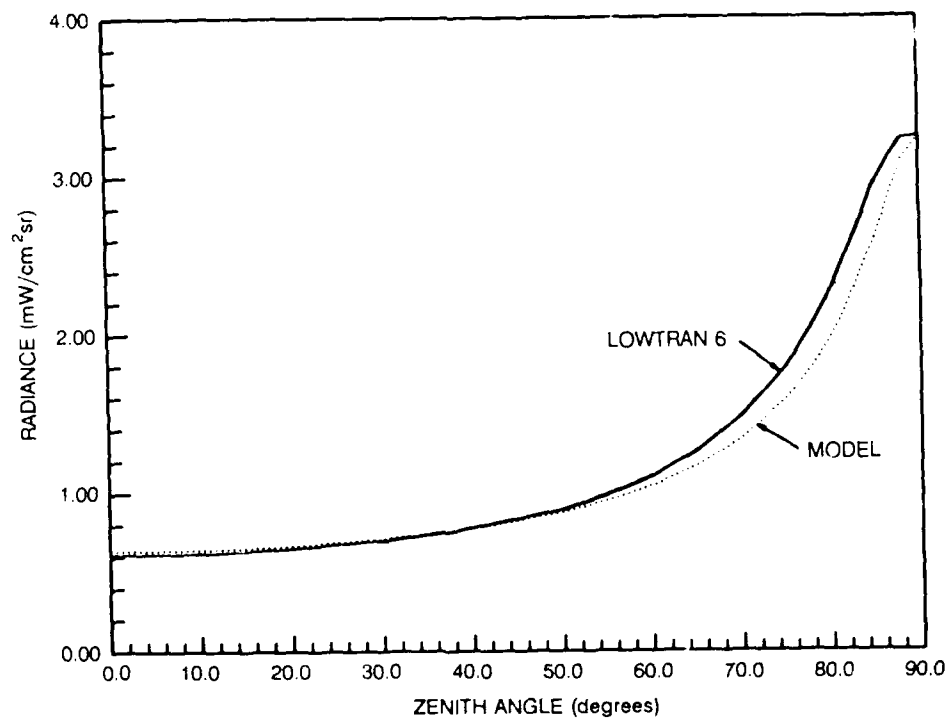
**Figure 3.** Comparison between transmittances obtained from the uniform model and LOWTRAN 6 versus zenith angle for 10 November 1988.



**Figure 4.** Comparison between transmittances obtained from the uniform model and LOWTRAN 6 versus zenith angle for 30 June 1987.



**Figure 5.** Comparison between radiances obtained from the uniform model and LOWTRAN 6 versus zenith angle for 10 November 1988.

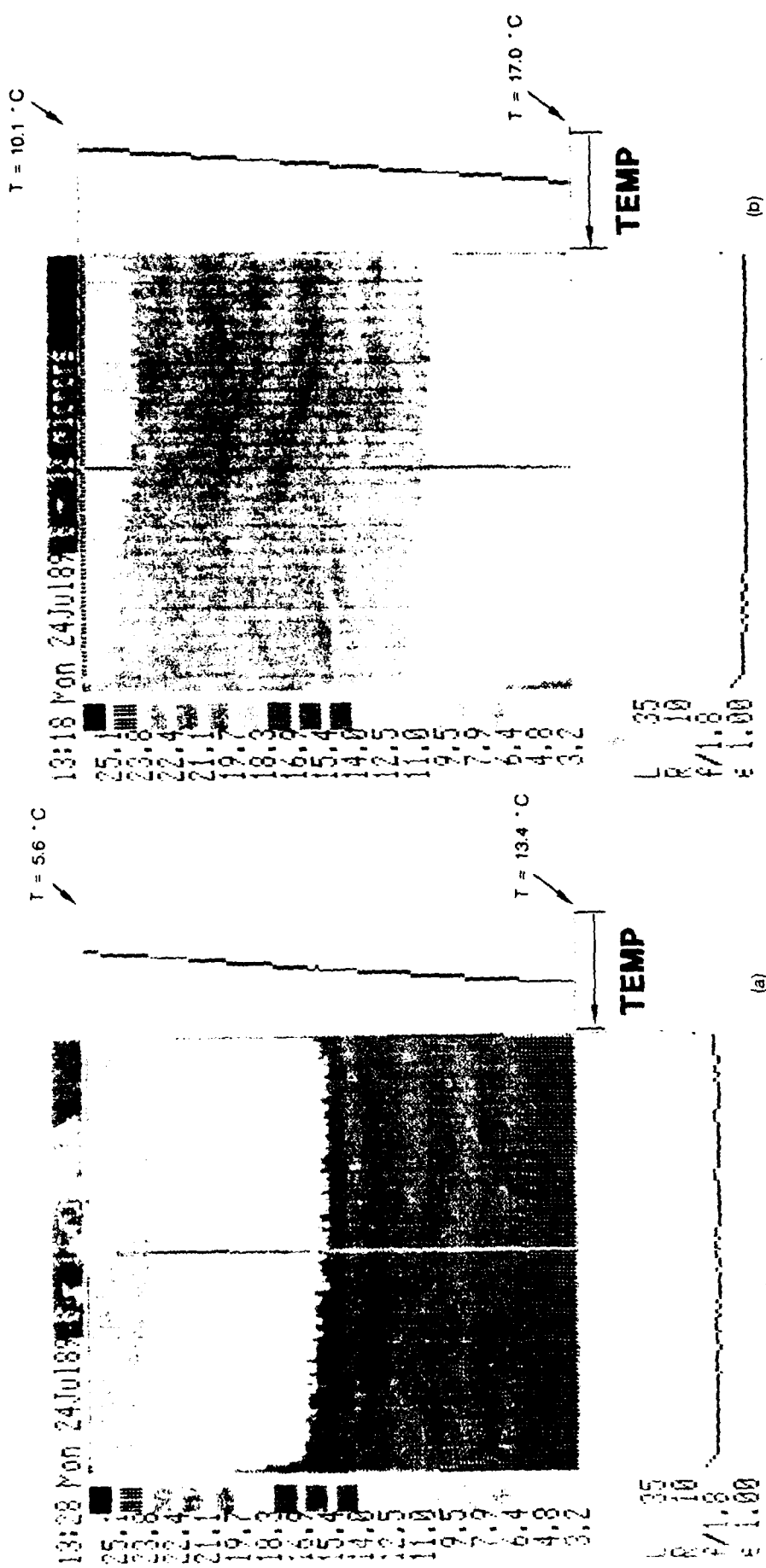


**Figure 6.** Comparison between radiances obtained from the uniform model and LOWTRAN 6 versus zenith angle for 30 June 1987.

## DISCUSSION

The above development indicates that a measurement of radiance gradient at two different angles can be used to determine transmittance under particular conditions. Transmittance values obtained from the two-model calculations compare fairly well for the conditions which existed at the time of each test. This result would be expected if the processes which affect the optical characteristics were taking place in a fairly small altitude range, for example, only near the surface. In this situation, good agreement could be expected. The simplified model neglects scattering, as a consequence, in the presence of heavy aerosol concentrations (i.e., for zenith angles close to the horizon where the aerosol optical depths may be large) the transmittances obtained from the two models should differ appreciably. Additional tests are required.

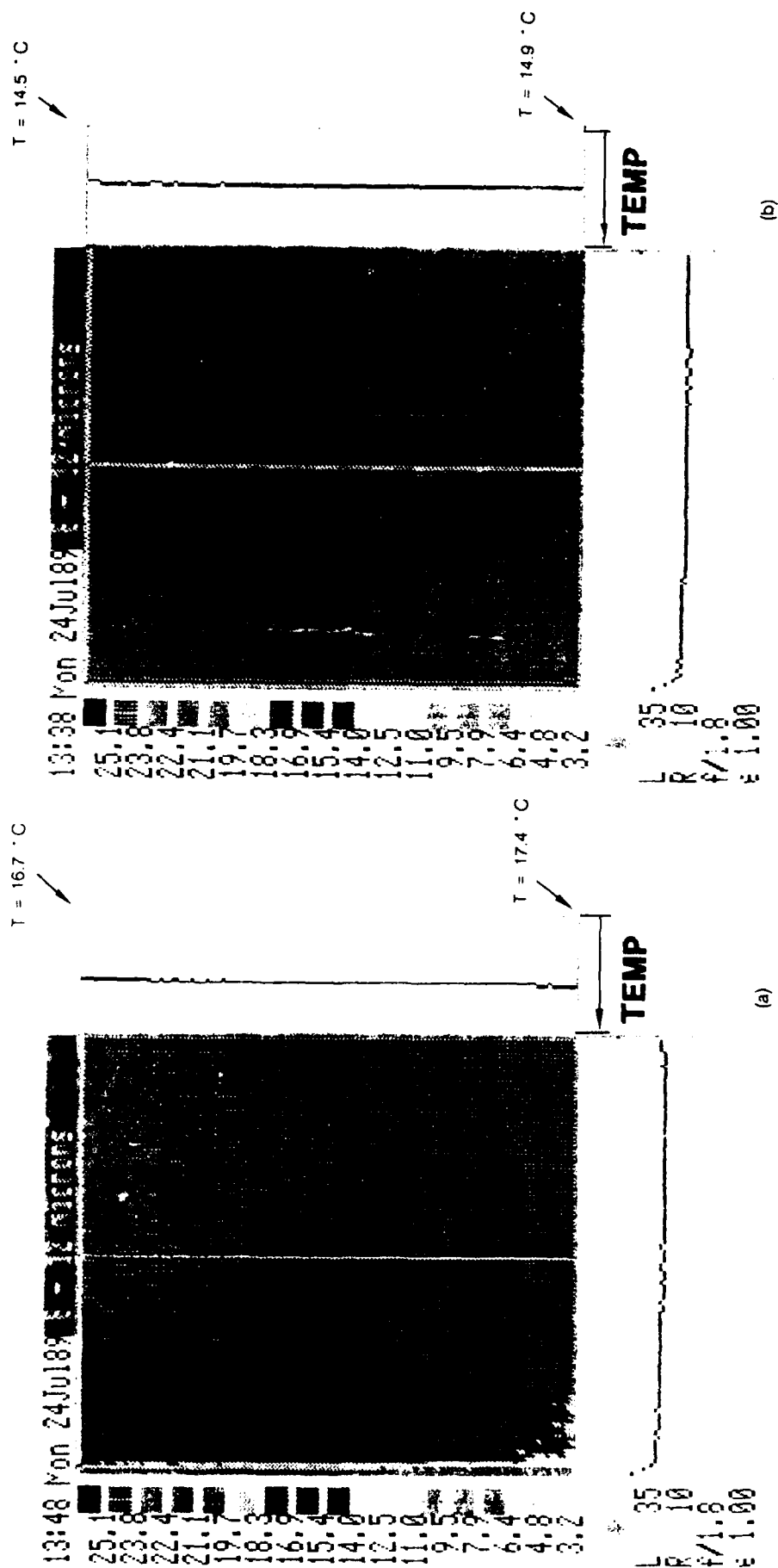
If the simplified model proves reliable, the concept could be used to develop an instrument to make the measurements. Absolute calibration of the device would not be necessary since only the ratio measurements are needed. Basically, a narrow field-of-view, uncalibrated radiometer would be suitable. Figures 7(A) and 7(B) are examples of sky radiances taken with an AGA THERMOVISION Model 780 imaging system with a 2.95-degree field-of-view lens. For these measurements the scanner was located at an elevation of 33 meters on the Point Loma peninsula in San Diego and was directed to the south over the ocean. The response of the system is determined by placing a blackbody of known temperature ( $\pm 0.1^\circ\text{C}$  for temperatures  $< 50^\circ\text{C}$ ) in front of the lens aperture. The digitized video signal transfer function of the system then allows the blackbody temperature to be reproduced to within  $\pm 0.2^\circ\text{C}$ . The temperatures of the different colors in each thermogram are identified by the color bars displayed on the left which correspond to the midpoints of the temperatures printed above and below each bar. The Thermal Video Processor System (THERMOTEKNIX) available with the AGA system allows the thermal scene to be displayed in a format consisting of 128-pixel lines (0.023 degree/pixel line). The effective blackbody temperature corresponding to each pixel can then be displayed on the screen by positioning horizontal and vertical cursors at the appropriate position. Vertical temperature profiles in the scene are displayed on the right-side of each thermogram. Figures 7(A) and 7(B), correspond to radiances centered about 3 and 5 degrees, and demonstrate the strong linear gradients of  $2.64^\circ\text{C/degree}$  and  $2.33^\circ\text{C/degree}$  at these low elevation angles. In these cases, the AGA system was calibrated and the temperatures displayed at the tops and bottoms of the thermograms are exact. As the scanner was raised in elevation, the colder sky temperatures were out of range of the system settings and the thermal levels had to be changed to record the scenes. In figures 8(A) and 8(B), the temperatures displayed are uncalibrated, but their differences are exact, giving much smaller linear gradients of  $0.237^\circ\text{C/degree}$  and  $0.136^\circ\text{C/degree}$  at the 30- and 40-degree elevations respectively. These cases show that, while linear gradients in radiance exist over a small field-of-view, better resolution is obtained for measurements made at larger zenith angles. However, aerosol scattering nearer the horizon may violate the basic assumptions of the model.



SKY RADIANCE 1232PDT 29JUNE1989 3-DEGREE ELEVATION (a)

SKY RADIANCE 1225PDT 29JUNE1989 5-DEGREE ELEVATION (b)

Figure 7. Calibrated thermograms of infrared (8 - 12  $\mu\text{m}$ ) sky radiances at elevation angles of (a) 3 degrees and (b) 5 degrees.



SKY RADIANCE 1242PDT 29JUNE1989 30-DEGREE ELEVATION

SKY RADIANCE 1240PDT 29JUNE1989 40-DEGREE ELEVATION

**Figure 8.** Uncalibrated thermograms of infrared (8 - 12  $\mu\text{m}$ ) sky radiances at elevation angles of (a) 30 degrees and (b) 40 degrees.

## REFERENCE

Kneizys, F.X., E.P. Shettle, W.O. Gallery, J.H. Chetwynd, Jr., J.H. Abreu, J.E.A. Selby, S.A. Clough, and R.W. Fenn. August 1983. *Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 6*, Air Force Geophysics Laboratory Technical Report No. 83-0187.