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## Soil Moisture

TECHNICAL REPORT

# A PARAMETERIZATION OF EFFECTIVE SOIL TEMPERATURE FOR MICROWAVE EMISSION

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ABSTRACT

The observed microwave brightness temperature of soils depends upon the soil temperature profile, which in a remote sensing application will not be known in any detail. In this paper we discuss a parameterization of effective soil temperature, which when multiplied by the emissivity gives the brightness temperature, in terms of surface ($T_0$) and deep ($T_\infty$) soil temperatures as $T = T_\infty + C (T_0 - T_\infty)$. A coherent radiative transfer model and a large data base of observed soil moisture and temperature profiles are used to calculate the best-fit value of the parameter C. For 2.8, 6.0, 11.0, 21.0 and 49.0 cm wavelengths the C values are respectively 0.802 ±0.006, 0.667 ±0.008, 0.480 ±0.010, 0.246 ±0.009, and 0.084 ±0.005. The parameterized equation gives results which are generally within one or two percent of the exact values.

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## INTRODUCTION

The moisture content in the surface layer of soils is an important parameter in rainfall-runoff prediction, agricultural yield forecasting, and boundary layer heat exchange for meteorological and climatic studies. In situ observations of this parameter, although accurate, are not practical for large areas, particularly when global information is needed. Microwave techniques are being studied (Schmugge et al., 1980) to estimate soil moisture for large areas on a timely and cost-effective basis from aircraft and satellite platforms.

A microwave radiometer measures the intensity of microwave radiation emitted from soils. All points within a soil emit thermal radiation, and in the microwave region the intensity of this radiation is directly proportional to the thermodynamic temperature (Rayleigh-Jeans approximation). From the point of origin to the soil surface, the intensity is attenuated by the intervening soil, whose absorption (the imaginary part of the dielectric constant) is related to moisture content. The net intensity (called the effective temperature) at the soil surface is, therefore, a superposition of intensities emitted at various depths within the soil. The energy crossing soil-air interface is determined by an effective emissivity. The observed microwave intensity is the product of this effective emissivity (e) and the effective temperature (T):

$$T_B = eT \tag{1}$$

It is clear that the observed microwave intensity depends upon both soil moisture and soil temperature. Although soil moisture and temperature are not totally independent variables since they are governed by a coupled set of differential equations, for similar surface layer moisture the soil temperature could be widely different due to season, cloudiness and boundary layer heat exchange. If variations in microwave intensity are to be correlated with moisture only, then the observed intensity should be normalized by the effective radiating temperature of the soil. We note that effective temperature depends upon moisture through the soil absorption's dependence on moisture content.

The exact values of effective temperature depends upon the details of the soil moisture and temperature profiles. Detailed information about these profiles is generally not available for the remote sensing of soil moisture. Toward this end, it is desirable to have a method for estimating effective temperature using minimum soil profile information. This paper discusses such a method using surface and deep soil temperatures. The surface temperatures may be observed from remote platforms for clear sky conditions using infrared radiometers or it may be obtained from meteorological data of near surface air temperature. The deep soil temperature can be modeled based on geographic location and season. A model for surface and deep soil temperatures has been discussed by [illegible] (1980).

## PARAMETRIC EQUATION

From radiative transfer theory the effective temperature can be expressed mathematically as

$$T = \int_0^\infty T_s(x)\ \alpha(x)\ \exp\left[-\int_0^x \alpha(x')\,dx'\right]dx \tag{2}$$

where $T_s(x)$ is soil thermodynamic temperature at depth x, and attenuation coefficient $\alpha(x)$ is related to imaginery part of soil dielectric constant $\epsilon''(x)$ as

$$\alpha(x) = \frac{4\pi}{\lambda}\ \epsilon''(x) \tag{3}$$

$\lambda$ being the wavelength of observation.

The effective temperature will be close to the soil surface temperature for small $\lambda$ or high $\epsilon''$ (i.e., wet soil). As $\lambda$ increases or $\epsilon''$ decreases, the effective temperature will be the soil temperature averaged over some depth, called the thermal sampling depth (Wilheit, 1978).

If we consider a soil temperature profile of the form

$$T_s(x) = T_\infty + (T_0 - T_\infty)\, f(x) \tag{4}$$

(where $T_0$ and $T_\infty$ are surface and deep soil temperatures, and $f(x)$ is the functional dependence on depth) then the effective temperature can be written as:

$$T = T_\infty + (T_0 - T_\infty)\, C \tag{5}$$

where

$$C = \int_0^{\infty} f(x)\, \alpha(x)\, \exp\left[-\int_0^{x} \alpha(x')\, dx'\right] dx \tag{6}$$

For given soil profiles, the value of C decreases as wavelength increases. For a given wavelength, C is sensitive to the soil profiles when the effective temperatures are calculated; the exact value of C is important when the difference between surface and deep soil temperatures is large. We treated equation (4) as a parametric equation, the parameter being C.

A coherent radiative transfer model (Wilheit, 1978) was used to calculate exact effective temperatures using 720 soil moisture and temperature profiles observed at USDA facilities in Phoenix, AZ during March 1971 (Jackson, 1973). These profiles are from half-hourly observations throughout the day for fifteen days. The soil was irrigated prior to the experiment, and allowed to dry naturally throughout the observational period yielding a range of profiles from wet and essentially uniform to those at the end which had very hot (50°C) dry surface layer (Figure 1). The soil dielectric constant used in this study is taken from Wang and Schmugge (1980) with texture 32% sand and 22% clay.

A scatter plot of exact effective temperatures and surface temperatures is shown in Figure 2. It clearly illustrates that as the wavelength increases, the effective temperature depends less on the surface temperature, e.g., at $\lambda = 2.8$ cm, a 43° difference in surface temperature, the effective temperature changes about 40° and at $\lambda = 49.0$ cm effective temperature changes by about 8°. The magnitude of C reflects this fact. As the wavelength increases the effective temperature corresponds to a deeper soil layer temperature, which have less diurnal variation.

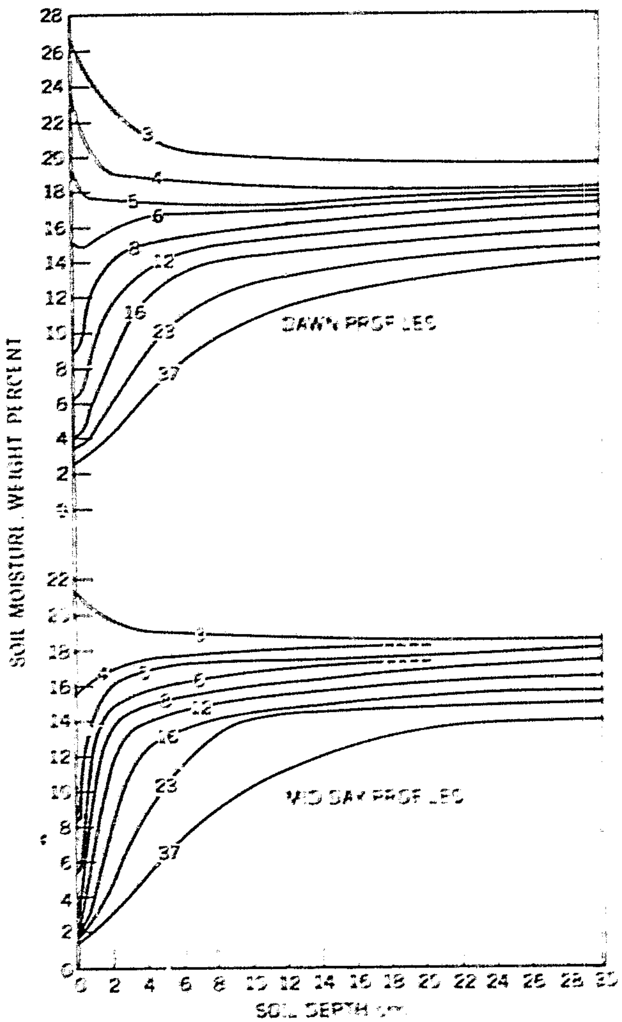


Figure 1a

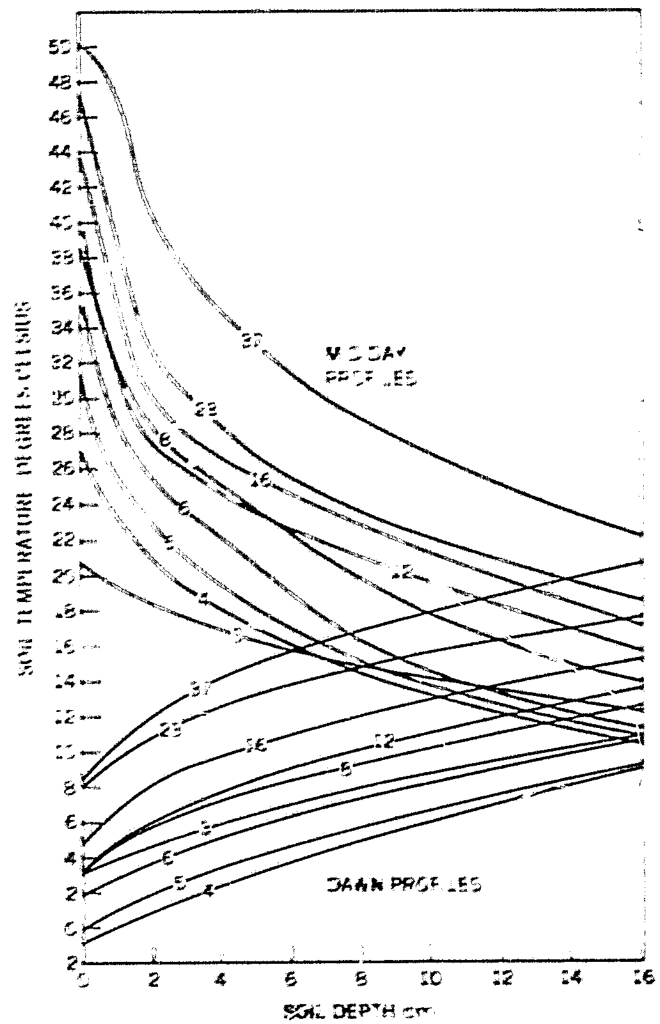


Figure 1b

Figure 1. Representative soil moisture and temperatures profiles observed at Phoenix during March. (a) Moisture, (b) temperature. The curves are labeled by the number of days after irrigation.

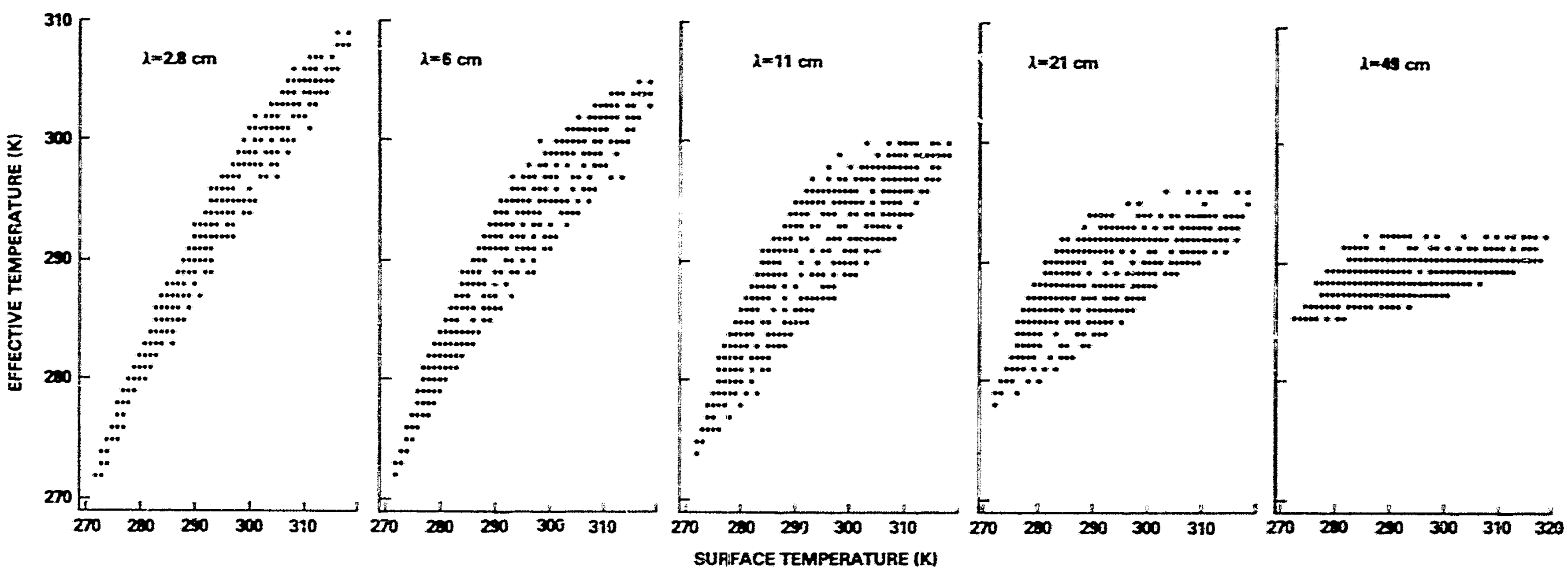


Figure 2. Scatter plots of exact effective temperatures vs surface temperatures for different wavelengths

The parameter C was determined by a least-square analysis of the exact effective temperatures with equation (4). The results are given in Table 1. The soil temperature at the depth of about 130 cm varied between 15.5 to 17.5°C.

## ERROR ANALYSIS AND DISCUSSION

A statistically determined value for C does not reflect the quantitative accuracy of the parametric equation for a specific temperature and moisture conditions of a soil. The diurnal trend of the percentage error, δ, between exact and approximate effective temperatures,

$$\delta = \frac{[T\,(\text{approx.}) - T\,(\text{exact})]\ 100}{T\,(\text{exact})} \tag{7}$$

for wet (March 5), moderately wet (March 11) and dry (March 25) soils are shown in Figures 3a and b for the X- and L-band (2.8 and 21.0 cm) cases. The volumetric water content in the top 2 cm layer varied from about 0.35 to 0.05 $cm^3/cm^3$, and the surface temperature ranged from 272 to 315 K. A moisture dependent error can be seen for both wavelengths. For wet soils the parametric equation results are higher and for dry soils the results are lower than the exact values. High surface temperature for dry soil cases tends to counteract this error, causing an overestimate of effective temperature. The error for L-band is slightly higher (1.5%) than for X-band (1%). These errors are small, compared to the errors resulting from the normalization of brightness temperature by the surface temperature at long wavelengths, e.g., Burke et al. (1979) found cases where the brightness temperature was greater than infrared surface temperature, which would have lead to a ratio of brightness and surface temperatures greater than one. It is therefore important that the ratio of brightness and surface temperatures is not interpreted as the emissivity. The term normalized brightness temperature is used as a synonym for emissivity in this paper.

An indication of the importance of using the normalized brightness temperatures ($T_{Bn}$) or the emissivity rather than straight brightness temperatures ($T_B$) for correlating with soil moisture can be seen in some data acquired with an airborne 21 cm radiometer over a test site in Hand County, South

Dakota. The data were acquired over a 3 year period covering the months of April through October. The infrared surface temperature ranged from 5 to 42°C. The correlation coefficients for $T_{Bn}$ and $T_B$ with surface 0 – 5 cm soil moisture (SM5) are given in Table 2. These results clearly show that by minimizing the effect of soil temperature variations, an improved correlation of brightness temperature with the soil moisture can be obtained.

Parameterization of effective temperature in terms of surface and deep soil temperatures eliminates the need for the details of soil temperature profiles. Although the soil profile data base used in the parameterization is regional (Phoenix, AZ) and of limited season (March), it embodies the characteristics of a naturally drying soil and includes a wide range of surface temperatures. We expect the parametric equation to remain useful for other regions and seasons. This parameterization will aid in the use of microwave radiometer data for inferring soil moisture.

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Table 1

The best-fit values of the constant C in Equation (4)

| Wavelength (cm) | C |
|---|---|
| 2.8 | 0.802 ± 0.006 |
| 6.0 | 0.667 ± 0.008 |
| 11.0 | 0.480 ± 0.010 |
| 21.0 | 0.246 ± 0.009 |
| 49.0 | 0.084 ± 0.005 |

Table 2

The correlation coefficients for normalized ($T_{Bn}$) and unnormalized ($T_B$) brightness temperatures with surface 5 cm soil moisture (SM5)

| | All Data (n = 180) | | | Pasture Only (n = 35) | | |
|---|---|---|---|---|---|---|
| | $T_B$ | $T_{Bn}$ | SM5 | $T_B$ | $T_{Bn}$ | SM5 |
| $T_B$ | 1 | 0.986 | 0.869 | 1 | 0.992 | 0.926 |
| $T_{Bn}$ | 0.986 | 1 | 0.886 | 0.992 | 1 | 0.951 |

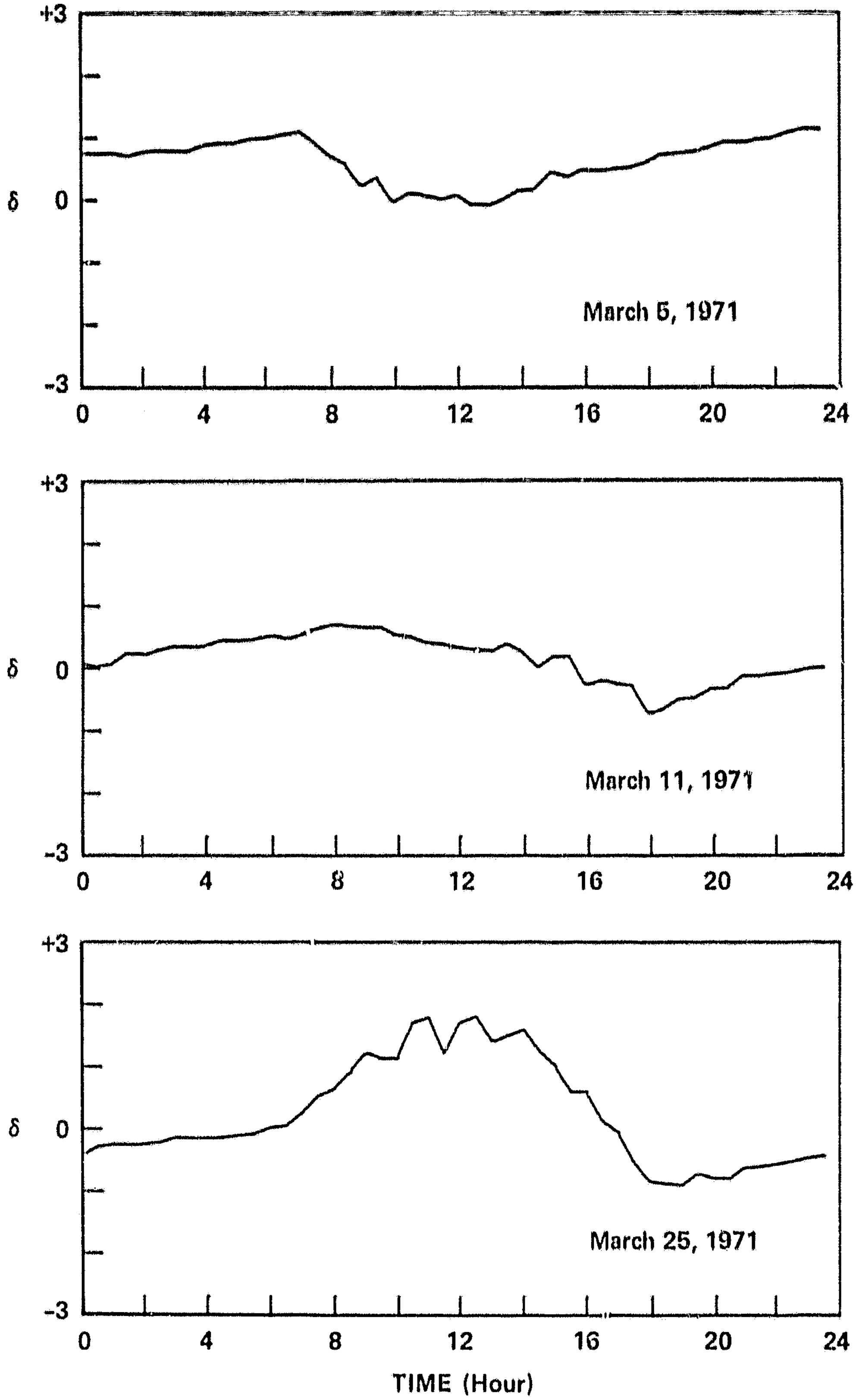


Figure 3a. The diurnal variation of percent error (see Eqn. 6) between exact and parameterized effective temperatures – X-band

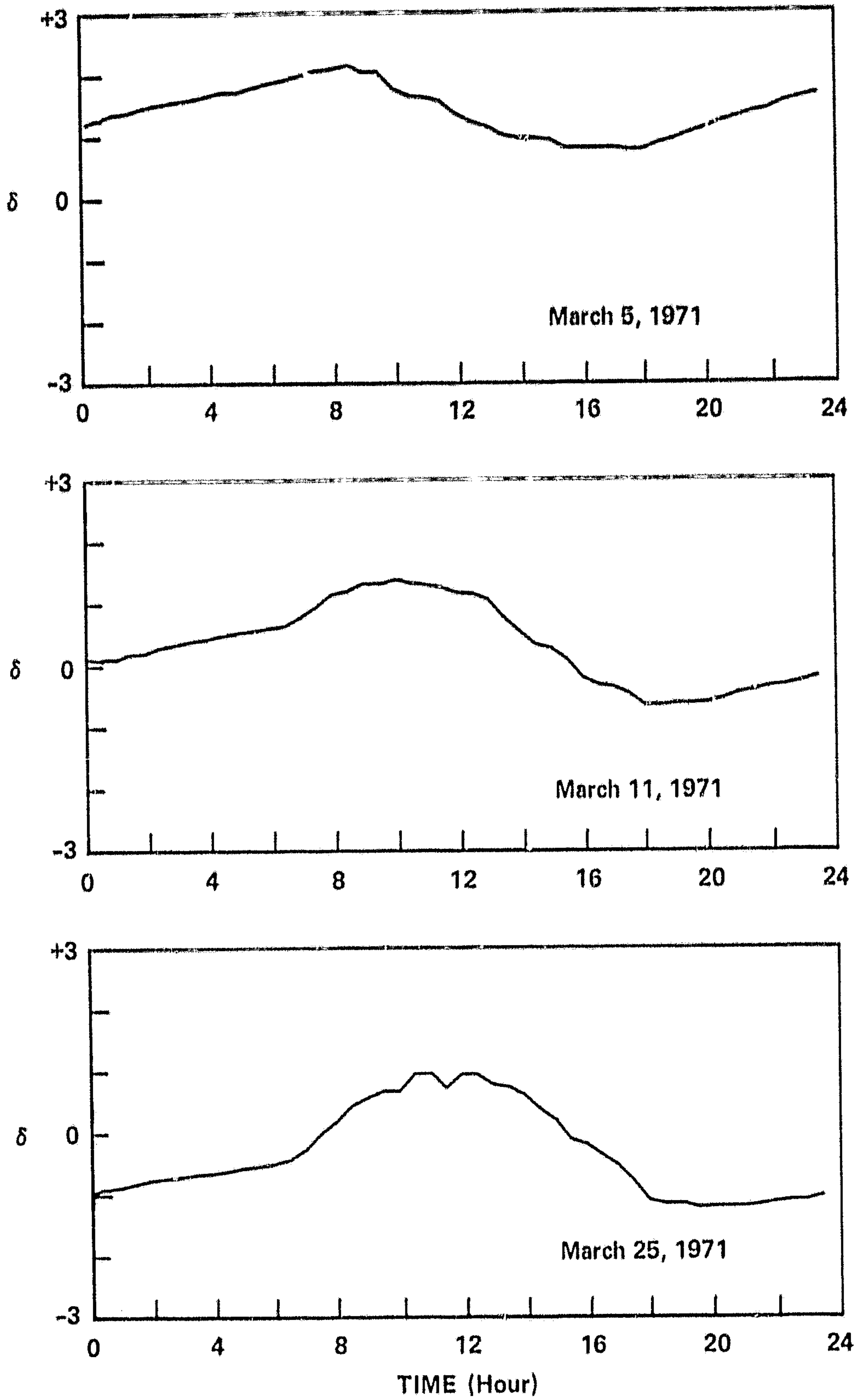


Figure 3b. The diurnal variation of percent error (see Eqn. 6) between exact and parameterized effective temperatures L-band