WHAT IS THE SURFACE TEMPERATURE OF THE MOON?

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Introduction: Surface temperature is fundamental property and we need accurate knowledge of it in order to understand planetary surfaces. In their own right, temperatures can be used to determine near surface thermophysical properties that can lead to an understanding of the processes that form the surface layer and regolith. Infrared measurements also contain spectral features dependent on surface mineralogy that are convolved with temperature dependent radiance. The accurate separation of the temperature and mineralogical signals in the spectra is essential for the determination of both surface temperatures and mineralogy.

This is an important problem for the interpretation of both thermal infrared and near-infrared observations of the lunar surface [e.g., 1-7]. With knowledge of surface temperature, it is possible to separate these two effects, allowing for further analysis of surface mineralogy and thermophysical properties. Methods have been developed to retrieve surface temperatures and, as is often necessary with shorter wavelength data, recover surface reflectance free of residual temperature effects [1,2,4,6].

The lunar surface has two properties that greatly complicate the notion of surface temperature; 1) the surface is extremely rough [3,8], and 2) the regolith is highly insulating [e.g., 9]. These two properties ensure that thermally isolated surfaces can be separated by just a few millimeters and can have vastly different temperatures depending on the local solar incidence angles [10-12] (Fig. 1). Consequently, remote observations of the lunar surface typically have a wide variety of temperatures within the measurement field of view. This leads to properties such as infrared "beaming", for example [13].

The emitted spectral radiance from a surface of mixed temperatures cannot be approximated by a model that only uses a single temperature. Under most circumstances, this assumption will result in a blue slope in the resulting emissivity or thermally corrected reflectance spectra [3,7]. The effects of anisothermality are most severe at short wavelengths and the resulting effects on the spectrum are greatest at high angles of solar incidence with relatively low average temperatures. In fact, the highest temperature surfaces with the lowest angles of solar incidence are the least susceptible to this effect (Figs. 2-3).

Model: In order to properly account for surface anisothermality, it is necessary to account for surface roughness effects. For this work, we use a simple radiative equilibrium model for daytime measurements. This closely approximates the lunar surface temperatures because of the slow rotation and low thermal inertia of the lunar surface. Where the sun is below the local horizon, surface temperature is set to 100K (similar to nighttime surface temperatures). To model roughness, we use a simple Gaussian distribution of slopes similar to that of [8]. This reduces the surface

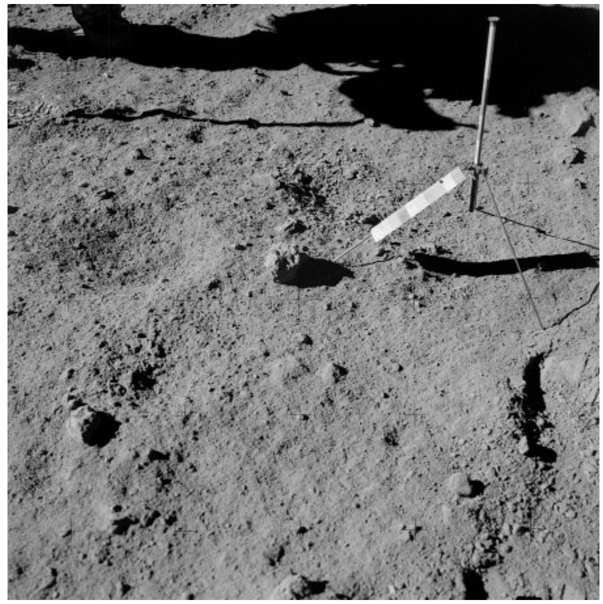

Figure 1. The lunar regolith is both rough and highly insulating. Temperatures of sun-facing versus shaded surfaces in this image can vary by nearly 200K. (Apollo image AS15-82-11105)

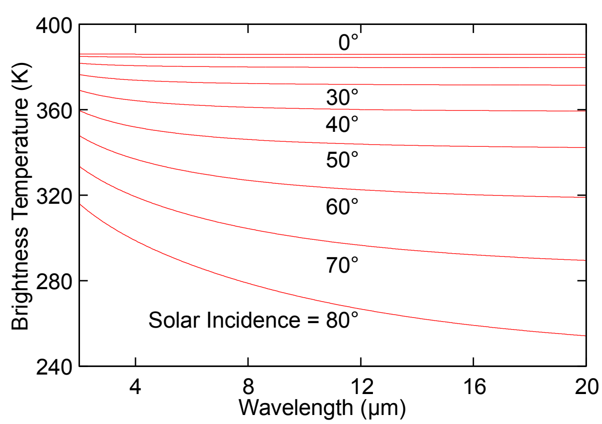

Figure 2. Modeled brightness temperatures for a typical lunar surface roughness (25° RMS). Apparent temperature variations and spectral slopes become severe at high angles of solar incidence and short wavelengths.

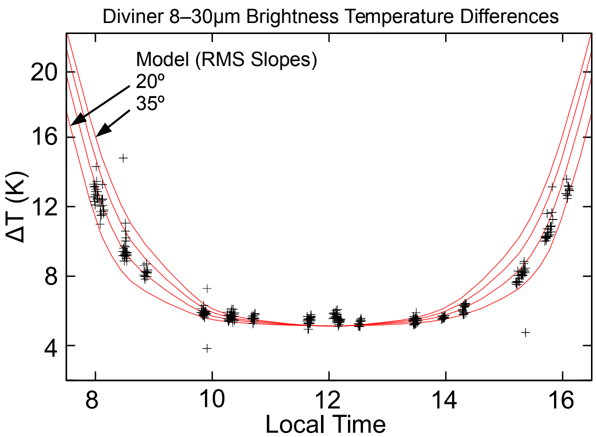

Figure 3. Diviner measurements (black crosses) for 300-315°E, -1 to 1°N compared to thermal roughness models (red lines). In agreement with the modeling, measured brightness temperature differences are most severe outside of local times of ~1000-1400.

slopes/roughness to a single parameter (RMS slope distribution), while maintaining reasonable fidelity to natural surfaces. Using the modeled temperatures for each slope/azimuth combination and slope distributions, the mixture of Planck radiances are calculated in proportion to their contribution to the measurement field of view. The resulting modeled spectral radiance can be directly compared with spacecraft measurements (Fig. 3) [e.g., 7].

Results: Lunar Reconnaissance Orbiter Diviner radiometer data show clear signs of severe anisothermality as expected. Multiple angle observations of a surface have shown brightness temperature variations of up to 65 K with the varying proportion of sub-pixel shaded and sunlit surfaces in the measurement field of view. In addition, shorter wavelength brightness temperatures deviate from longer wavelengths with increasing solar incidence (Fig. 3). Comparison of the modeled brightness temperatures with LRO Diviner measurements shows good agreement with a 25° RMS surface slope distribution, broadly similar to previous work [8].

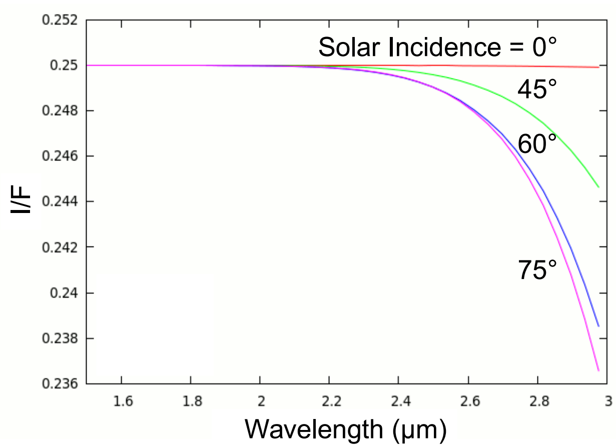

Figure 4. Modeled I/F spectra for a surface with a 25° RMS slope distribution and a constant reflectance of 0.25. Modeled spectra were corrected for emitted radiance assuming an isothermal surface and the brightness temperature derived at 2 μm wavelengths. The assumption of an isothermal surface results in significant slopes present in the resulting corrected spectra that is highly dependent on solar incidence.

Implications: Interpretation of thermally corrected lunar surface reflectance or emissivity spectra must either incorporate roughness modeling or be restricted to low angles of solar incidence. Accounting for roughness is essential for the interpretation of lunar compositions, but has not been implemented for the thermal correction of lunar near infrared measurements [2,4,6].

The lack of accounting for surface roughness is likely to be at least part of the cause of the variable intensity of the 3 μm OH^- absorption on the Moon. Although a distinct absorption feature is present and is clearly attributed to H_2O/OH^- [14-16], the variability in its strength shows a pattern and magnitude similar to that expected from surface roughness effects (Fig. 4). For example, the blue slope will be most intense at high latitudes and during early morning/late afternoon.

Similar effects are likely to be present in NIR measurements of any airless body, and a better understanding of the effects of roughness and anisothermality on emitted radiance can lead to greatly improved corrections and derivation of surface temperature distributions in these datasets.

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