A WAVELENGTH DEPENDENT VISIBLE AND INFRARED SPECTROPHOTOMETRIC MODEL FOR THE MOON BASED ON ROLO DATA.

B.J. Buratti[1], M. Staid[2], C. M. Pieters[3], M. D. Hicks[1], T. S. Stone[4], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Mail Stop 183-501, Pasadena CA 91109. [2]Planetary Science Inst., Tucson, AZ, USA. [3]Brown University, Providence RI, USA. [4]USGS, Flagstaff AZ, USA. [Bonnie.J.Buratti@jpl.nasa.gov]

Introduction: Much of the variation in specific intensity and spectral albedo on the Moon is not intrinsic but rather due to changing radiance viewing geometry. In order to detect and map subtle spectral features of minerals and volatiles across the lunar surface, such as iron-and titanium-bearing minerals and water ice, a quantitative model describing the directional properties of reflected solar radiation must be developed as a function of wavelength. With NASA placing increased importance on lunar studies, specifically mapping of surface components that hold scientific value for future exploration, it is important to develop such a model for use with a wide spectrum of lunar cameras and spectrometers.

NASA's Moon Multispectral Mapper (M3), an imaging spectrometer scheduled to be launched with the Indian Space Agency's Chandrayaan-1 spacecraft later this year [1], provides motivation to develop a spectrophotometric model across the visible and near IR. The database used for the model was produced from the USGS's Robotic Lunar Observatory (ROLO) dedicated ground-based lunar calibration project [2,3].

ROLO Data: The need for a well-characterized calibration target for space-based and ground-based remote-sensing studies was realized decades ago. A dedicated program to gather photometric data for the Moon over the spectral range attainable from Earth (0.347 – 2.39 µm) and over solar phase angles of 1.55-97 degrees, was initiated by Hugh Kieffer and his colleagues [2]. Extensive measurements have been published [e.g. 3], and calibrated telescopic images and additional data provided by the USGS has been used for this study. In particular, 11 lunar regions were the subject of focused analysis by Kieffer and Stone [3] providing extensive radiometric measurements and phase information for these sites.

The Photometric Model: We obtained 36,000 photometric data points from the ROLO observations for each of the 11 reference regions defined in [3]. Exoatmospheric radiance data from [3] was further calibrated to units of reflectance through normalization over a solar irradiance model. The observations were corrected for "limb-darkening" (changes in specific intensity due to changes in the incidence and emission angle) and solar phase angle effects using the following equation:

$$R(\lambda, \text{lat},\text{long},\alpha) = I/F(\lambda,\text{lat},\text{long},\alpha)(\mu_o+\mu)/\mu_o * f(\lambda,\text{Apollo16},30^o)/f(\lambda,\text{Apollo16},\alpha)$$

where R is the reflectance at the specific measurement location (given by the geographical latitude and longitude) and wavelength (λ) corrected for limb-darkening and normalized to ROLO Apollo 16 measurements at 30º based on the ROLO-modeled solar phase behavior of the Apollo 16 site. The photometric geometry is defined by the cosine of the incidence angle (μ_o), the cosine of the emission angle (µ), and the solar phase angle (α). For spacecraft, these parameters are given by auxiliary pointing information associated with the instrument scientific data. The correction for limb-darkening is given by the $(\mu_o+\mu)/\mu_o$ term, which defines lunar or "Lommel-Seeliger" scattering behavior. The reference solar phase angle of 30 degrees was chosen because the Brown University RELAB measurements of the Apollo 16 samples were obtained at that viewing geometry [4]. The Apollo 16 site was chosen as the fiducial region because "ground-truth" laboratory measurements for it are the most extensive.

Analysis and modeling of the lunar solar phase function proceeded along the following steps:

1. Solar phase functions (fλ(α)) were extracted for each of the 11 sites
2. Equations (4th-order polynomial and an exponential term) were fit to fλ(a) for each region at each ROLO wavelength. Interpolations were done to produce fits at one nanometer resolution.
3. Since the Apollo 16 landing site was not one of the ROLO focus regions, a mixing model of fλ(α) for this site was created by seeking consistency with the measured spectrum of the landing site at 30º. The model's components were the fλ(a) for the highlands and mare.
4. A file giving the solar phase corrections at 1º in α and 1nm in spectral granularity was produced. The range is 0-90º and 0.347-2.39µm (from ROLO).

In addition, analysis of reddening in both highlands and maria was done.

An example of the ROLO disk resolved solar phase function is given in Figure 1 for data obtained in Mare Serenitatis. Note that both waxing and waning curves are shown, and that there is some disagreement between the two curves for reasons that we are still investigating. Although full-disk solar phase curves can be expected to exhibit differences due to the placement of different terrains on the lit portions of the waxing and waning Moon, disk-resolved measurements should not exhibit these differences. For our analyses, we used the waxing measurements.

Figure 2 shows the surface phase function in increments of 10 degrees of solar phase angle for the Mare Serenitatis region. Figure 3 shows the same data for the Apollo 16 region; this data was created by mixing the highland and mare solar phase functions in a combination that gave consistency with the measured spectrum of the landing site at a solar phase angle of 30 degrees (step #4 above).

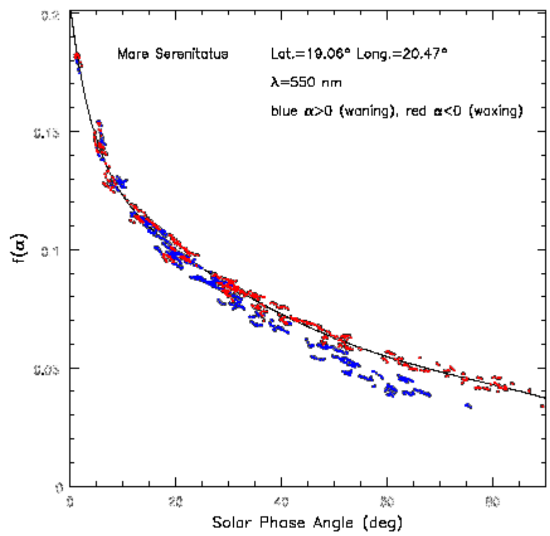

Figure 1. The solar phase curve of Mare Serenitatis, extracted from the ROLO 550 nm data.

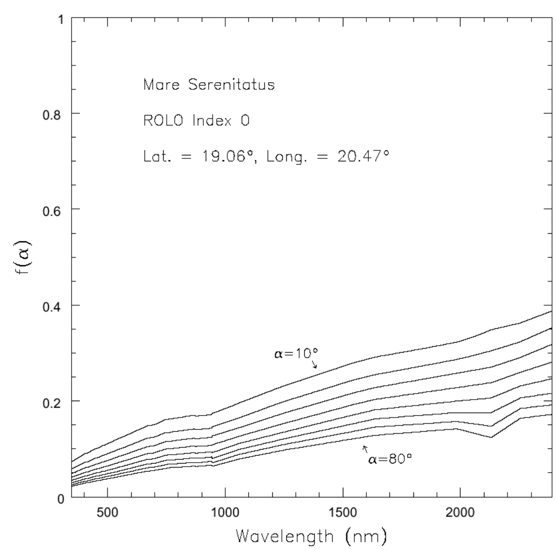

Figure 2. The unsmoothed solar phase function of the same region, as a function of wavelength at 10º intervals.

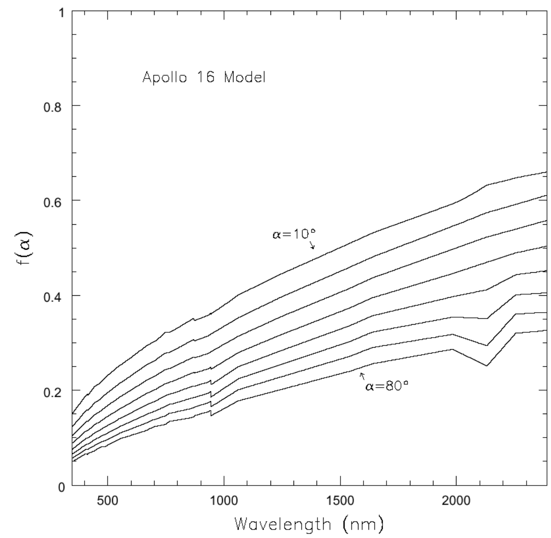

Figure 3. The unsmoothed solar phase function of the Apollo 16 landing site, shown as a function of wavelength at 10º intervals.

Applications: Detailed spectroscopic analyses of the Moon require a smooth file of the solar phase correction factor f(λ,Apollo16,30º)/f(λ,Apollo16,α) at ~one nanometer increments in wavelength and one degree increments in solar phase angle. An initial draft of such a file is illustrated graphically in Figure 4. Remaining issues that need to be worked are improved smoothing of the data; validation of extrapolation to 3 µm; and differential phase reddening.

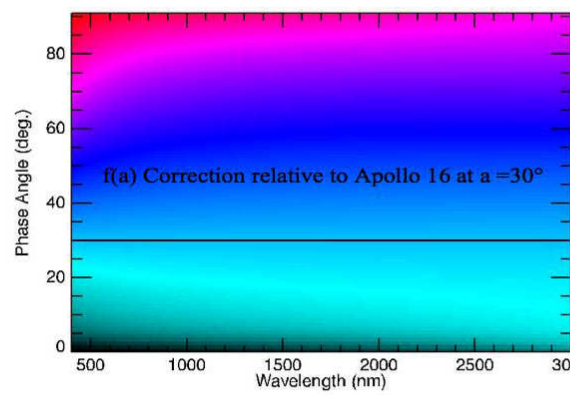

Figure 4. An initial smoothed relative solar phase correction factor based on the above photometric model for Apollo 16. Color indicates intensity of the correction.

Reference: [1] Pieters, C.M., et al. (2006) LPSXXXCII #1630; (2007) *LPSC XXXVIII* #1295. [2] Kieffer, H.H. and Wildey R.L. (1996), J. Atm. And Ocean Tech., 13, 360-375. [3] H. H. Keiffer and T.S. Stone (2005). *A. J.* 129, 2887-2901. [4] Pieters 1999, http://www.planetary.brown.edu/ relabdocs/Apollo16_62231.html