Recalibrating the Moon's Thermometer: LRO Diviner Nonlinear Detector Response and Opposition Effect Corrections.
S. Gyalay[1], M. Aye[2], and D. A. Paige[1], [1]University of California, Los Angeles (szilard3@ucla.edu), [2]University of California, Boulder.

Overview: The Lunar Reconnaissance Orbiter (LRO)'s Diviner Radiometer has observed the Moon for the past eight years, continuously measuring lunar radiance across 9 channels (of 21 thermophile detectors each) from the visible to far infrared wavelengths (0.35 to 400 μm) [1]. This data is used to characterize the Moon's thermal environment and composition.

Within the same channel, we expect thermophile detectors to return measurements with only slight differences due to the spread of the detectors' views of the lunar surface. However, the spread of observed brightness temperatures is greater at higher temperatures of the longer wavelength channels. Furthermore, we see channels 8 (50-100 μm) and 9 (100-400 μm) measurements exceed those of channels 3-5 (7.8, 8.25, and 8.55 μm respectively) at low solar phase angle (the angle between the observer, the observed, and the sun), where channels 3-5 were designed to detect the emissivity maximum of lunar materials. Herein, we exhibit probable causes of these issues, and demonstrate how they can be corrected (Figure 1).

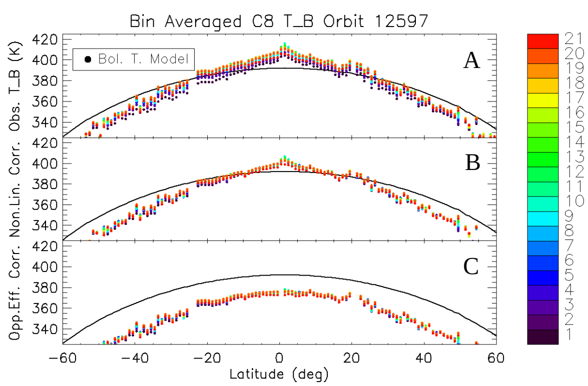

Figure 1: A: Channel 8 brightness temperature (per each of 21 detectors, with binned averages per degree latitude) of a single LRO orbit which passed over the noon equator, with a modeled bolometric temperature [2] for comparison of general shape. **B:** The same orbital data after we apply a nonlinear detector response correction. **C:** The same orbital data after applying both the nonlinear detector response and opposition effect corrections.

Nonlinear Detector Response Correction: The signal detected by a thermophile (or detector response) scales linearly with the radiance incident upon the thermophile. However, systemic errors will introduce nonlinearities within this detector response. These may include how different parts of the instrument respond to being heated. These nonlinearities manifest mostly in longer wavelength channels due to their lower signal. We can derive the nonlinear detector response of each of Diviner's detectors from pre-flight radiometric calibration, and then correct for it in our lunar data.

In-flight, Diviner performs a two-point radiometric calibration to correct for thermal and electronic drift. A space observation is used as the zero reference, and an observation of the internal blackbody (of which the temperature is also recorded) is used to calculate signal gain.

During pre-flight radiometric calibration, Diviner observed two external blackbodies in addition to its internal blackbodies (held constant here and in space at around 300 K). One external blackbody (the fixed, cold blackbody) was held constant at 90 K to simulate space, while the other (the variable, warm blackbody) ramped up in temperature to simulate the lunar surface. Of the three ramps, the first ramp examined the broadest range of variable blackbody temperature from 20 K to 420 K.

As it does while orbiting the Moon, Diviner determines the radiance of the variable blackbody by multiplying its signal by a gain, converting that signal to radiance. In this case, the gain is $B(T_I)/(C_I - C_F)$, where $B(T)$ calculates the radiance of a perfect blackbody at temperature T for a given channel by convolving Diviner's channel bandpass with the Planck curve for T, T_I is the internal blackbody temperature, and C_I and C_F are the signal counts from the internal and fixed blackbodies, respectively. The gain is multiplied by the signal counts from the variable blackbody C_V (also offset by C_F) to find our observed radiance of the variable blackbody as

$$R_O = (C_V - C_F) * B(T_I)/(C_I - C_F).$$

As we know the temperature of the variable and fixed external blackbodies (T_V and T_F respectively), we can model the radiance of the variable blackbody as $R_M = [B(T_V) - B(T_F)] * B(T_I)/[B(T_I) - B(T_F)]$. The function that transforms the radiances observed during pre-flight radiometric calibration to those modeled from the blackbody temperatures during calibration will correct the nonlinear detector response per detector of Diviner. After correcting for the emissivity of the external blackbodies relative to Diviner's internal blackbody, we fit this function with a 6^{th} degree polynomial, from which we can correct observed brightness temperatures (Figure 2).

Opposition Effect Correction: We found that channels 8 and 9 rises in brightness temperature above channels 3-5, where the maximum emissivity of most lunar materials lies. However, this only happened in the hottest regions of the Moon—close to the equator and near Noon. Furthermore, this effect was greater in highlands than in *maria* (Figure 3A, B). If this were a property of the lunar regolith, it is not likely that channel 8 and 9's emissivity would change so greatly relative to the other channels. This increase in channels 8 and 9 brightness temperature above the other channels correlates with channel 2 reflected solar radiance both as a function of solar phase angle and location. We interpret this correlation as due to incomplete blocking of reflected solar radiation. The sharp increase in reflected solar radiance at low phase angle is due to the opposition effect, and is stronger in the highlands than the *maria* (Figure 3C, D) [3]. Whether light is leaking through the blocking filters (less than 1% of channel 1 or 2's radiance is needed to produce the extra radiance we see) or is simply heating the filters which then reradiate in the thermal wavelengths has yet to be determined.

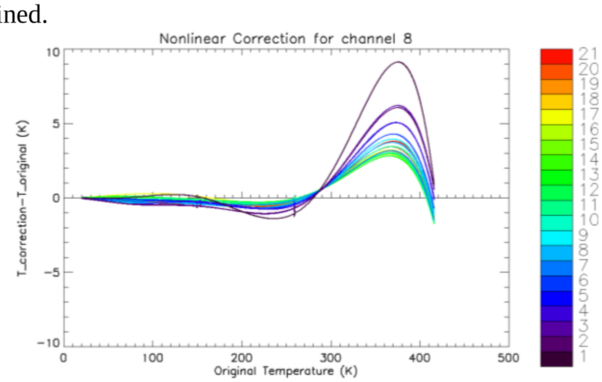

Figure 2: For each of channel 8's 21 detectors, we plot the difference between these corrected and observed brightness temperatures is as a function of originally observed brightness temperature. This is accomplished by taking a brightness temperature and using our nonlinear detector response correction on the observed brightness temperatures corresponding radiance. This corrected radiance can then be converted back to a brightness temperature.

We can remove this unblocked reflected solar radiance in channels 8 and 9 using data from channel 2 However, channel 2 and channels 8 or 9 will observe the same point on the Moon at slightly different solar phase angles *g*. We can adjust the brightness of a channel 2 measurement to be as if viewed at the same phase angle as a channel 8 or 9 measurement. This adjustment is made by finding how bright a channel 2 observation R_2 is relative to two phase curves: one derived for highlands $R_H(g)$, and another for *maria* $R_M(g)$ (Figure 3C, D). This provides a fractional highlands weight W_H where 1 is on or above the highlands phase curve, and 0 is on or below the *maria* curve. We then use a linear combination of these two phase curves, adding the difference in brightness across the difference in phase angle to the original channel 2 observation:

$$R_2' = R_2 + \Delta g\left[W_H\frac{dR_H(g)}{dg} + (1-W_H)\frac{dR_M(g)}{dg}\right]$$

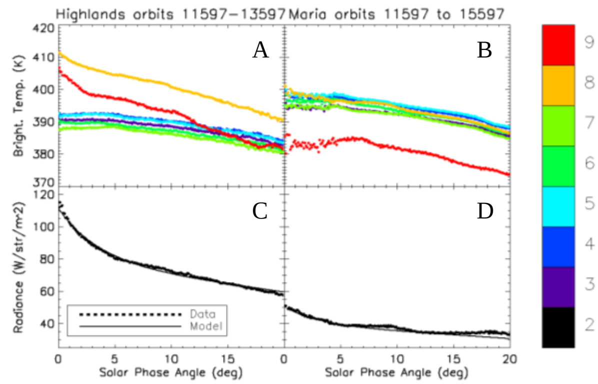

Figure 3: Brightness temperature of channels 3-9 at low phase angles in both highlands (**A**) and *maria* (**B**). Note that while channels 3-7 plateau in brightness temperature at low phase angles, channels 8 and 9 continue to increase, correlated with the increase seen in channel 2 radiance (**C**, **D**).

We average these adjusted channel 2 radiances R_2' within a fraction of a degree latitude and longitude and within the same orbit for each individual channel 8 or 9 measurement *R*, and subtract *R* by the average R_2' multiplied by a scaling factor χ. For channel 8, $\chi \cong 0.0007$, and for channel 9 $\chi \cong 0.0002$.

$$R' = R - \chi\sum R_2'$$

Conclusions: Correcting for nonlinear detector response brings together diverging detector measurements within the same channel, while correcting for the lightleak removes the unexpected radiance in channels 8 and 9 that correlate with the opposition effect in channels 1 and 2 (Figure 4).

Future Work: While the second and third preflight radiometric calibration ramps did not cover the same variable external blackbody temperature range as the first ramp (20-420 K for Ramp 1, 90-300 K for Ramp 2 and 3), we find differences in the nonlinear response that we derive for each ramp. This is likely due to the difference between focal plane temperatures between ramps (284 K for Ramp 1, 334 K for 2, and 305 K for 3). The functional form of how the nonlinear detector response varies with focal plane temperature is yet to be ascertained.

References: [1] Paige (2009) *Lunar Reconaissance Mission*, 125. [2] Hurley et al. (2014) *Icarus 255*, 159. [3] Hapke (2009) *The Theory of Reflectance and Emittance Spectroscopy*. [4] Burrati et al. (1996) *Icarus 124*, 490.