Recalibrating the Moon's Thermometer: LRO Diviner Nonlinear Detector Response and Opposition Effect Corrections

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Big Picture

-Created a procedure to recalibrate Diviner thermal channels to account for two sources of error in radiance detection (Fig. 1):

-Nonlinear Response of Detectors

-Opposition Effect

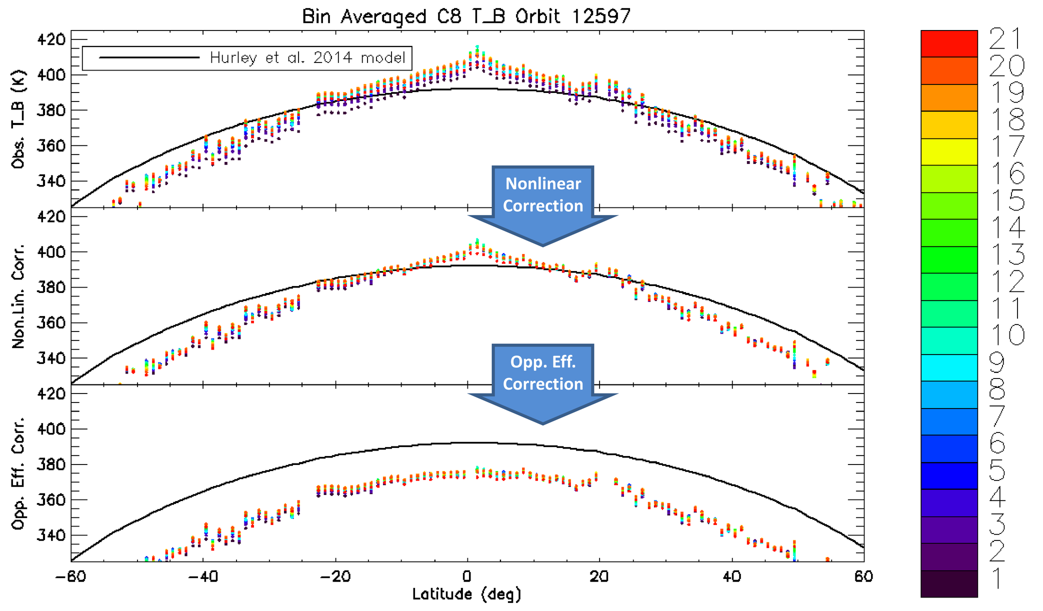

Figure 1: Binned brightness temperature data of a particular LRO orbit. The black line is a model of lunar temperature at the latitude and longitude of the data points [1]. Colored dots represent binned averages of brightness temperature for each detector of channel 8. Top: original detected brightness temperatures, Middle: brightness temperatures after a nonlinear detector response correction, Bottom: brightness temperatures after both a nonlinear detector response correction

Background

-Lunar Reconnaissance Orbiter (LRO) Diviner has 9 channels:

-2 channels measuring reflected VNIR radiation (1-2)

-7 channels measuring emitted IR radiation (3-9) [2]

-Each channel observes a bandpass with its 21 thermophiles.

Nonlinear Detector Response

-Motivation: During pre-flight radiometric calibration, detected radiance was not equal to modeled radiance (Fig. 2).

-Partly due to lower emissivity of target blackbodies during calibration.

-Detected radiances were not (within reasonable error) identical across all detectors of a channel, lead to "striping" in the data.

-Correction: Fig. 3 demonstrates how correcting for the nonlinear response in Fig. 2 affects the observed brightness temperature.

-Fig. 4 shows how the nonlinear detector response correction ameliorates the spread in detector response.

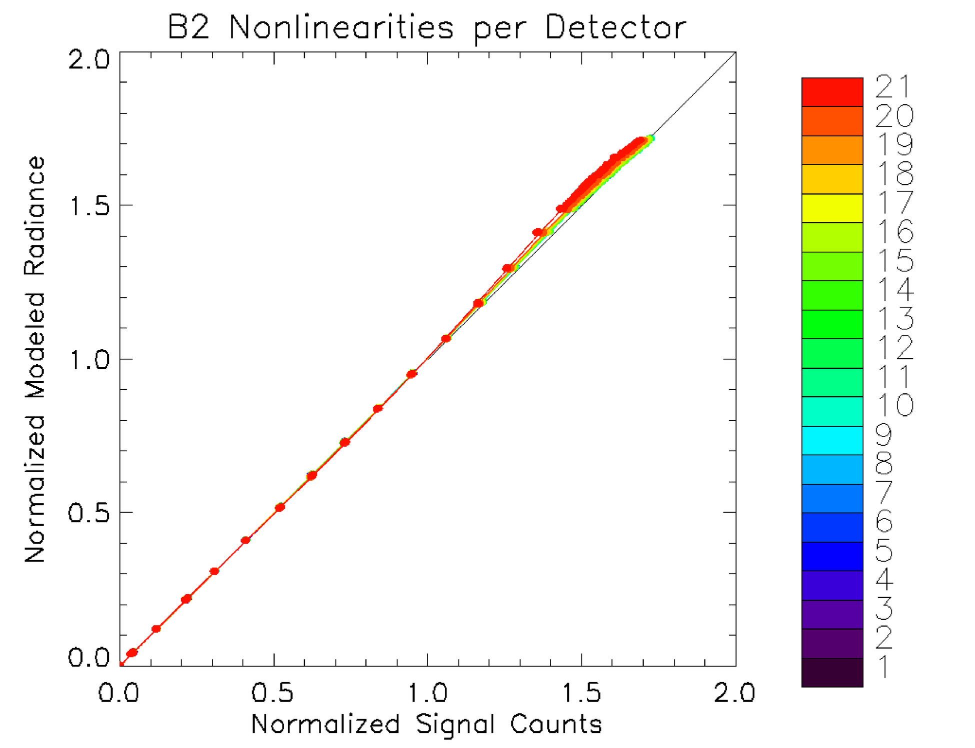

Figure 2: Normalized modeled radiance as a function of normalized signal counts (corrected for the calibration blackbody emissivity). There is a nonlinear response between the radiance emitted by the calibration blackbodies and what is observed. This can be corrected for using a polynomial fit (line) of this data (points).

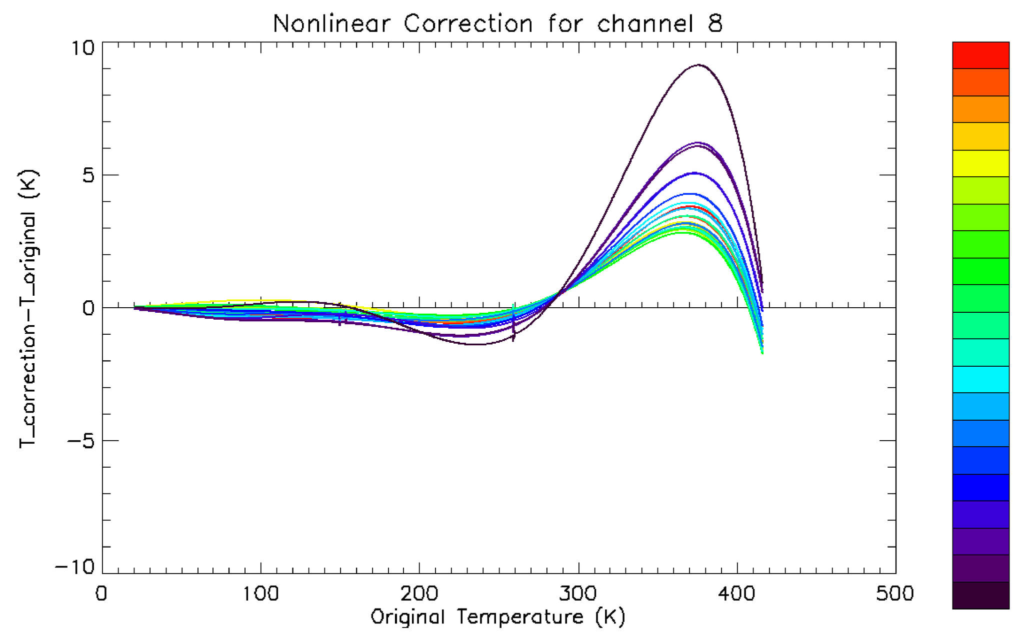

Figure 3: How accounting for the nonlinear detector response exhibited in Fig. 2 affects observed brightness temperatures in Ch 8.

Opposition Effect

-Motivation: Channels 8 and 9 feature unexpectedly high brightness temperatures close to the equator around midday (Fig. 5).

-Higher when observing highlands than maria

-Reminiscent of Opposition Effect known to exist in VNIR wavelengths, as seen by Clementine [3]

-We know opposition effect would not occur in thermal wavelengths due to conductivity of Lunar regolith [4].

-Interpret correlation between ch 2 radiance and ch 8-9 brightness temperature as incomplete blocking of reflected solar radiation.

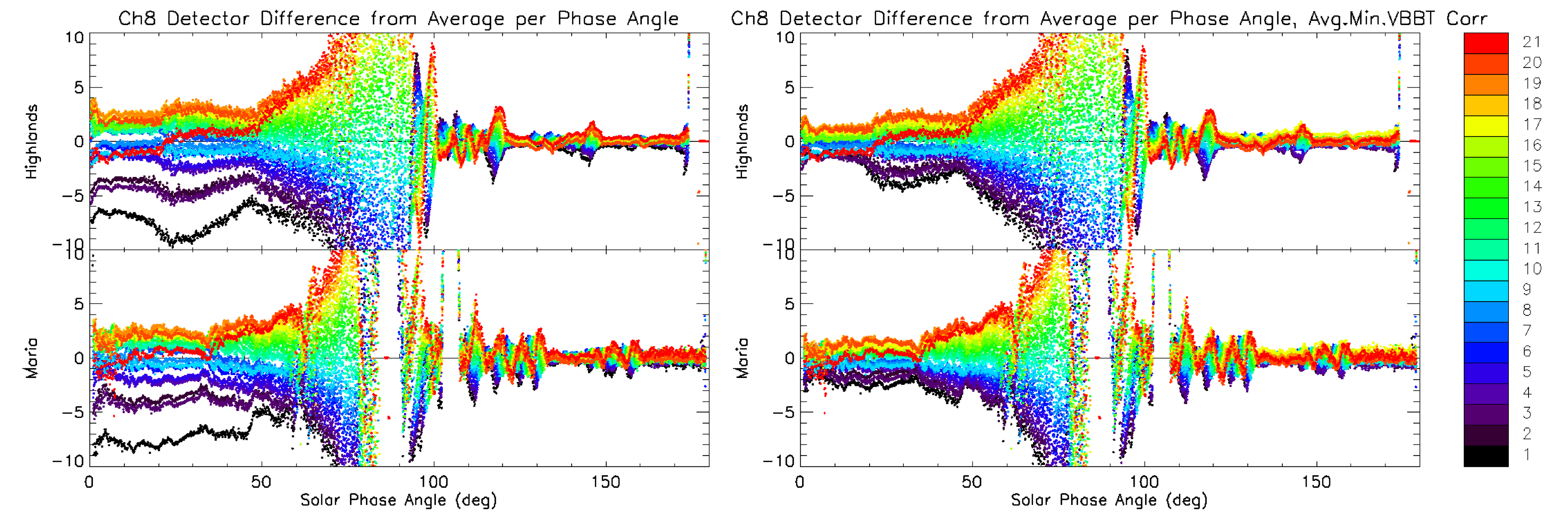

Figure 4: For each phase angle bin of channel 8 data from orbits 11597 to 17597, we isolate data between highlands (top) and maria (bottom), and then compute the binned average brightness temperature per diviner detector as well as the average brightness temperature across all detectors, and then we find the difference between the detector average and the overall average. The left has no nonlinear response correction, and the right is after the nonlinear correction. This further shows that despite varied solar beta angle across the 6000 orbits, our correction reduces detector striping.

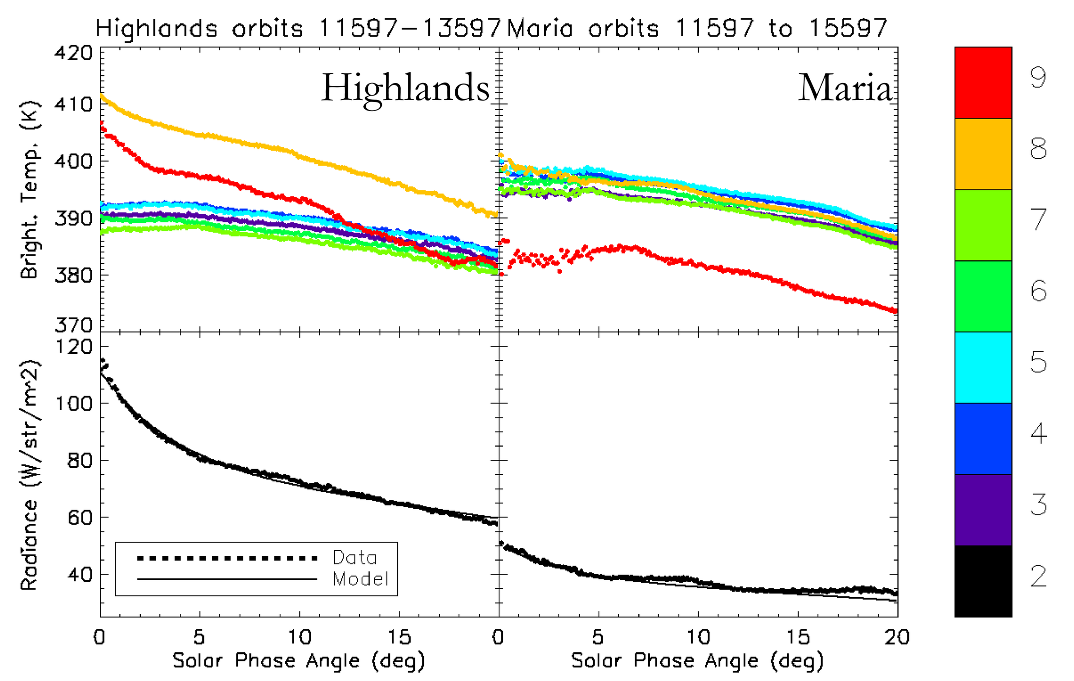

Figure 5: Top: Solar-phase-angle-binned average ch3-9 brightness temperatures for both Highlands (left) and Maria(right). Bottom: Binned average ch2 radiance, including model.

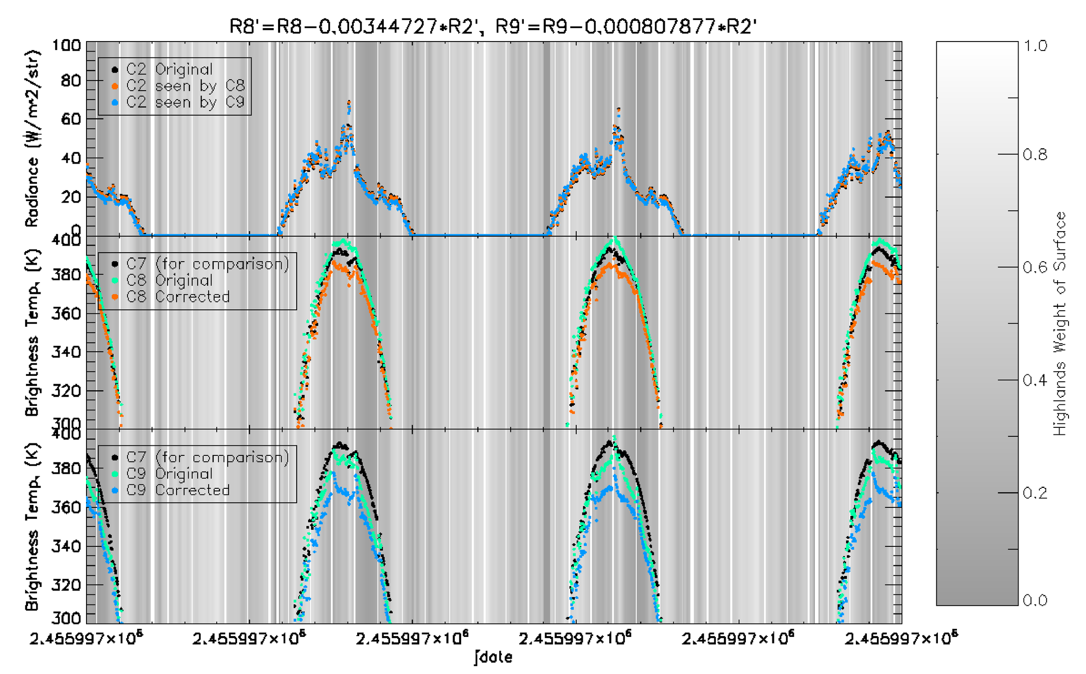

Figure 6: Top: Ch 2 radiance in black. In red and blue are how these radiances would appear to Ch 8, 9 respectively due to the difference in phase angle. Middle: Ch 7 brightness temperature data in black. Original Ch 8 data in green, with lightleak-corrected data in red. Bottom: Same as middle but for Ch 9 with correction in blue. Background: Shade of grey shows how dark the regolith observed is.

-Correction: We correct for the channel 8 and 9 radiance by subtracting a factor multiplied by the channel 2 radiance taken along the same orbit, which has been adjusted as to be viewed by the same phase angle as channel 8 or 9 (Fig. 6).

Conclusions

-Correcting for the nonlinear detector response brings together the diverging detector responses.

-Correcting for the light leak accounts for the extra radiance in channels 8 and 9 that correlate with higher channel 2 radiance at low phase angle, especially over lunar highlands.

Next Steps

-Determine the factor by which to correct for the opposition effect, as well as create a more efficient correction procedure.

-Comparison of lunar emissivity spectra to laboratory spectra.

References

[1] Hurley et al. 2015, *Icarus 255*, 159. [2] Paige et al. 2009, *Lunar Reconnaissance Orbiter Mission*, 125. [3] Buratti et al. 1996, *Icarus 124*, 490. [4] Hapke 2009, *Theory of Reflectance and Emittance Spectroscopy*. [5] Betts et al., *J. Phys. E: Sci. Instrum. 18*, 689. [6] Nightingale & Crawford 1991, *Metrologia 28I,* 233. [7] Greenhagen et al. 2010, *Science 329*, 1507.

Methodology

Current In-Flight Calibration

-$gain = \frac{B(T_I)}{C_I - C_S}$, where $B(T_I)$ is modeled radiance at internal blackbody temperature, and C_I and C_S are counts of radiation measured from the internal blackbody and space, respectively.

-Radiance $R = (C_M - C_S) * gain$, where C_M is counts of radiation from the moon.

Pre-Flight Radiometric Cal.

-Fixed blackbody (~90K) is used to simulate space (Fig. 9)

-Variable blackbody (20-420K) used to simulate the Moon (Fig. 9)

-Internal blackbody held constant (around 300K) in each of three calibration ramps (Fig. 9)

Nonlin. Det. Response Corr.

-Relative emissivity of external blackbodies as compared to internal blackbody found by guessing until the model could be nonlinearized to match observations. Emissivity of black paint in blackbodies not known past 50 µm [1, 5, 6].

-Instead of using our "space" of 90K, use the an average of the variable blackbody radiance of within the lowest 1K it reached (around 20K) for space for calibration of lab data.

-Normalized modeled rad: $R_{M,N} = \frac{B(T_V)-B(T_F)}{B(T_I)-B(T_F)} \frac{B(T_I)}{B(T_N)}$

-Normalized signal counts: $R_{C,N} = \frac{C_V - C_F}{C_I - C_F} \frac{B(T_I)}{B(T_N)}$

-Nonlinearity fitting: $R_{M,N} * \varepsilon = \beta(R_{C,N})$, where $\beta(R) = \sum_{i=1}^{6} b_i R^i$

-ε found where $\frac{C_V(T_I) - C_F}{C_I - C_F} = \frac{\beta^{-1}(\varepsilon B(T_I))}{\beta^{-1}(B(T_I))}$

-Thus, $R_{N,\,corrected} = \beta(RN_{,\,detected})$

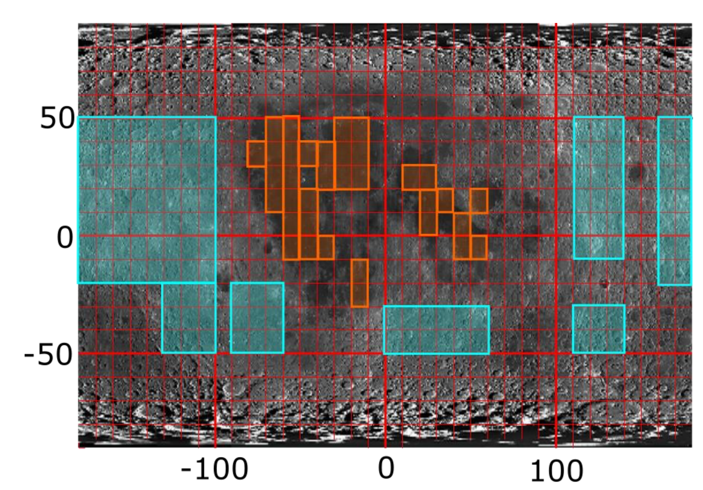

Figure 7: Clementine Lunar Albedo Map. Orange marks regions of the moon where data was used to form the maria phase curve in Fig. 5, while blue marks regions used to form highlands phase curve.

Opposition Effect Correction

-For each ch 8 (or 9) radiance measurement, we can find how the ch 2 radiance would look like from the viewing geometry of Ch 8 (or 9). Each ch 8 (or 9) radiance corrected using all ch 2 radiances within a 1/32 degree bin during that orbit.

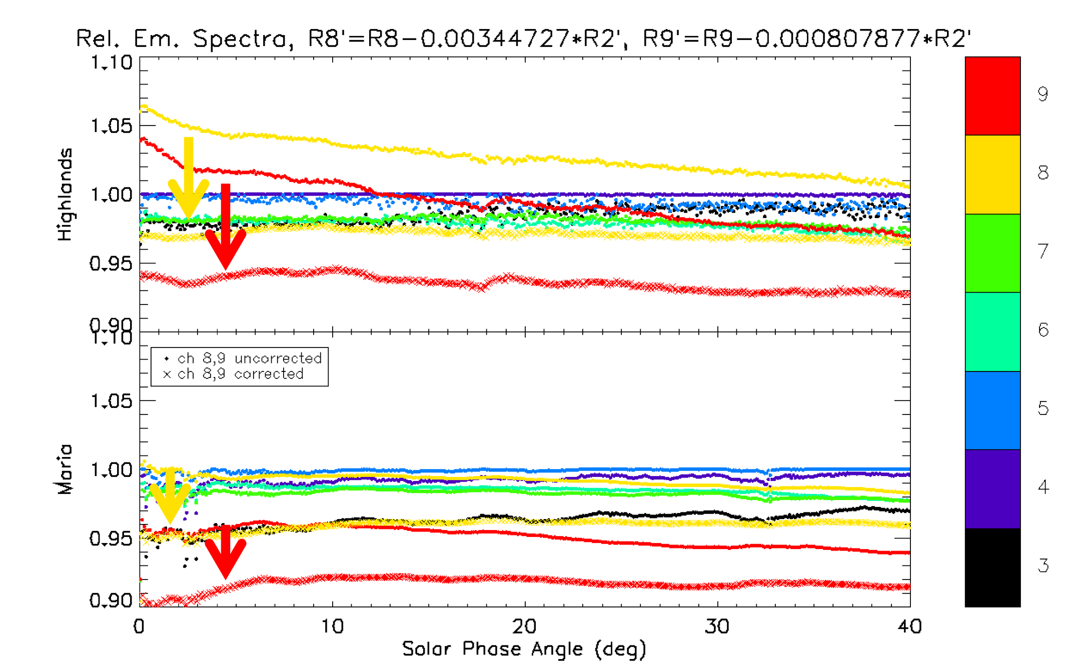

Figure 8: Relative emissivities per solar phase angle across highlands (top) and maria (bottom) data. Arrows show how subtracting the lightleak reduces ch 8,9 relative emissivity. Emissivity of 1.0 is assumed to be at Christiansen Frequency, determined as per [7]. For this rough global look at the relative emissivity, a map of the average fraction of the highlands vs maria phase curves was used as a proxy for ch 2.