ANALYSES OF THERMAL NOISE IN CURIOSITY'S GROUND TEMPERATURE MEASUREMENTS.

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Introduction: The Mars Science Laboratory (MSL) Curiosity rover has been studying the Martian climate within the 154 km wide Gale crater for a decade. On board Curiosity, the Rover Environmental Monitoring Station (REMS) collects meteorological data from the surrounding environment [1]. REMS includes a Ground Temperature Sensor (GTS) to determine the temperature on the Martian surface [2]. The GTS is the first ground-based instrument on Mars capable of continuously assessing the surface temperature [3,4]. These measurements also provide ground-truth to orbital measurements [5,6].

Fig. 1 shows 1 Hz temperature measurements (blue) taken by the GTS as a function of Local Mean Solar Time (LMST) on sol 531 (Ls ~ 84°). The average temperature over the first five minutes of each hour is represented by the red dots. At 03:00 LMST, there is a decrease in temperature immediately followed by an increase at 04:00. This decrease is > 5 K, while the noise at night (for a 5 min average) is around only 2 K indicating that it might be an outlier [4]. This behavior is also found on other sols.

These potential outliers and the key sources of uncertainty contributing to the systemic error within Curiosity's ground temperature measurements is the point of investigation. Identification of measurements with high uncertainty will contribute to a more accurate set of temperature measurements.

Data and Original GTS Calibration: REMS uses a 1 Hz sampling rate. The primary interval of sampling, called a nominal block, recurrently takes measurements for the first five minutes of every hour. The second approach samples in extended blocks, consisting of one or more consecutive hours followed by five additional minutes in the subsequent hour.

The 1 Hz data from these sampling intervals are available in NASA's Planetary Data System (PDS). Data downloaded from the PDS in this investigation included ground temperature for all available sols as well as temperatures of the GTS infrared (IR) detector and its electronic system formed by the REMS Application Specific Integrated Circuit (ASIC). The GTS uses a thermopile as detector, converting the IR flux from the ground into an electrical signal to be read by the ASIC. The ASIC amplifies, samples and digitalizes the thermopile readout voltage as well as the thermopile inner temperature measured by a temperature contact sensor [2]. Since the performance of the ASIC, in terms of noise and offset voltage, is affected by its operating temperature, this temperature is also measured by the REMS Instrument Control Unit (ICU). The ASIC temperature is measured by a contact temperature sensor glued to the ASIC's package. Its readings are used in the retrieval algorithm of ground temperature to estimate and compensate for the offset of ASIC thermopiles channel. The compensation of the offset voltage is based on the results of ASIC calibration tests on Earth.

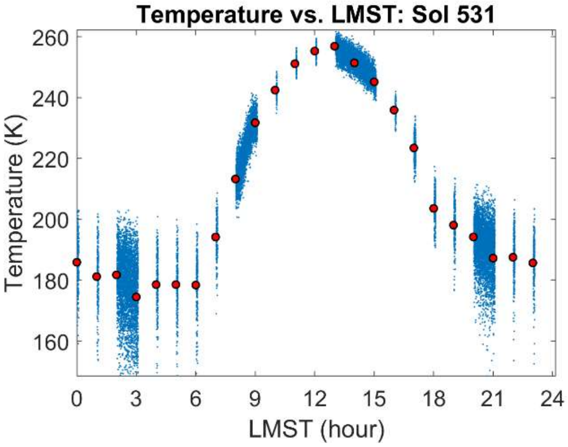

Figure 1. *Five-minute averages at the beginning of each hour (red) superimposed over 1 Hz GTS data (blue). Some 1 Hz measurements were excluded from the figure as they fell below the displayed temperature range, but were included in calculating the averages.*

Methods: All data from the first five minutes of each hour were averaged for the ground, thermopile, and ASIC temperatures. Additionally, the data from those five minutes were plotted as 20-second moving averages. The five-minute moving averages were catalogued into two categories: one comprising of nominal blocks and the first five minutes of extended blocks, and the second one with the averages midway through or at the end of extended blocks.

Results: Comparing values obtained at the same hour during sols when the rover was parked reveals that unexpected decreases in temperature correspond to averages taken after the GTS has been running for extended durations (second category).

As an example, there was an extended block from 02:02 to 03:06 LMST on sol 531 (Fig. 1), resulting in a significantly lower temperature than anticipated for the 03:00 average. This is also illustrated in Fig. 2, where a significant difference between the last five minutes of the extended block on sol 531 and two nominal blocks on adjacent sols (Sol 529, 530) is highlighted. Notable decreases in temperature such as this repeatedly occur throughout the mission, as shown in Fig. 3.

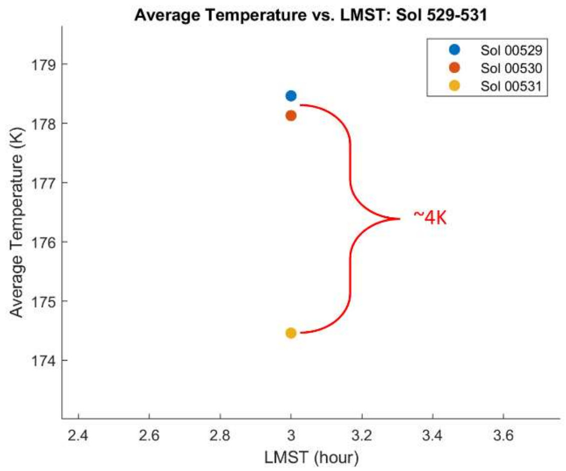

Figure 2. *Average temperature at 03:00 LMST for three consecutive sols in which the rover was stationary. Sol 531 (yellow marker) was measured during an extended block, whereas Sols 529, 530 (blue and orange, respectively) were measured during nominal blocks.*

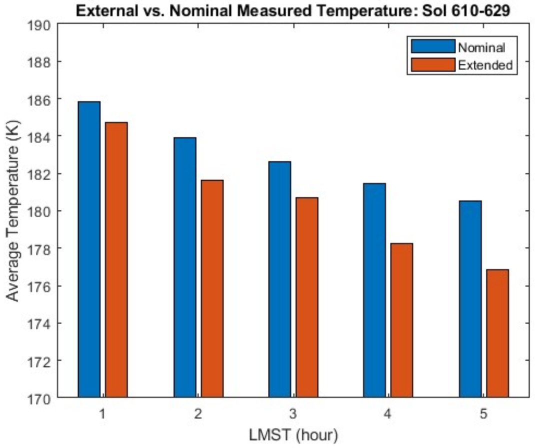

Figure 3. *Nominal (blue) and Extended (orange) temperature averages over a range of 20 Sols in which the rover remained stationary.*

A leading hypothesis to explain the unexpected decreases in ground temperature midway through or at the end of extended blocks (category 2) was the effect of the thermopile temperature fluctuations. However, analysis suggests no correlation between thermopile operating temperature and the measured ground temperature.

Discussion: The calibration tests on Earth for ASIC offset compensation did not take into account operations using extended blocks, being test set-up closer to nominal blocks. In addition to this, the ASIC temperature sensor is located outside the ASIC package, near a heater that is controlled to keep the ASIC temperature inside operating range (activation at temperatures below 218 K). These two aspects lead to significant and varying differences between the measured temperature for the ASIC and the real temperature of the silicon die inside the package, which determines the offset in the calibration equation [2]. In particular, the average difference between the measured ASIC and silicon die temperatures is greater during extended blocks, with an average difference of up to 9 K, compared to the difference in temperatures for nominal blocks, with an average difference of up to 4 K. As a consequence, uncertainty is introduced in the estimation and compensation of ASIC thermopile channel offset.

Conclusions: Extended blocks lead to a greater divergence from the average temperature calculated from the temperature of surrounding sols at the same LMST. This issue is accentuated at colder temperatures, but still present during warmer periods.

The root cause is the uncertainty in the estimation of the offset voltage of the ASIC thermopile channel. This uncertainty is higher during extended blocks at colder temperatures because of a greater difference between ASIC measured and real silicon die temperatures. Additionally, colder temperatures imply a poorer global responsivity of thermopile because of the lower target irradiance, which also leads to higher ground temperature errors.

Finally, since calibration tests on Earth were not representative of Martian operating conditions during extended blocks, additional research needs to be conducted to determine if the nominal or extended blocks are more accurate and to improve the accuracy through a better estimation of ASIC thermopile channel offset. Nonetheless, uncertainties in REMS/GTS available in the PDS include the errors from the amplifiers offset calibration, and therefore they do not require further corrections.

References: [1] Gómez-Elvira J. et al. (2012) *Spa Sci Rev* 170. [2] Sebastián et al. (2010) *Sensors*, *10*(10). [3] A.R. Vasavada, et al. (2017) *Icarus* 212. [4] Martínez G.M et al. (2017) *Spa Sci Rev* 212. [5] Edwards C.S. et al. (2018) *JGR: Planets*, *123*(5). [6] Christian J.R. et al. (2022) *JGR:Planets*, *127*(5).

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