Mars 2020 Surface Mission Modeling Landing Site Thermal Environments

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Abstract—**This paper presents work done by the Mars 2020 Mission Planning Team to characterize landing site thermal environments. A process was developed to take in ground temperature simulation data for each landing site and efficiently discretize it into a handful of thermal bin environments. The Mars 2020 Thermal Team then performed detailed heater and energy modeling in each of those environments. The heater modeling results were implemented into a Monte Carlo based surface mission model to understand mission performance impacts. The Mars 2020 Instrument Teams used the results to inform their design and to better understand how the thermal conditions at each landing site affected their instruments.**

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1. INTRODUCTION

The Mars 2020 mission is introduced in Section 2. Section 3 lists the eight candidate landing sites. Environment variability is addressed in Section 4. The curve-fitting algorithm and resulting thermal environment bins are discussed in Section 5. Impacts on heating, the surface mission model, and future operations are addressed in Sections 6-8. Section 9 provides a summary.

2. MARS 2020 MISSION

The Mars 2020 (M2020) mission will deliver a rover to the surface of Mars; the rover will be designed to take scientific in situ measurements on Mars. The mission will also acquire, encapsulate, and cache individual scientifically selected samples of martian material for possible return to Earth by a future mission. The Mars 2020 Project primary science goals are to:

(A) Characterize the processes that formed and modified the geologic record within a field exploration area on Mars selected for evidence of an astrobiologically-relevant ancient environment and geologic diversity.

(B) Perform the following astrobiologically relevant investigations on the geologic materials at the landing site. Determine the habitability of an ancient environment and for those interpreted to have been habitable, search for materials with high biosignature preservation potential.

(C) Assemble rigorously documented and returnable cached samples for possible future return to Earth.

(D) Contribute to the preparation for human exploration of Mars by demonstrating In-Situ Resource Utilization (ISRU) technologies to enable propellant and consumable oxygen production from the Martian atmosphere for future exploration missions.

The Mars 2020 rover is largely based off of the design of the Mars Science Laboratory (MSL) but with all new instruments and an all new Sampling Coring and Caching subsystem that is capable of drilling and storing solid rock cores. A diagram of the rover is shown in Figure 1

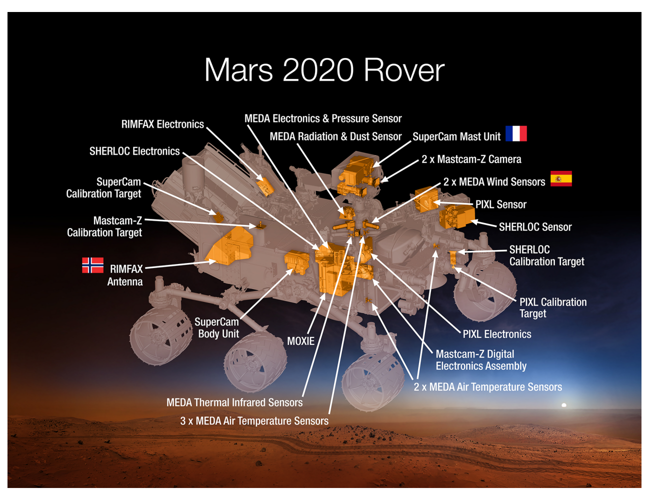

Figure 1. Mars 2020 Science Instruments

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Mars 2020 Mission Challenges

The Mars 2020 mission timeline is aggressively paced, with the goal of collecting 20 samples in the 1.5 Mars Years (MY) allocated for the primary mission. A comparison of the M2020 prime mission to MSL's first 1.5 MY is shown in Figure 2. The challenges of achieving more in the same amount of time has motivated the project to develop detailed mission models to understand the surface mission's sensitivity to various parameters and conditions.

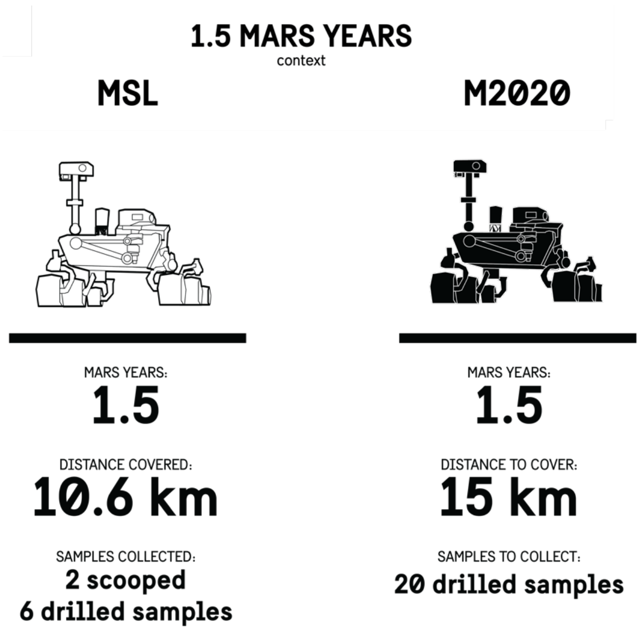

Figure 2. Mars 2020 and MSL Mission Comparison

3. Landing Site Candidates

One of the most important open science questions at this stage in the development of M2020 is the upcoming NASA Headquarters decision finalizing the choice of landing site. Site selection for Mars 2020 is an open process, informed by inputs from the international scientific community through a series of dedicated workshops and guided by NASA Headquarters. This paper is based off work done to support the 3rd landing site selection workshop, which considered eight candidate landing sites. The sites are diverse, being scattered across a wide range of latitudes as shown in table 1.

Table 1. **Candidate Landing Sites**

Site Name	Latitude
Columbia Hills (Gusev Crater)	14.5°S
Eberswalde	23.8°S
Holden Crater	26.6°S
Jezero Crater	18.4°N
Mawrth	24.0°N
Northeast Syrtis Major	17.9°N
Nili Fossae Trough	21.0°N
Southwest Melas Basin	9.8°S

Landing Site Thermal Environments

Each landing site experiences different seasonal temperature variation and diurnal (daily) temperature cycles. Using a Mars General Circulation Model (GCM) developed at Jet Propulsion Laboratory (JPL), simulation data including ground and atmospheric temperatures and solar loads was produced for all eight landing sites. Information on the GCM model can be found in Richardson et al. [1], Toigo et al. [2], and Mischna et al. [3].

The landing sites can be separated into two distinct groups. Northern sites like Jezero, Mawrth, NE Syrtis, and Nili Fossea are relatively temperate, with more benign seasonal changes and neither extreme hot or cold temperatures as shown in Figure 3 (MSL's landing site, Gale, is included here for reference since it has a similar climate). Southern sites like Holden, SW Melas, and Eberswalde experience more seasonal variability and also experience colder winters and hotter summers than northern sites as shown in Figure 4.

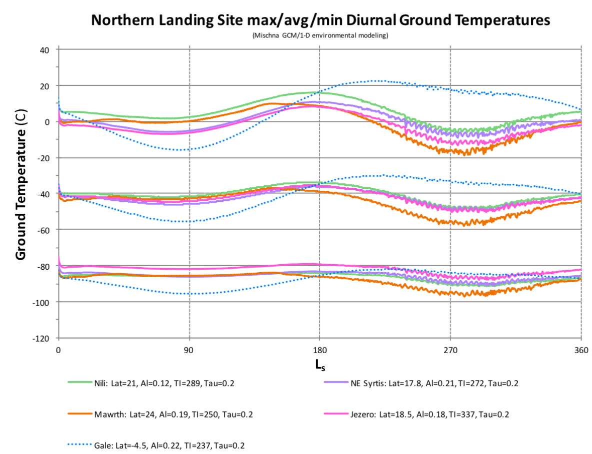

Figure 3. **Northern Site Ground Temperatures**

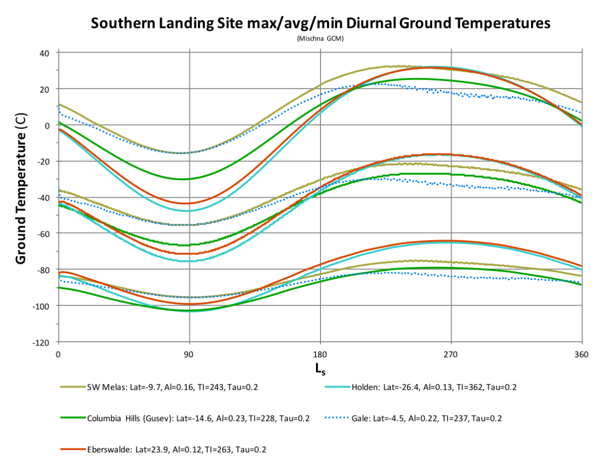

Figure 4. **Southern Site Ground Temperatures**

Local true solar time (LTST) ground temperature contours for all sites are shown in Figure 3. LTST differs from the local mean solar time (LMST) that normally governs the timing of rover operations. LTST is ideal for environment modeling because it doesn't thermally shift throughout the year unlike LMST. The hottest period of the Mars day is consistently at the same time throughout the Mars year. Details about LTST and LMST conversion can be found in Appendix A.

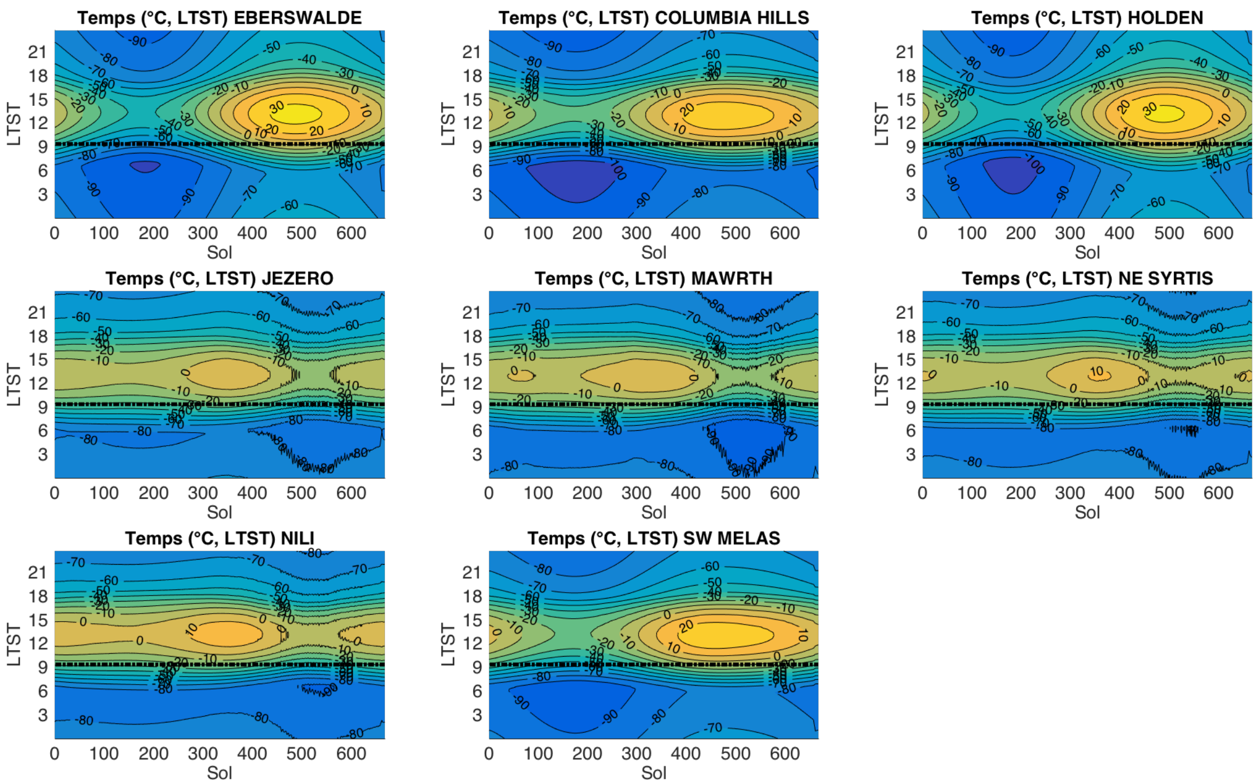

Figure 5. **Ground Temperature Contours**

Impacts to Mission Performance

Landing site thermal environment variability presents a significant mission performance challenge. Colder temperatures increase the amount of heating required by the rover. Survival heating is continuously required by the rover to keep its core systems and instruments at a healthy operating temperature. Warm-up heating is used to warm actuators, instruments, and subsystems so that they can be used to perform science investigations. Spending more energy on heating taxes the rover's energy reserves and in turn leaves less energy available for science activities. The net result of this is that colder sites have worse mission performance, taking longer to complete the same mission. Additionally, both extreme hot and cold temperatures can limit the operations of particular instruments or subsystems to certain times of day.

4. Understanding Environment Variability

Although the GCM provided a multitude of data, because of the difficulty of modeling the thermal conditions of the various rover systems, only a handful of diurnal temperature curves (or thermal environments) could be selected for further detailed study. The challenge was to select the environments in such a way that they could be used to stand in for the higher resolution landing site data with enough fidelity that the landing sites could be distinguished from one another and their mission performance impacts compared.

Environment Bins

A curve-fitting algorithm was developed that discretized the landing sites into six thermal environments bins. Each site was assigned various thermal bins throughout the year to approximate seasonal changes. Thermal bins were used across landing sites such that the same bin could for example be used to represent fall at one site and winter at another.

Reducing the Data

Modeling efforts focused on ground temperatures at 9:30 am LTST. This time represents a usual starting time for MSL preheats and also represents the coldest time period during the critical path, the time after uplink and before the afternoon decisional downlink pass and during which most of the science of the mission occurs. Ground temperature was chosen because it was a good proxy for the overall thermal environment. Figure 6 shows the site ground temperature thermal contours sliced at 9:30 am LTST.

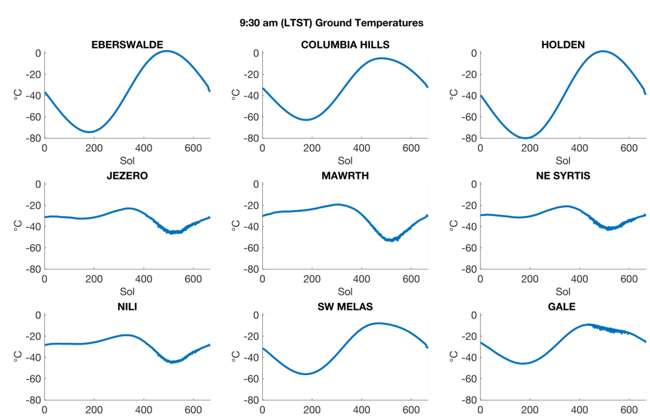

Figure 6. **9:30 LTST Temperare Curves**

5. CURVE-FITTING ALGORITHM AND RESULTS

The problem was formulated as a nonlinear six-dimensional optimization problem where the goal was to find a set of integer bin temperature thresholds, defined as $\vec{b}$ in Equation 1, that best fit the thermal data across the sites.

$$\vec{b} = b_1, b_2, b_3, b_4, b_5, b_6 \tag{1}$$

The solution space was 130°C in each of the six dimensions, making it sufficiently large as to be difficult to completely explore. A sampling approach was employed that took six samples at integer values in each of the six dimensions. Then all the possible permutations of those samples were calculated such that each permutation was a set of six bin values in the form of $\vec{b}$. Then each set of bins was used to curve-fit the landing site 9:30 am LTST ground temperature curves using a strategy where each ground temperature data point was assigned to the closest available bin. Then for each site, the resulting curve-fit was scored against the original data by calculating the R^2 measure of fitness (additional information on the R^2 formula can be found in Appendix C). To ensure that the algorithm prioritized fitting the more extreme southern sites, each of the site specific scores were multiplied by a weighting factor derived from site variance before being summed to produce the overall score as shown in Equation 2.

$$score = \sum_{site=1}^{8} R^2_{site} * V_{site}/V_{total} \tag{2}$$

The highest scoring set of bins in each round of sampling was found and used to shrink the search space by 25% in each dimension, centered around the bin value for that dimension. This process was repeated was until the search space became smaller than 6°C in each dimension, at which point the highest scoring set of bin values was returned.[2]

Results

The best six bins were found to be -73°C, -56°C, -42°C, -30°C, -21°C, and -6°C. The curve-fits are shown in Figure 7 and demonstrate good agreement across all landing sites to the original data.[3]

Individual bin results are shown in Figures 8-13. Colored lines show the subset of diurnal curves assigned to that bin while gray lines show the full population of diurnal curves over one Mars year across all sites. The vertical dashed line represents 9:30 am LTST and the curved dashed lines show the $\pm\sigma$ diurnal curves. The $-\sigma$ results for each bin are used to produce the dashed curve-fit line shown in Figure 7.

[2]This algorithm is not guaranteed to find the global maximal solution only a local one

[3]MSL's landing site, Gale, included here for reference

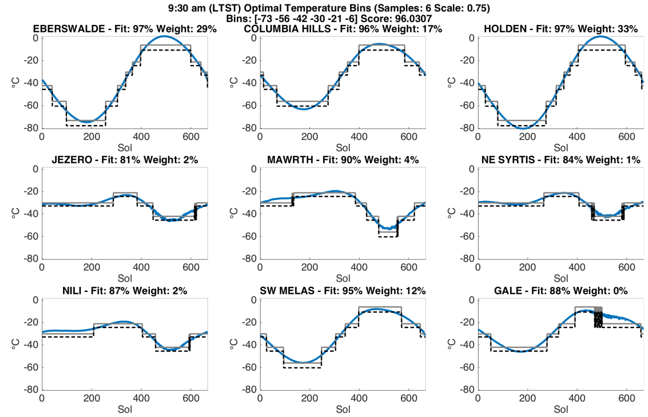

Figure 7. Optimal Temperature Bin Curve Fits

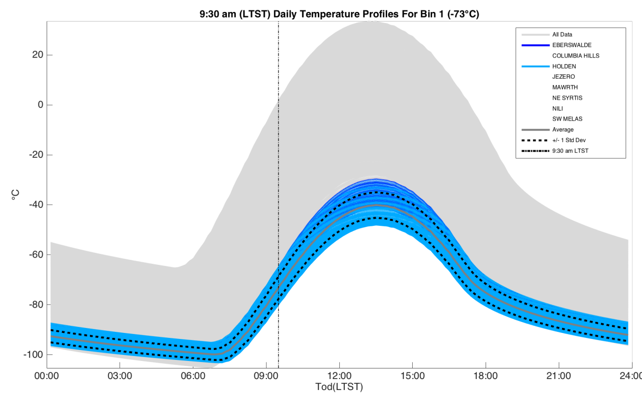

Figure 8. Bin 1 Population

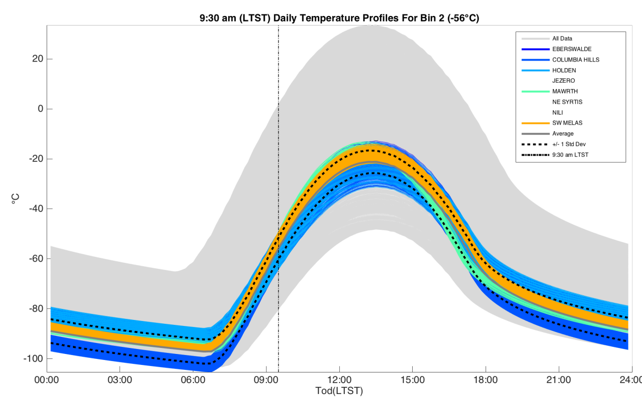

Figure 9. Bin 2 Population

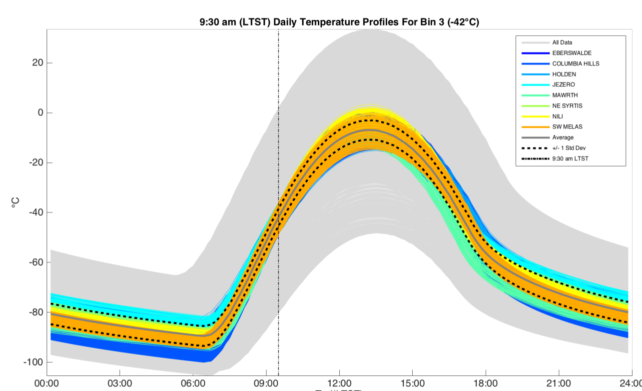

Figure 10. Bin 3 Population

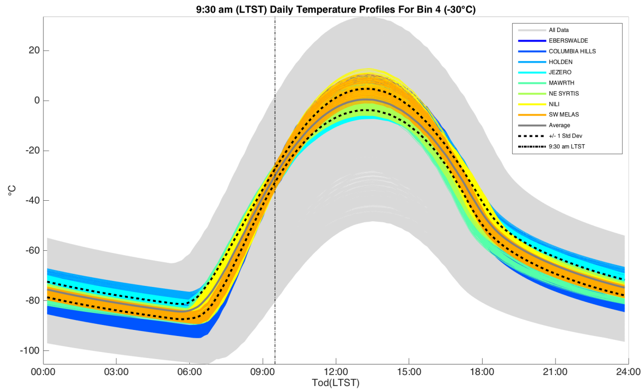

Figure 11. Bin 4 Population

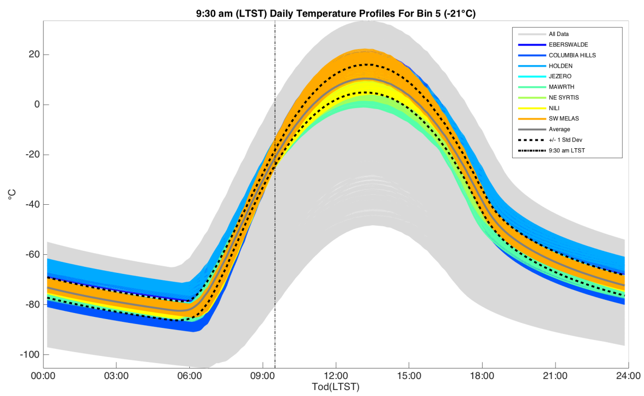

Figure 12. Bin 5 Population

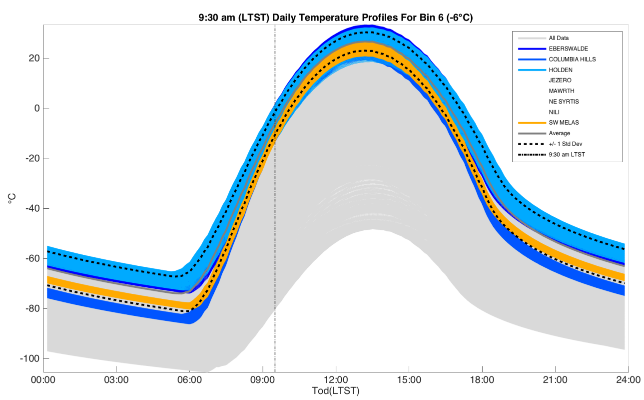

Figure 13. Bin 6 Population

Identifying Matching Datasets

For each bin, the $-\sigma$ diurnal temperature curve was compared to all diurnal curves in the original dataset. Using R^2, the closest match was found, as shown in Figure 14. This was done to ensure that bin environments represented a real complete dataset of consistent GCM simulation data including above ground temperatures and solar load levels.[4] The $-\sigma$ diurnal curve was chosen because it represents a conservative temperature for each environment as colder temperatures are more stressing.

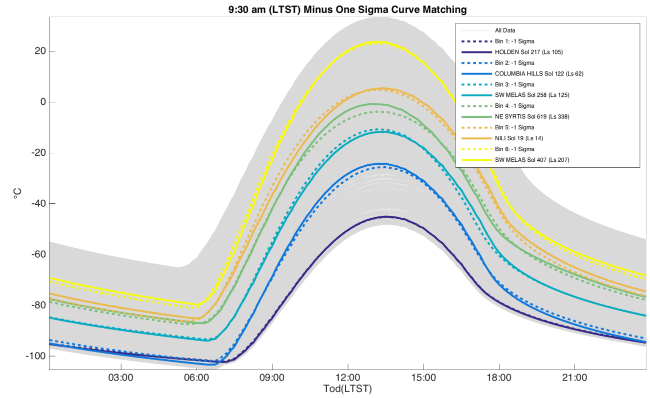

Figure 14. Curve Matching

The matches, listed below, are used as stand-ins to represent the six bin environments.[5] Table 2 shows how the bins are utilized across each site. Bins 3-5 are used at every site, bins 1 and 6 are only used at southern sites, and bin 2 is used at southern sites and Mawrth, the coldest northern site.

- **Bin 1:** Holden - Sol 217
- **Bin 2:** Columbia Hills - Sol 122
- **Bin 3:** SW Melas - Sol 258
- **Bin 4:** NE Syrtis - Sol 619
- **Bin 5:** Nili - Sol 19
- **Bin 6:** SW Melas - Sol 407

Table 2. Site Bin Usage Over One Mars Year

Site Name	% in Bin 1	2	3	4	5	6
Colum. Hills	0	31	14	11	16	28
Eberswalde	24	16	11	8	11	30
Holden	29	14	10	8	11	28
Jezero	0	0	26	60	14	0
Mawrth	0	11	17	34	38	0
NE Syrtis	0	0	18	61	21	0
Nili	0	0	21	50	29	0
SW Melas	0	23	19	13	19	26

6. THERMAL TEAM RESULTS

Using the selected bin environments, the Thermal Team conducted detailed modeling to determine survival and warm-up heating energy costs, shown in Figures 16 and 17. As expected, colder bin environments require much more survival and warm-up heating energy.[6] Rover subsystem acronyms featured in these charts are defined in the list below.

- **RPFA:** Rover pyro fire assembly
- **SCMU:** SuperCam mast unit
- **PIXL:** Arm mounted geologic spectrometer
- **SHERLOC:** Arm mounted organic spectrometer
- **RA:** Rover Arm
- **SHA:** Sample handling arm
- **RSM:** Remote sensing mast
- **HGA:** High gain antenna
- **EECAM:** Engineering cameras

[4] See comparison of matched bin solar load levels in Appendix B

[5] Sols of year, not mission Sols

[6] Figures borrowed from a Thermal Team presentation[4]

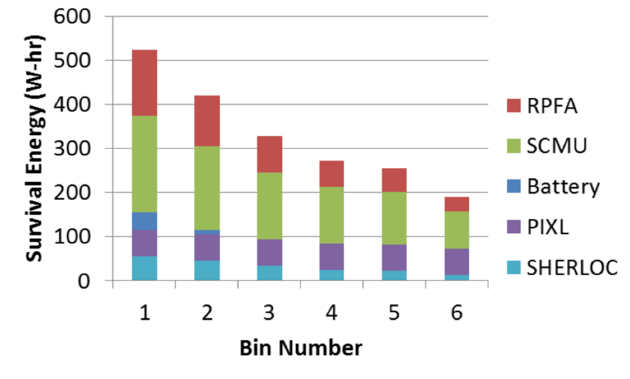

Figure 16. **Survival Heating**

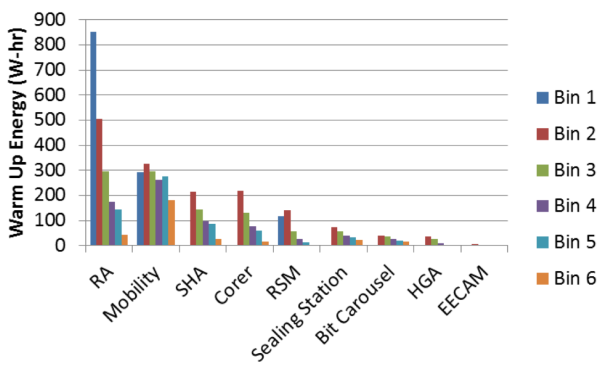

Figure 17. **Warm-Up Heating**

7. SURFACE MISSION MODEL IMPACT

The Mission Planning Team has developed a Monte Carlo based surface mission performance model as part of the project's efforts to better understand mission sensitivity to various input parameters. The thermal modeling results were integrated into this model to determine the effect on site specific mission performance. The model was tuned in such a way as to isolate the effect of the thermal environment conditions at each landing, with all other parameters being the same across the sites. The resulting mission performance box plots are shown in Figure 15. Each site shows a unique impact to the mission timeline that is in family with what was expected based off Mars GCM data.

8. IMPACT ON OPERATIONS

These modeling efforts have the potential to strongly impact Mars 2020 surface operations. Currently, MSL uses two thermal environments, switching between them seasonally based on the performance of heating events. However, actual Mars conditions are routinely quite different than the conditions the thermal environment were built to simulate. This causes overmodeling of heating events and results in undue conservatism in energy modeling. After the final landing site is selected for Mars 2020, a similar analysis as that described in this paper could be performed to computationally determine a set of representative thermal environments and additionally generate a schedule to optimize when those environments should be used. This would allow the mission to more accurately model heating events and thereby increase the amount of energy available to use for planning science activities.

Special Impact to SHERLOC

The SHERLOC Instrument will use a phase change material to help regulate its internal temperature. This environment analysis has allowed the Instrument Team to customize their choice of material to match the expected conditions at the landing sites. This will increase the range of temperatures over which the instrument can be operated.

9. CONCLUSION

This research resulted in six common thermal environments being produced that can be used in prescribed combinations to uniquely represent the thermal conditions at each landing site. The Thermal Team used these environments to make heating estimates and the Mission Modeling Team integrated those heating estimates into the overall surface mission model to determine how the conditions at each site affected mission performance. Going forward this approach has applications to Mars 2020 operations and potentially other future surface missions as well.

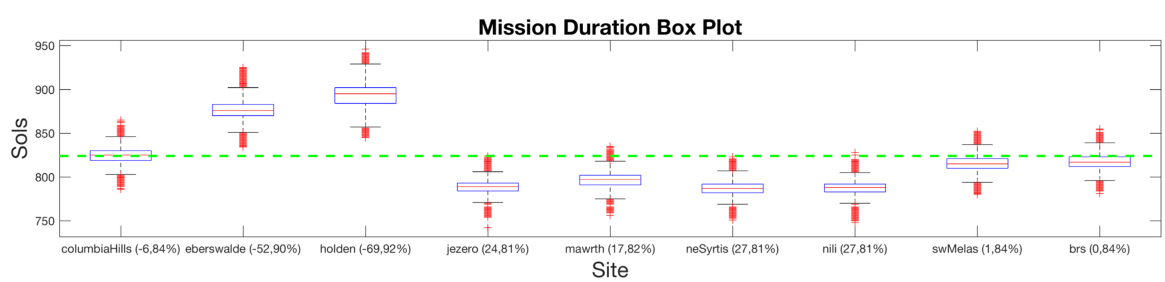

Figure 15. **Surface Mission Model Thermal Environment Impact**

Appendices

A. Time Conversion

LTST and LMST are converted to one another using the cyclical relationship shown in Figure 18

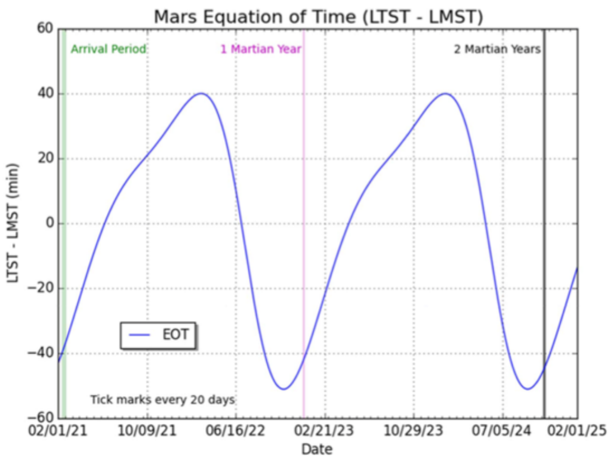

Figure 18. **LTST and LMST**

B. Solar Load

Solar load is an additional output of the Mars GCM model. Figure 19 shows the solar loads from the matched bin environments compared to the $-\sigma$ bin population solar loads. The Figure shows that although there isn't perfect correlation, especially between the bin 4 and 5 levels, the solar loads end up reasonably well matched.

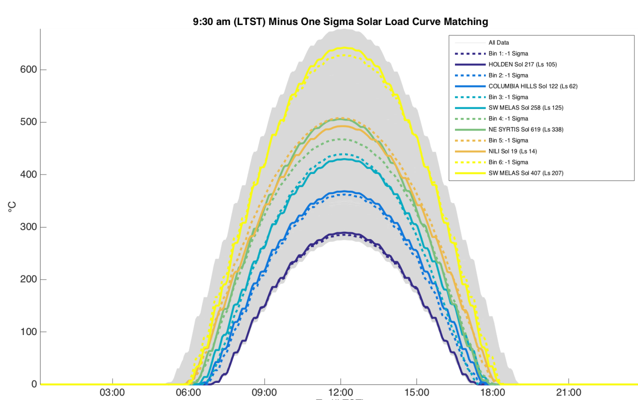

Figure 19. **Solar Load Bin Match Curves**

C. R^2 Measure of Fitness

R^2, or the coefficient of determination, represents the proportion of captured to uncaptured variance in the data. The formula for calculating R^2 is shown in Equations 3-5.

$$R^2 = 1 - SS_{Residual}/SS_{Total} \tag{3}$$

$$SS_{Residual} = \sum_i (y_i - f_i)^2 \tag{4}$$

$$SS_{Total} == \sum_i (f_i - \overline{y})^2 \tag{5}$$

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- **Mars 2020 Thermal Team-** for conducting the thermal analysis and for the heater energy charts.
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BIOGRAPHY

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