MSL FROST DETECTION CAMPAIGNS

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Introduction: We report results of the frost detection campaigns performed by the Curiosity rover during the first 3332 sols of the Mars Science Laboratory (MSL) mission. Also, we describe the observational strategy and target selection of these campaigns to support NASA's Mars 2020 and future missions in the search for frost on Mars.

We use environmental measurements from the Rover Environmental Monitoring Station (REMS) to predict frost formation, and ChemCam Laser Induced Breakdown Spectroscopy (LIBS) to detect enhanced hydration levels. Only when both instruments return positive results, we interpret that the formation of frost is likely.

Out of 14 campaigns (Table 1), only on sol 2548 (Ls ~ 89°) in Martian Year (MY) 35 both REMS and ChemCam LIBS returned results consistent with frost formation. However, we note that these results were not unambiguous, and that future lab studies will improve our understanding of ChemCam sensitivity to frost.

REMS and ChemCam Instruments: REMS is the weather station onboard MSL. It includes six sensors measuring atmospheric pressure, UV fluxes, wind velocity (which stopped working at around sol 1500), air temperature, ground temperature, and relative humidity [1–3]. The REMS sampling strategy consists of 5-min-long hourly samples at 1 Hz, with interspersed full hour sample periods at 1 Hz to cover every time of the sol over a period of a few sols.

The LIBS instrument, part of the ChemCam instrument package, is able to perform remote and sensitive elemental analysis that includes the identification of submicron-thick frost layers [4–5].

Environmental Context: Fig. 1 shows REMS measurements of ground temperature (T_g), relative humidity (RH), and water vapor volume mixing ratio (VMR) for the first 3332 sols of MSL mission. In every MY, the ground temperature shows the coldest annual values and the RH shows the highest annual values between late southern fall and early winter.

Target name	Target type	Sol #	Ls (°)	Local Season	MY	Did REMS predict frost?	Did ChemCam detect enhanced hydration?
Crestaurum	Soil	75	193	Spring	31	No	No
Cumberland	Drill tailings	290	327	Summer	31	No	No
Young Point	Fine soil	317	343	Summer	31	No	No
Sandy Dam	Fine soil	545	91	Winter	32	No	No
Gobabeb	Dune	1236	101	Winter	33	Maybe	No
Fiskus	Rock + vein	1251	108	Winter	33	No	No
Oak Tree	Fine-grained soil	1879 -1886	89 - 92	Winter	34	No	Maybe
Lebombo	Rock w/ veinlets	1879 -1886	89 - 92	Winter	34	No	No
Sandwick	Fine-grained soil	1898 - 1900	98	Winter	34	Yes	Maybe
Schroeder	soil	2049 - 2050	174	Late Winter	34	Maybe	Maybe
Kilpatrick	**soil**	**2548**	**89**	**Late Fall**	**35**	**Yes**	**Yes**
Kinnordy	soil	2565	97	Winter	35	No	No
Kittybrewster	soil	2582	104	Winter	35	No	No
Mangersta	Fine-grained soil	3230	143	Winter	36	No	No

Table 1. List of frost/hydration detection campaigns by the Curiosity rover during the first 3332 sols of the MSL mission. Only on sol 2548 in MY 35, both REMS and ChemCam returned results indicating the likely formation of frost on a soil patch informally named Kilpatrick. 'Maybe' indicates positive results without enough certainty.

The nighttime VMR shows annual maximum values at Ls ~ 160°, when the water vapor column abundance at Gale is highest [5].

The RH reached saturation levels in MY 35, although fog has not been detected by the mission.

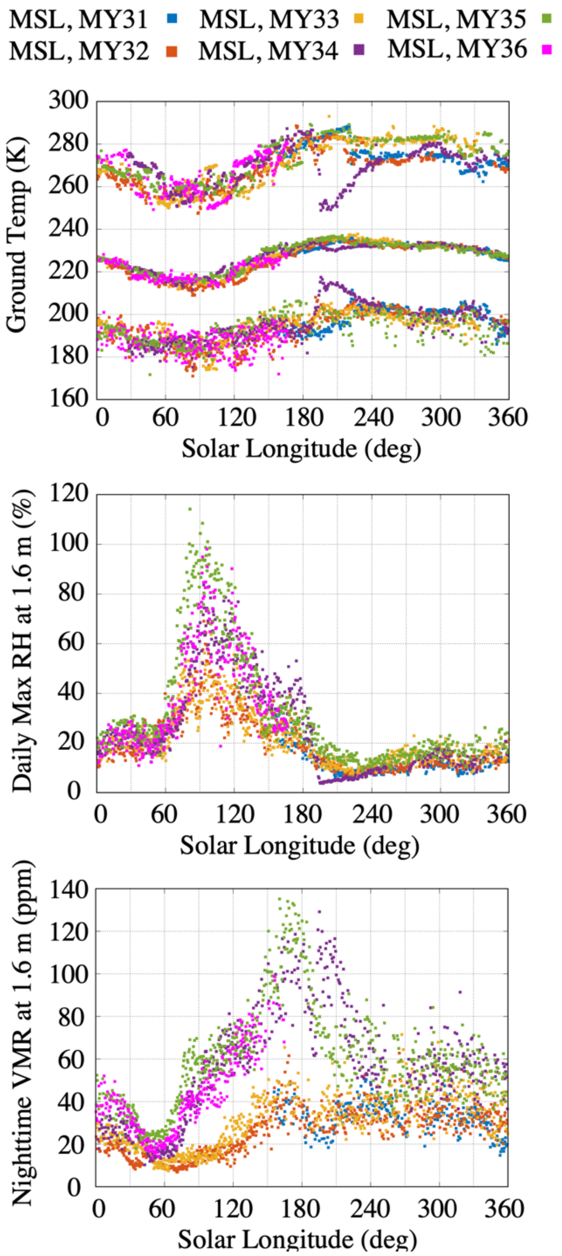

Figure 1. Interannual and seasonal evolution of the daily maximum, mean and minimum ground temperature (top), daily maximum RH (middle), and nighttime VMR (bottom). The daily maximum RH is generally achieved between 04:00 and 06:00 LMST, when the temperature is coldest. VMR values are obtained at the same time as the RH shown above.

To predict frost events with REMS, we compare T_g with the frost point (T_f) calculated as $e_s(T_f) = e =$ VMR×P, where e_s is the saturation vapor pressure over ice [6], e is the water vapor pressure at 1.6 m, and P is the atmospheric pressure. In establishing this comparison, and due to the lack of humidity measurements at the ground, we implicitly assume that the water vapor content is constant in the first 1.6 m. Uncertainties derived from this assumption will be assessed as part of an ongoing manuscript.

Fig. 2 shows the seasonal evolution of the maximum and minimum T_g (black), along with T_f values calculated when the RH at the ground ($\sim e/e_s(T_g)$) is highest (blue), which typically occurs right before sunset (LMST ~0500–06:00). Most frost events are predicted to occur seasonally within the Ls 90°–110° period, when the ground temperature falls below the frost point.

We note that T_g measurements in the second half of MY 35 and in MY 36 are subjected to strong electronic noise at nighttime, and thus the uncertainty in minimum T_g values is larger.

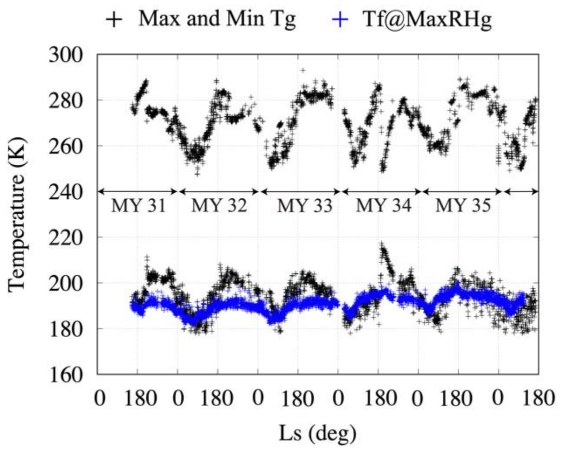

Figure 2. Seasonal evolution of the maximum and minimum ground temperature measured by REMS (black), and of the frost point calculated when the RH at the ground, RH_g $\sim e/e_s(T_g)$, is highest (blue). The ground temperature falls below the frost point on several sols during fall and winter (mostly in the Ls 90°–110° period), and on a few sols during summer and spring, suggesting potential frost events.

Target Selection: Three types of targets have been considered as part of our Frost Detection Campaigns: (1) soil/sand, (2) rocks, and (3) ventifacted rock fingers. Each type presents pros and cons for the potential formation of frost.

Soil/sand has low thermal inertia, and therefore it can get colder overnight. However, this type of terrain is porous, and thus water vapor might diffuse to some depth before forming frost. Rocks are not porous but have high thermal inertia, and thus stay warmer overnight. Finally, ventifacted rock fingers have relatively low thermal inertia and are not porous, but it is challenging to estimate their temperature (the REMS ground temperature sensor has a field of view of a few m^2, while the size of ventifacts is of the order of cm).

Because frost at the Viking 2 landing site preferentially formed and persisted on soils as opposed to rocks (Fig. 3), it was decided to select this type of terrain in the campaigns of MYs 35 and 36 (Table 1).

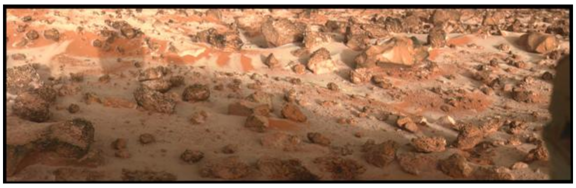

Figure 3. Color image by Viking Lander 2 camera showing frost preferentially on the soil. Credit: NASA/JPL.

Observational Strategy of MSL Frost Campaign in MY 35: Three targets were analyzed by ChemCam LIBS during this campaign: Kilpatrick on sol 2548 at L_s = 89° (Fig. 4); Kinnordy on sol 2565 at L_s = 97°; and Kittybrewster on sol 2582 at L_s = 104°. All targets met the following selection criteria: (1) a fine-grained soil patch, (2) larger than 5 cm in size and (3) more than 3 m from the rover. This was decided to ensure thermal insulation from higher thermal inertia rocks, and to avoid thermal contamination from the rover.

For each target, a ChemCam raster was collected a few minutes before sunrise (~05:50 LMST), when temperature is at its coldest and RH at its highest, and another was collected around 13:00, when temperature is at its warmest and RH at its lowest. Each raster consisted of 10 points spaced along a line (Fig. 4, top), with 10 shots on each point. The hydrogen emission peak at 656.6 nm is extracted from the spectra [5,7] and several signal normalizations are tested to compare day/dawn pairs of observations.

Contemporaneously to ChemCam, REMS measurements of T_g, RH and P were collected to document the rapidly changing environmental conditions near sunrise. From these measurements, the frost point at the surface was determined assuming constant mixing ratio in the lower 1.6 m of atmosphere.

Results of MSL Frost Campaign in MY 35: Fig. 5 shows the ground temperature (red) and frost point (blue) for Kilpatrick (top) and Kinnordy (bottom) on sols 2548 and 2565, respectively. For Kittybrewster, not shown, the diurnal evolution of both quantities was similar to that of Kinnordy. Only at Kilpatrick the environmental conditions were favorable for the formation of frost, where the ground temperature fell well below the frost point between 05:00 and 06:00 LMST.

Fig. 6 shows ChemCam LIBS normalized H signals at Kilpatrick (top) and Kinnordy (bottom), both at daytime (left; ~13:00 LMST) and dawn (right; ~05:40 LMST). Only for Kilpatrick there was enhanced average H signal in shots at dawn relative to daytime, above point-to-point signal variability. For Kinnordy, there is no difference in the H signal during dawn vs daytime, suggesting there was no detectable change in water content overnight. Results for Kittybrewster, not shown, are similar to those of the Kinnordy target (i.e., no H enhancement).

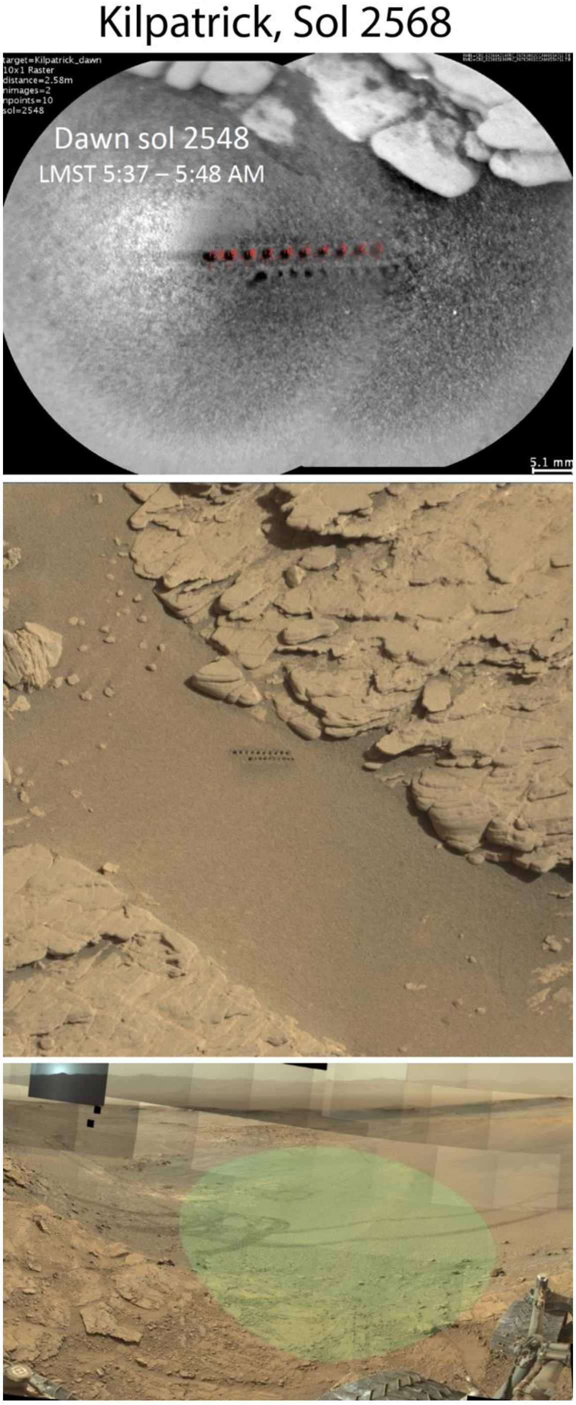

Figure 4. (Top) ChemCam Remote Micro-Imager image of Kilpatrick target on sol 2548. (**Middle**) Mastcam image of the surroundings. (**Bottom**) Navcam image with REMS' field of view of ground temperature on sol 2548.

Conclusions: Out of 14 frost detection campaigns performed along the MSL traverse, only on sol 2548 (Ls ~ 89°) in MY 35 both REMS and ChemCam LIBS returned results consistent with the formation of frost. REMS observations suggested frost formation between 05:00 and 06:00 LMST and ChemCam LIBS showed enhanced average H signal in shots at dawn relative to daytime, above point-to-point signal variability. We interpret these results as likely frost formation. However, we are not able to determine the phase or distribution of this transient water, and adsorbed water layers on soil grains are also a possible cause.

Point-to-point variability and signal normalization are the main limitations of these LIBS measurements. Future lab studies should improve our understanding of ChemCam sensitivity to frost.

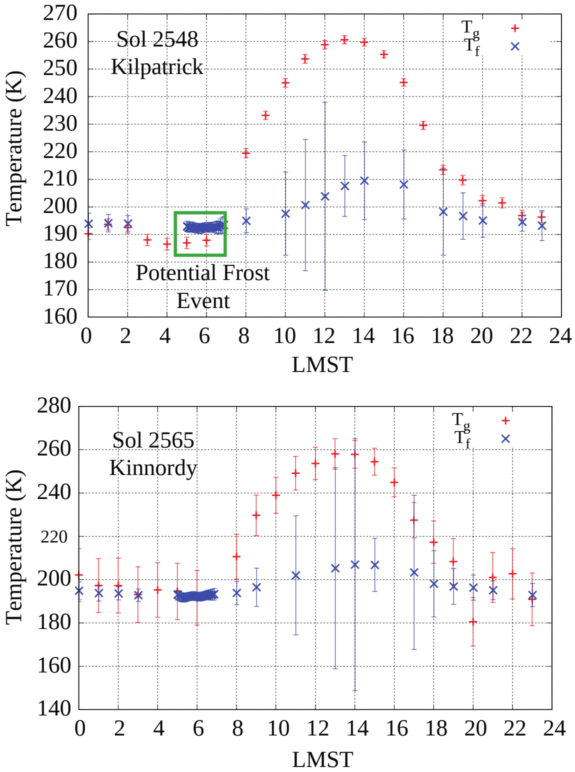

Figure 5. Diurnal evolution of ground temperature (red) and frost point temperature (blue) on sols 2548 (top) and 2565 (bottom). Between 05:00 and 06:00 LMST on sol 2548, the ground temperature fell well below the frost point, indicating favorable conditions for frost formation. Sunrise was ~05:50 LMST on both sols.

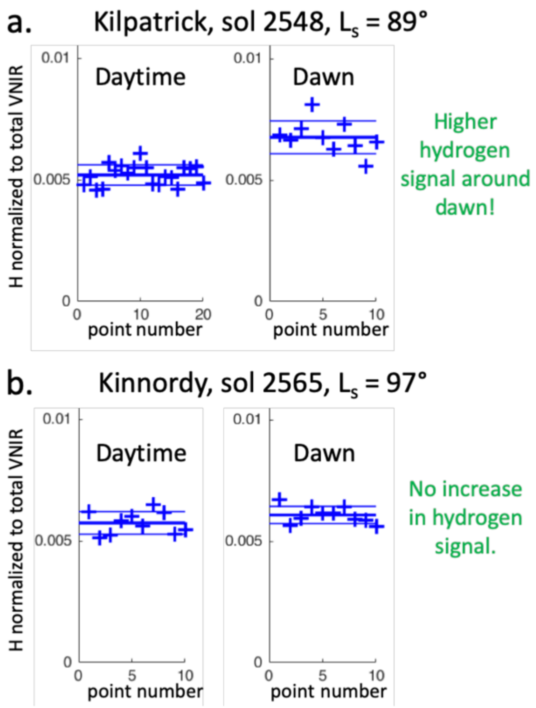

Figure 6. Comparison of ChemCam LIBS hydrogen signal collected at targets Kilpatrick (a) and Kinnordy (b) during the day (left) and dawn (right).

References: **[1]** Gómez- Elvira, Javier, et al. "Curiosity's rover environmental monitoring station: Overview of the first 100 sols." *Journal of Geophysical Research: Planets* 119.7 (2014): 1680-1688. **[2]** Martínez, G. M., et al. "The modern near-surface Martian climate: a review of in-situ meteorological data from Viking to Curiosity." *Space Science Reviews* 212.1 (2017): 295-338. **[3]** Newman, Claire E., et al. "MarsWRF convective vortex and dust devil predictions for Gale Crater over 3 Mars years and comparison with MSL- REMS observations." *Journal of Geophysical Research: Planets* 124.12 (2019): 3442-3468. **[4]** Meslin, P-Y., et al. "Soil diversity and hydration as observed by ChemCam at Gale Crater, Mars." *Science* 341.6153 (2013): 1238670. **[5]** Schröder, S., et al. "Hydrogen detection with ChemCam at Gale crater." *Icarus* 249 (2015): 43-61. **[6]** McConnochie, Timothy H., et al. "Retrieval of water vapor column abundance and aerosol properties from ChemCam passive sky spectroscopy." *Icarus* 307 (2018): 294-326. **[7]** Rapin, William, et al. "Quantification of water content by laser induced breakdown spectroscopy on Mars." *Spectrochimica Acta Part B: Atomic Spectroscopy* 130 (2017): 82-100.