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Report on the recovery of the ChemCam instrument onboard the Curiosity rover after a High Voltage anomaly

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Abstract

Curiosity rover was launched on November 26, 2011 and landed in Gale Crater on August 6, 2012, where it continues the exploration of the Martian surface. It has spent on the red planet more than 3750 sols (Martian day), taken more than one million raw images and traveled over 29 kilometers on the surface of Mars. What began as a two-Earth-year mission celebrated its 10th anniversary in August 2022. In January 2021 (Sol 3007), after more than 9 years of nominal operations on Mars, the ChemCam instrument sent data indicating that the High Voltage (HV) required to trigger the laser was not as stable as usual. ChemCam operations on Mars were paused for a few days to investigate. With only the available telemetry and a laboratory breadboard, since it is obviously impossible to work directly with the hardware on Mars, the engineers were able to lower the risk rating in only 2 weeks. Once the analysis concluded that there was no risk to either the other functions of the instrument or the rover, Jet Propulsion Laboratory (JPL) mission leads cleared ChemCam to resume all of its activities, but with restrictions. Subsequent to the anomaly, at each downlink, the team performed specific checks and produced reports to adjust the constraints to maximize the science return while preserving the life of the instrument

This paper will relate the analyses performed and the model for defining the operational constraints of ChemCam when using laser now.

Keywords: MSL, ChemCam, recovery, preservation

Acronyms/Abbreviations

CNES - Centre National d'Etudes Spatiales
HK - House Keeping
HV - High Voltage
IRAP - Institut de Recherche en Astrophysique et Planétologie
JPL – Jet Propulsion Laboratory
LIBS – Laser Induce Breakdown Structure
LANL - Los Alamos National Laboratory
MSL – Mars Science Laboratory

1. Introduction

1.1 The Mars Science Laboratory Mission

Ten years ago, in 2012, a jetpack put NASA's Curiosity rover on the Red Planet, beginning the mission to find evidence that billions of years ago Mars had the conditions necessary to sustain microscopic life. Since then, Curiosity has driven more than 29 kilometers and ascended more than 625 meters exploring Gale Crater and the foothills of Mount Sharp within it. The rover analyzed 41 rock and soil samples, relying on a suite of science instruments. Curiosity studied the sky, capturing images of clouds and Mars' moons. It also studied radiation on Mars to prepare for future human exploration on the Martian surface. The primary goal of the MSL mission was achieved: Curiosity determined that liquid water and the chemical building blocks and nutrients needed to sustain life were present for tens of millions of years in Gale Crater (Vasavada et al., 2022 [3]). The crater once held a lake, which may have varied in size over time. Each higher layer on Mount Sharp serves as a record of a more recent era of Mars' environment (Fraeman et al., 2021 [4]).

Curiosity's mission was recently extended for another three years, allowing it to continue one of the major astrobiology missions on Mars: now the rover is driving through a new region thought to have formed as water disappeared from the surface, leaving behind sulfate minerals.

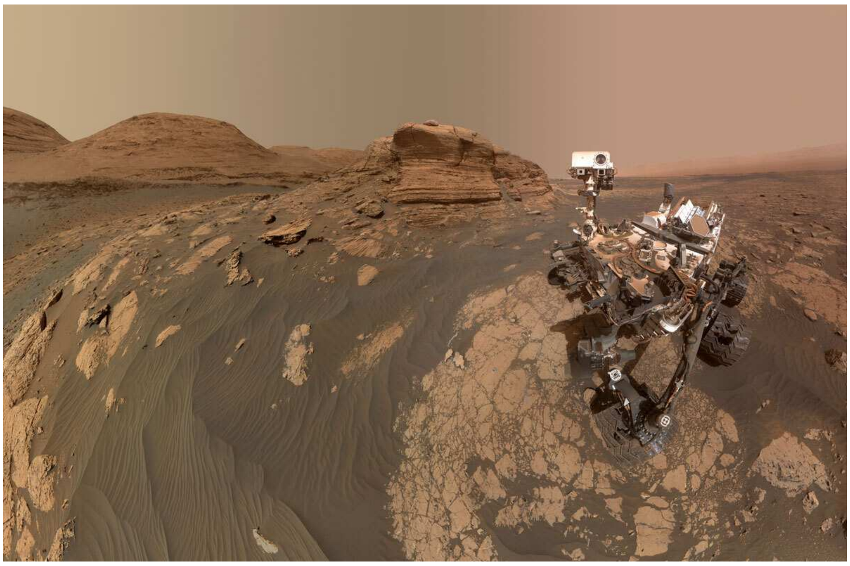


Fig. 1: Curiosity's Selfie at Mont Mercou: with ChemCam on the mast (or "head") of the rover. Credits: NASA/JPL-Caltech/MSSS

1.2 ChemCam instrument

The ChemCam instrument is an international collaboration led by Los Alamos National Laboratory (LANL) in the United States and the Institut de Recherche en Astrophysique et Planetologie (IRAP) in France, where the project is supported by the Centre National d'Etudes Spatiales (CNES) (Maurice et al. 2012; Wiens et al. 2012).

The ChemCam instrument consists of two units. Located at the top of the Curiosity rover mast (Mast Unit) and in the rover body (Body Unit). Built by Thales Optronics, under contract to CNES, the ChemCam laser was the first pulsed laser of its power class to operate on the surface of an extraterrestrial planet. The main purpose of ChemCam is to perform Laser-Induced Breakdown Spectrometry (LIBS) to analyze the elemental composition of rocks and soils. ChemCam's tightly focused laser beam (350-550 μm in diameter) enables the targeting of fine-scale terrain features up to 7 meters. The spectrum of laser-induced plasma light reveals the chemical composition of targets within seconds.

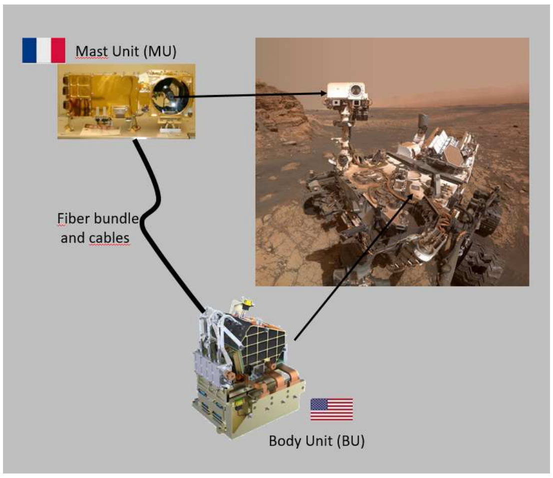


Fig. 2: Localization of ChemCam Instrument into Curiosity Rover

ChemCam's Remote Micro-Imager (RMI) was originally designed as a context imager of targets to determine the location and effects of LIBS pits. The RMI is also used to make long-distance feature observations. In addition to LIBS and imaging, ChemCam provides passive reflectance spectroscopy from 400 to 850 nm by using its spectrometers without the laser.

2. Broad use of ChemCam in the science blocks

ChemCam is one of the most used instruments onboard Curiosity. Its remote and rapid analysis capacity offers opportunities for observations on every sol.

For about 9 years, we made extensive use of the ChemCam instrument, and its analyses were included in about 45% of the mission's remote science observation sets. On average seven new targets have been analyzed each week, with 9 measurement points at each target and at least 30 laser shots at each point. Such a series of points on a target is nicknamed a raster, e.g. a 10x1 raster is a line of 10 successive points. At the time of the malfunction, the instrument had performed more than 860 000 shots without any issues.

3. Instrument technical requirements

ChemCam laser provider (Thales Optronics) performed some tests to estimate the lifetime of the laser during ground tests in 2008 of the pre-launch phase. The LIBS laser was specified to 3 million shots for Mars operations and the laser components were evaluated to withstand about 20 million shots.

4. The failure

In January 2021 (Sol3007 – which was 6 terrestrial years beyond the planned prime mission as envisioned by NASA's Jet Propulsion Laboratory), the ChemCam instrument on board the Mars Curiosity rover sent data indicating that the High Voltage required for firing the laser was not as stable as usual.

The rover's fault protection system is designed for scenarios when there are anomalies within the instrument or issues that can immediately propagate to the rover. If an issue arises, the rover puts the faulted instrument into safe mode ("Sick") and pauses science operations until the issue is addressed. On this High Voltage failure, we were not in a case where the rover detected such risk. No event was raised at rover's level.

After a set of activities, the rover sent the data to one of the three orbiters that relay the data to the earth (MRO, Odyssey and TGO). Upon receipt of our data, we had to assess instrument health and safety by verifying all related telemetry. At that point, we noticed that an instrument-level alarm was raised: the High Voltage (HV) that activates the pockels cell to trigger the ChemCam laser became unstable and exceeded the alarm threshold during the third of four consecutive activities, 10x1 LIBS rasters on Mars (figure 3). The instrument first performed 600 shots, and then paused for 5 minutes (as required since we were performing more than 1000 shots within a single science block). After this pause, the instrument’s High Voltage started to be unstable until the end of this Sol’s activities. Despite this issue, our downlink assessment showed that the laser was still firing normally and the returned spectral data were normal. As usual in anomaly situations, the ChemCam operations were paused to investigate.

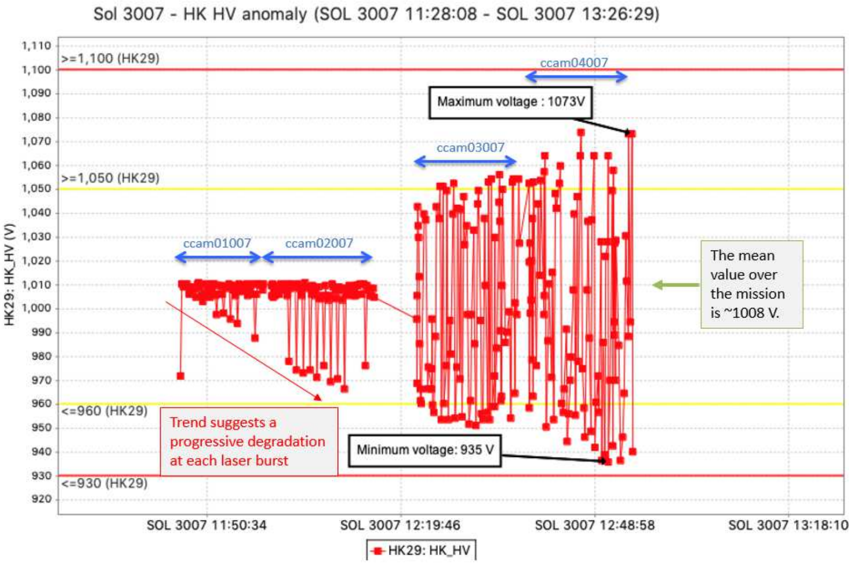


Fig. 3: Behavior of High Voltage during the anomaly (red squares connected by lines). Alarm levels are shown by yellow (alert) and red (action) horizontal lines. The four rasters are indicated by blue arrows.

The HV was usually around 1010 V, but it went much higher and lower on Sol 3007 (although it did not go below ~930 V). This HV board must provide both a High Voltage and a swift drop for the laser to fire. Fluctuations were seen even when the laser was not firing. We did not see any other signs of issues.
We reviewed the data from Sol 3007 plan and no unusual activities (at the rover level) were executed in parallel with this occurrence. No unusual parameter settings were made for this ChemCam activity.
Our first response was to keep ChemCam OFF until further analysis.

As defined in the anomaly’s management process, JPL opened an ISA (Incident, Surprise and Anomaly) report. We started the meetings immediately to identify the path forward. At this point, the main activities on our side were:

- Request JPL to remove the already on-board ChemCam commands for Sol 3009 from the flight plan to avoid any further immediate ChemCam activity.
- Estimate the risk of propagation to other parts of the ChemCam instrument or to the rover before powering ON the HV convertors again.
- Analyze all the housekeeping data to identify the root cause.
- Propose a plan to move forward to continue using ChemCam even with restrictions.

The instrument experts who designed and integrated the instrument in 2008 have been asked to assist the operational team.

5. **Recovery**

5.1 The risk of propagation

The first step was to provide JPL with an FMECA (Failure Mode, Effects and Criticality Analysis) report.

Through modeling, analysis of the electronic design, and laboratory experiments conducted during the qualification phase, it was determined that the likelihood of a failure propagating to other ChemCam functions or the rover was very low.

The main point was that the only impact associated with this anomaly was internal to ChemCam. In other words, if the HV line switch remained OFF, there was no risk of a failure occurring or propagating to other parts of the instrument and even less to the rover. This provided reassurance that there was no risk in operating in passive mode (when the convertors are not switched ON).

To better understand the anomaly, the instrument engineers at IRAP decided to build an electronic board with spare components, nearly identical to the one on Mars, and perform experiments on this board to test critical components on the ground. Fortunately, most of the components were still available in the laboratory and only two weeks were needed to assemble a board similar to the one on Mars. A series of analyses revealed that the key component was a transistor. Testing on this breadboard enabled the team to define an in-flight strategy to identify the root cause, proceeding gradually.

A decision and operational flowchart was developed to guide the test sequence at each step.

One of the more damaging propagation possibilities would have led to the loss of most of the Mast Unit's functionality due to a short circuit. Testing this hypothesis was one of the first steps: the +12V current was evaluated on the ground after an in-flight test as part of the recovery plan and this possibility was discarded (see diagram in figure 4).

5.2 Restarting the activities

As explained in the previous section, the analysis of the propagation/root cause was closely related to the restart of operations.

The first step was to confirm how to completely avoid turning on the HV as part of the recovery plan. The team identified all commands that would power on the suspect HV parts, and those commands were restricted until the necessary additional analysis was completed. The nominal sequence of activities to power the instrument included setting ON the HV line. Therefore, we had to use lower-level commands than usual.

We requested permission from JPL to restart with only a passive activity (without High Voltage in the loop) only one week after the issue. This step was authorized as we had demonstrated that no propagation to the rover or internally in the ChemCam instrument could occur with the HV line OFF. We were then under Mission Lead constraints that prevented us from using LIBS and High Voltage.

We progressively reintroduced the passive activities with only one activity per sol and with ground in the loop between each activity. A single-point passive spectrum on ChemCam's calibration target assembly was performed on Sol 3015, a 5x1 passive raster on Sol 3017, a 10x1 RMI mosaic on Sol 3020, and a passive sky activity on Sol 3022.

Following these successful steps, we were authorized to perform these passive activities regularly. Seventy-three (73) passive activities were thus performed between Sols 3020 and 3071, meaning that ChemCam was still largely used even if restricted.

Between each activity, the housekeeping data were carefully analyzed to check the behavior of the instrument with NO activation of the HV line. All data were nominal; there was no evidence of other failures. These results enabled us to present to JPL our first findings and the subsequent request to go further.

The next step was to turn on the HV for a short time and analyze the state of the High Voltage. We had imagined three scenarios:

- HV is stable for one or two points and can be used in a limited manner;
- HV oscillates when powered on, laser can be used but quality may be affected: if the data show current oscillating this would suggest that the HV issue may be propagating.
- HV current is set to zero meaning the loss of the line.

Going deeper:

After that, the instrument team spent several weeks ground-testing various modes that might cause some instability.

The main suspect was a capacitor controlling the voltage. This hypothesis was further tested by the French team on the reconstructed breadboard, in cold and hot conditions. Those laboratory tests definitively confirmed that there was no risk of propagating this issue beyond the board. Since a difference was observed between hot and cold conditions, analog tests on Mars were necessary, one cold and one hot.

The next step was to request a series of tests that would gradually reintroduce laser activities.

Between Sol 3071 (27 Mars, 2021) and Sol 3093 (18 April 2021), seven sequences of diagnostics were conducted on Mars with the flight model:

- The first HV test was designed to obtain more information about the status of the HV and its electronics. A potential degradation risk of the HV itself or its controller had been identified but was mitigated by a very short activity. We created a unique sequence to power on the instrument, take housekeeping, turn ON the convertors, take new housekeeping data and then switch OFF. This sequence was tested in the IRAP clean room (on the Engineering Qualification Model, EQM) and also on the testbed at JPL.
  The first sequence reintegrating the HV for a very short duration was uploaded on Sol 3071.
  The diagnostic of this test was that the High Voltage was stable over a duration of about 30 seconds. A modulation was visible over about five seconds immediately after power up, which might be longer than before. It was difficult to confirm this behavior because during nominal operations we do not have not those HouseKeeping data after powering on the convertors.

- The second step (Sol 3074) was to repeat this same sequence but later in the day to have warmer conditions. We observed that the modulation lasts longer at warmer temperatures, for about 13 seconds.

- Diagnostic case 3 (Sol 3076) aimed to test stability over a longer period under warm conditions. The duration of the activity increased from 30 sec to 180 sec. This confirmed that over three minutes we had no fluctuation and led us to ask the project to proceed to the next step with a single laser shot (Reminder: at that point, we still had no laser activity, only a power ON over a longer period).

- For test 4, the command sequence would perform a single LIBS shot, after being tested on the ChemCam EQM and on the testbed at JPL. This sequence was run on Sol 3081, under cold conditions. To get more information, this activity was run on one of our calibration targets to see if the laser itself was healthy. A moderate spike in the High Voltage current appeared after the laser shot, and the HV returned to its nominal stable level within four seconds. The science data also confirmed that the laser was healthy.

- Run five was held on Sol 3083. The sequence was the same as for step 4, but in warmer conditions. This test confirmed that the HV current was less stable in a warmer environment as it took longer (more than ten seconds) to stabilize.

- Diagnostic case 6 ran on Sol 3086 and aimed to perform three shots on our calibration target during the cold period of the day. The conclusion was the same as for a single shot.

- The last diagnostic case tested a different sequence of laser bursts with five initial shots, a pause, ten shots, a pause and then fifteen shots.

Figure 4 shows the diagram for this set of activities.

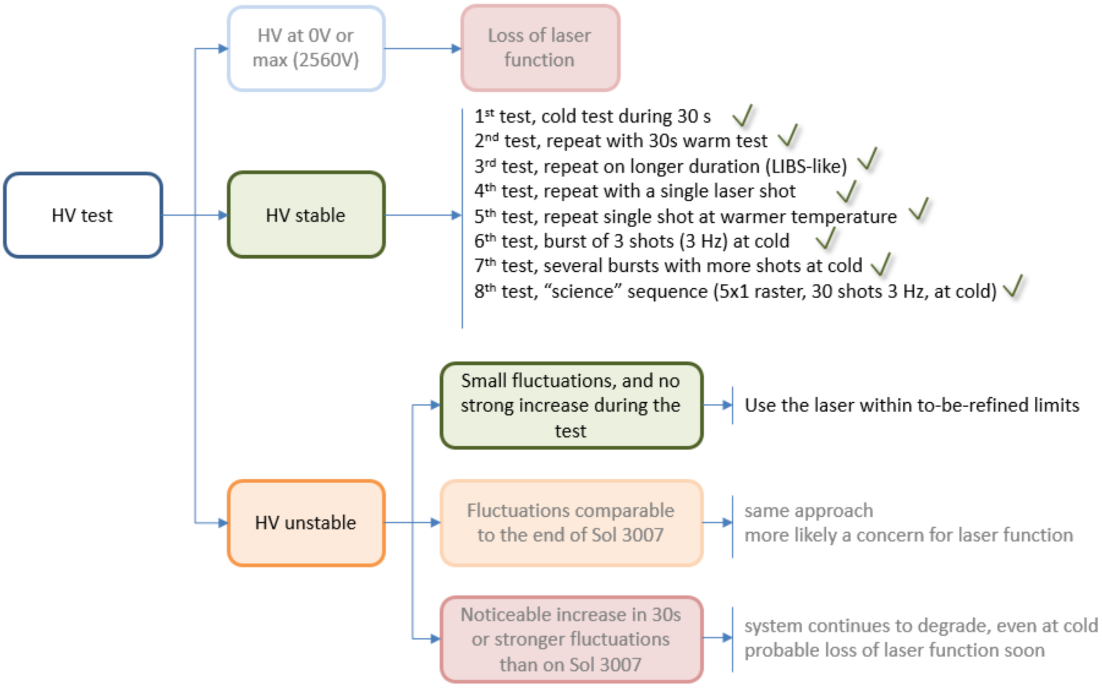


Fig. 4: Decisional recovery tree

Using all the data from this set of activities, we had more information about the state of ChemCam electronics, and we evaluated the possibility to recover the laser function of ChemCam. At that point, it was assessed that the instability could stay at a level compatible with the laser but with restrictions on use.

The seven diagnostic tests and the recovery “science” activity were successful. The High Voltage and the laser are still working and the conditions of use have been defined. Modulation of the HV is visible after a perturbation (power ON, laser fire) over five seconds (cold cases) to more than 10 seconds (warm cases), and then it stabilizes for the duration of these relatively short activities.

These results were consistent with instability in the High Voltage control loop, and suggested that the anomaly was aggravated the first time by the number of activities (number of targets, number of points) which, at that point became a limiting factor in the use of ChemCam.

At this point of the analysis, the most likely root cause seemed to be a partial failure of a capacitor in the loop controlling the HV stability: the electronic board self-warming may explain the evolution with time on Sol 3007, even if the amplitude of the oscillations seen on Mars could not be fully reproduced in laboratory.

6. Adapting our way to operate our instrument

We assessed that continuing to use the laser in the same way as before Sol 3007 was risky and could reach voltage levels either too low to operate the laser or too high and risky for the High Voltage itself.

Consequently, we had to develop a new way of using the laser in accordance with the conclusions of the expert team and to adapt to the following details:

- Use of ChemCam without the laser (i.e. passive and/or RMI activities): Having an additional passive activity after a LIBS activity, or in a separate Science block on the same sol, does not have any impact on the HV stability.
- We operated in such a way during the whole recovery period without any impact.
- Reliability of the laser: The science analysis of the calibration target spectra during the recovery period confirmed that the laser itself has no problems and only the HV control line was affected.
- Constraint on the time of day: ChemCam tests showed that the HV remains relatively stable when the instrument is cool; the laser continued to fire normally and return excellent science data.
- Consequently, use of ChemCam with the laser: These activities should be of short duration and preferably in a cold environment so that the HV remains stable.

Mission Lead constraints at the MSL project level were defined to restrict the use of ChemCam as follows:

We first reintroduced a raster of 5 points on a daily basis with ground in the loop between each raster. Thus, only five LIBS points of 30 shots were performed at a time. Note that additional commands were added to keep the HV board of the mast unit ON for as short time as possible and other commands to monitor this voltage after each event (ON, bursts).

As we have identified that the risk of occurrence of the anomaly is lower in cold conditions, a time restriction was set and initially defined as follows: the ChemCam activities should finish at the latest at 13:00 (Martian time).

At this point (Sol 3105), ChemCam activities resumed with limitations and, almost daily for each downlink, a survey report was completed with specific High Voltage and laser parameter checks.

After operating for more than 55 sols, except transient excursions at start-up, only small variations in HV were observed, within the allowed limits.

The behavior was still consistent with the most likely root cause: the degradation of a capacitor in the HV control loop.

A weak temperature dependence was confirmed over this period but remains under control with the operational constraints in place. The team having noted that the instrument was stable on all rasters since the resumption of regular activities, it was considered at this time that it was no longer necessary to have the ground in the loop between each raster, but that it was still necessary to continue to monitor the HV behavior.

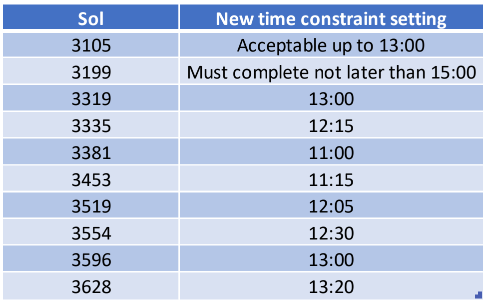
We were back in a stable situation for our instrument. Therefore, we decided to modify our script generating the LIBS raster sequences with the new way of commanding.

7. New mission lead constraints for preserving our instruments to continue performing science

Because we cannot repair the hardware on Mars, most fixes involve software or procedure updates. To solve hardware problems engineers and scientists must use the instrument differently, work around the problem, to still do the science they want to do while preserving the lifetime of the instrument. Here, the strategy required to adjust time constraints with seasonal thermal conditions.

All the restrictions are gathered in a so-called "Mission lead Constraint" managed at JPL level by MSL mission leads.

- We are still proceeding with only 5 points in the raster, only one LIBS activity per sol. An additional requirement was introduced on Sol 3319: the LIBS activity should be the first activity of a ChemCam block to avoid self-heating of the electronics before the high-voltage is used.
- After the initial time constraint, it was modified, as it is dependent on the weather on Mars. During one season, the external temperature was getting warmer and forced us to start a little earlier, then the temperatures dropped and it became possible again to start later as shown in figure 5.



Sol	New time constraint setting
3105	Acceptable up to 13:00
3199	Must complete not later than 15:00
3319	13:00
3335	12:15
3381	11:00
3453	11:15
3519	12:05
3554	12:30
3596	13:00
3628	13:20

Fig. 5: Evolution of timing constraints

At maximum, we were authorized to start a LIBS activity at 14:15. The experts at IRAP regularly update those timings. Up to Sol 3319, the definition of the time constraint was based on the end time of the activity. We decided that it was easier for planners to operate with a start time.

- Starting with Sol 3335, it was agreed that for activities longer than the nominal duration (with additional images, focus, or with autonomous targeting), the start time should be advanced to 50 minutes earlier.

With all these restrictions, the laser High Voltage is very stable. More than 700 sols after the appearance of the anomaly, this strategy enabled us to preserve the instrument and to consider the Extension of the Mission for 2023-2025.

About the future of ChemCam use

We are proud to be able to continue operating the ChemCam instrument even with restrictions, and this is very beneficial to the science team. Further technical analysis is underway to assess whether it would be possible to improve the operating conditions (more activity, longer, or later in the day) during the coldest season on Mars, although we must always be very careful.

6. Conclusions

The recovery of the ChemCam laser was accomplished through the coordinated efforts of an international team of engineers located in the U.S. and France. The teams worked on this recovery under more challenging conditions as we were in the midst of the COVID-19 pandemic, which did not allow workers to congregate as a team or even in their respective laboratories.

In 2022, what started as a two-Earth-year mission celebrated its tenth year on Mars. We have faced some problems but we are still in the game: Working around the clock in shifts, the team was able to remotely diagnose the ChemCam hardware on Mars and develop a new operational protocol for the laser. This accomplishment demonstrates effective teamwork under exceptionally challenging conditions to solve a complex problem on another planet.

The team's work and spirit for this recovery was recognized by the Explorer Club, which awarded the ChemCam engineering team the "Citation of Merit 2022".

As the next extended mission agreement for Mars Sample Laboratory begins, we are proud to have adopted this strategy that has allowed ChemCam to participate in new discoveries in Gale crater's sulfate units. The new mission extension was granted with confirmation that ChemCam will operate for three more years… and even more!

Acknowledgements

Many thanks to the JPL MSL project team for trusting us to resolve this anomaly and congratulation to the whole ChemCam team for stabilizing the instrument, allowing us to continue on this amazing mission of discovery of Mars for many years to come!

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