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Operations approach for keeping the Mars Science Laboratory ChemCam instrument safe from sun exposure

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Abstract

ChemCam is one of ten instruments on-board the NASA's Curiosity rover. ChemCam is mounted on the rover Remote Sensing Mast (RSM) and performs observations of Martian soils and rocks using Laser Induced Breakdown Spectroscopy (LIBS) as well as high-resolution imagery via its Remote Micro-Imager (RMI). Due to the geometry of internal optics, exposure of the ChemCam instrument to the sun can cause overheating and internal damage to the optical coatings and some other parts if precautions are not taken. The safety of the instrument is ensured by a set of rules that constrain the RSM motions. Those "Sun-safety" rules are implemented in the rover flight software. The Mars Science Laboratory (MSL) operations team has the responsibility to design activities that are sun-safe i.e. that are compliant with the sun-safety rules and will therefore be allowed to proceed by the rover flight software. Sun-safety rules apply not only to the ChemCam observations but also to the observations of the other cameras that are mounted on the RSM. Some of those observations require pointing the RSM and ChemCam towards the sun for science and navigation purposes; this is routinely and safely achieved by the use of dedicated operational tools and procedures.

Keywords: Mars Science Laboratory, payload operations, remote sensing, Sun exposure

Acronyms/Abbreviations
Chemistry and Camera (ChemCam)
Field of view (FOV)
Laser Induced Breakdown Spectroscopy (LIBS)
Mars Science Laboratory (MSL)
Remote Sensing Mast (RSM)
Remote Micro-Imager (RMI)

1. Introduction

1.1 The Mars Science Laboratory mission

The Curiosity rover of NASA's Mars Science Laboratory (MSL) mission has been exploring the red planet for over ten years. Since its landing in 2012, the car-sized vehicle has driven nearly 30 kilometres and climbed over 600 meters in Gale crater. Along its traverse, Curiosity has been performing in situ analysis to assess whether Mars ever was, or still is, an environment able to support microbial life [1].

NASA's Mars exploration program and its supported missions are guided by four goals:

1. Determine whether life ever arose on Mars
2. Characterize the climate of Mars
3. Characterize the geology of Mars
4. Prepare for human exploration

MSL has provided various significant results, significant advances in the pursuit of each of these goals, using the versatility of its science payload. In particular, Curiosity has demonstrated that early Mars lakes offered a biologically viable environment –one that could potentially have sustained of microbial life. These findings were made at an area named Yellowknife Bay, a shallow depression located at a few hundred meters from MSL's landing point.

The science instruments onboard Curiosity are highly capable, state-of-the-art tools for in-situ planetary science meant to aid Curiosity in its characterization of the geology, atmosphere, and environmental conditions on Mars, as well as its search for organic molecules. Curiosity's suite of science instruments include several cameras for remote imaging (Mastcam, ChemCam RMI), close-up in-situ imaging (MAHLI), and descent imaging (MARDI); two elemental composition instruments (ChemCam LIBS for remote sensing, APXS for contact); one mineralogy instrument (CheMin with contributions to some extent from Mastcam multi spectral and ChemCam passive observations); one in-situ instrument for organic and volatile characterization (SAM), a broad-scale hydrogen detection experiment (DAN), a radiation detector to understand hazards for humans (RAD), and a weather station (REMS). CheMin and SAM require powdered rock samples collected by a drill system mounted in the turret of the rover arm.

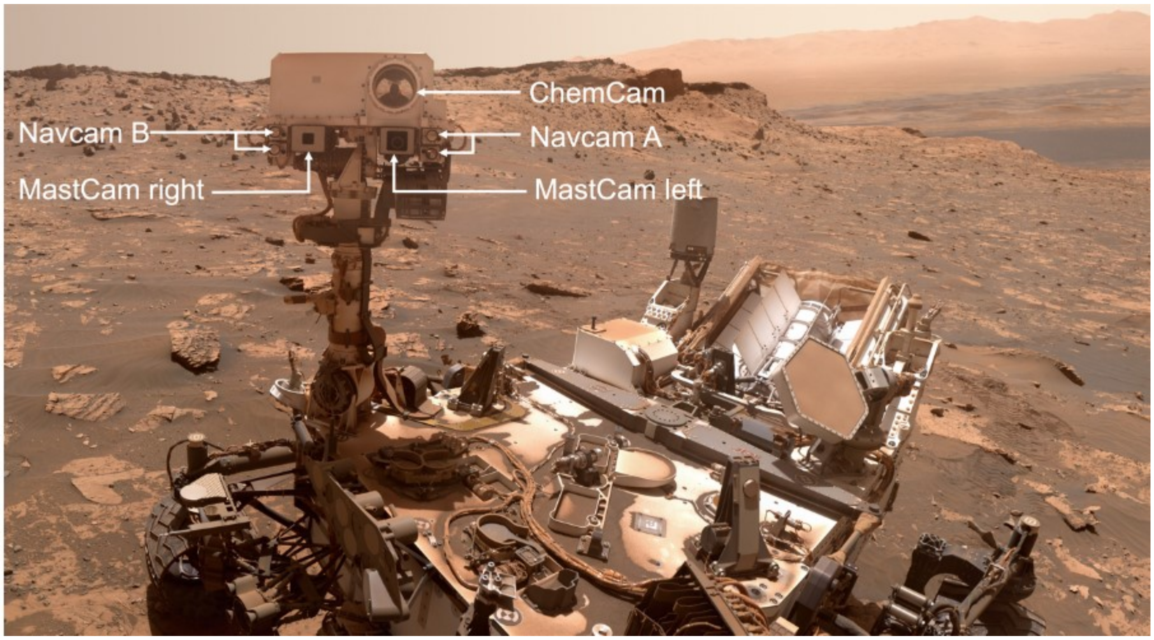


Fig. 1. Curiosity's instruments mounted on the Remote Sensing Mast. Curiosity's selfie in front of "Greenheugh Pediment" rock structure acquired on Sol 3303. Credits: NASA/JPL-Caltech/MSSS

1.2 The ChemCam instrument

1.2.1 Instrument description

ChemCam is a remote sensing instrument onboard Curiosity rover, mounted on the rover Remote Sensing Mast (RSM). ChemCam performs observations of Martian soils and rocks using Laser Induced Breakdown Spectroscopy

(LIBS), passive spectroscopy as well as high-resolution imagery via its Remote Micro-Imager (RMI). LIBS provides elemental composition measurements of Martian targets, the passive mode provides additional information of Fe-bearing minerals and some atmospheric species, and the RMI puts these observations into their morphologic context.

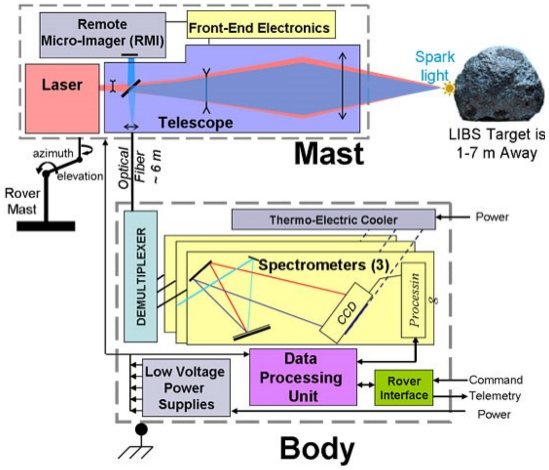


Figure 2: Block diagram of the ChemCam instrument

ChemCam consists of the first laser-induced breakdown spectroscopy instrument in planetary sciences, along with a telescopic remote micro-imager yielding the highest resolution remote rover images to date [www.msl-chemcam.com]. The purpose of the LIBS instrument is to provide elemental compositions of rocks and soils within about 7 meters, while the RMI gives scientists high-resolution images of the areas sampled by LIBS for context. In the LIBS technique, laser pulses are focused onto a sample. At sufficient power densities, that is, at more than 10 megawatts per square millimeter, atoms are ablated in excited states, and emit light [2,3]. The composition is then determined by spectrally resolving the emission lines characteristic of the elements, and calibrating them. The RMI provides the highest resolution rover images, after MAHLI in the arm workspace, and thus ChemCam is also used as an imager of geological features at longer distances.

As shown in Figures 2 and 3, the ChemCam instrument suite consists of two units: the Mast Unit contains the telescope, laser, remote micro-imager, and front-end electronics, while the Body Unit contains three spectrometers, a demultiplexer, a thermo-electric cooler, a data processing unit, power supplies, and the rover command interface. The Mast Unit focuses its telescope on a target, generates a series of laser pulses, and collects light for the LIBS analysis. It also takes images with the RMI. It is mounted atop the MSL mast to benefit from the mast's pointing capability. The telescope is required 1) to concentrate the laser beam onto the target, 2) to collect laser-induced plasma light, and 3) to acquire images for the RMI. It is a simple and compact Schmidt-Cassegrain telescope, with a fixed 110 mm diameter mirror and a moving secondary mirror.

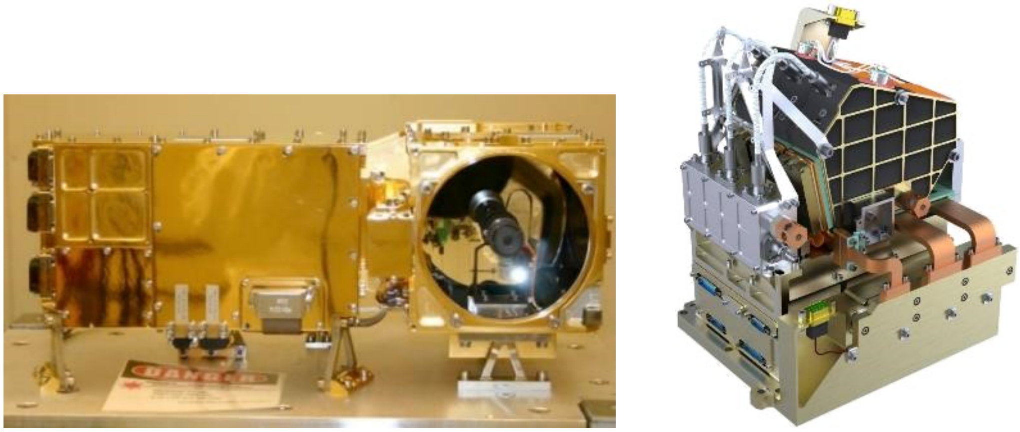


Figure 3: ChemCam Mast Unit (left) and Body Unit (right) flight units

1.2.2 Instrument sensitivity to Sun exposure

ChemCam is an instrument that focuses and collects light, using a Schmidt-Cassegrain telescope for LIBS and RMI measurements. As such, ChemCam is sensitive to Sun exposure, which can cause overheating and internal damage to the optics, the sensors, and some other parts.

Depending on the focal position of the secondary mirror, there are two different risks that could damage the instrument when pointed towards the Sun :

1. When the focus stage of the telescope is in "Sun-safe", a range of distances around 2 meters, the light coming from a source at infinity, such as the sun, is not focused directly on the optical components but still causes internal heating of the secondary mirror baffle. If this hot spot is stationary during an exposure that lasts more than a few minutes, the thermal load poses a risk for the secondary mirror and its baffle.
2. When the focus stage is in the "Sun-unsafe" range, overheating can affect various internal critical components such as the optic fiber or the CCDs, depending on the focal position. Damage can happen within a few seconds and result in severe degradation of the instrument's performances or even the loss of some of its capabilities.

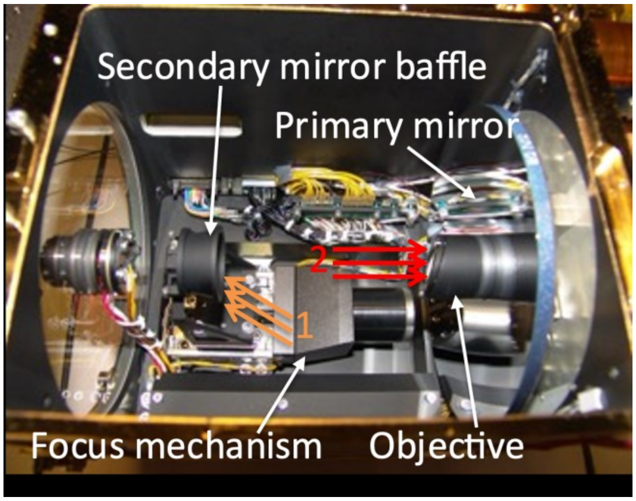


Figure 4: ChemCam risks for hardware due to overheating depending on focus position: (1) when "Sun-safe": exposure of secondary mirror baffle (2) when "Sun-unsafe": exposure of optic fiber and internal optics

2. ChemCam Sun-safety principles

2.1 Sun-safety architecture

The ChemCam Sun-safety strategy is defined as a set of operational rules that constrain the RSM pointing, in order to prevent any excessive heating on a single point or on sensitive optical parts that could damage the instrument. The ChemCam Sun-safety strategy applies not only to the ChemCam observations but also to the observations of the other cameras that are mounted on MSL's RSM- namely the Mastcam and Navcam cameras, which are pointing in the same direction as ChemCam (see Figure 1). Despite the constraints imposed by ChemCam Sun-safety, remote sensing instruments routinely execute observations requiring direct pointing of the sun – e.g. measurement of the atmospheric opacity by Mastcam or sun imaging by Navcam for rover attitude updates.

These operational rules are driven by the hardware risks exposed in the previous section and are divided into two categories:

1. When ChemCam focus stage is in the Sun-safe position range: the instrument can tolerate brief, passive transits of the Sun in its field of view, but cannot track the Sun for more than 3 minutes. This regime is typically used for observations made by other cameras than ChemCam, including observations that directly point at the Sun.

2. When ChemCam focus stage is in the Sun-unsafe position range: the Sun is not allowed to enter in a cone angle slightly larger than the ChemCam field of view to which margins are added. This regime is dedicated to ChemCam observations only.

The Sun-safety rules are implemented in the rover flight software to constraint the RSM motions and ChemCam focus displacements: if an observation violates a Sun-safety rule by attempting to move the RSM or the ChemCam focus stage, the rover flight software will reject the faulty command.

A summary of these rules is exposed in the next paragraphs of this section. For more details about the design of the Sun-safety strategy for MSL, please refer to [4].

2.2 RSM-mounted instruments observation in Sun-safe focal range

When ChemCam is Sun-safe, it means that the focus stage of the instrument position is at 2 ±0.2 meters and that it can tolerate Sun-exposure during a limited period. The Sun-safety policy protecting ChemCam when in Sun-safe position is controlled by 4 parameters:

1. **The ChemCam Sun-Safe Cone**, defined as a 16° half angle around ChemCam boresight. When the Sun stays within the ChemCam Sun-Safe Cone more than the **allowable tracking time**, subsequent RSM motions must point outside the ChemCam Cooldown Cone, defined as the ChemCam Sun-Safe Cone plus a 3.65° margin corresponding to 15 minutes of Sun motion.

Cone Sizing Source	Cone Contribution
ChemCam Sun-Safe Sensitivity	8°
Angular Margin	3°
Maximum Attitude Error	5°
Total Sun-Safe Cone	**16°**
15 minutes of Sun motion	3.65°
Total Cool Down Cone	**19.65°**

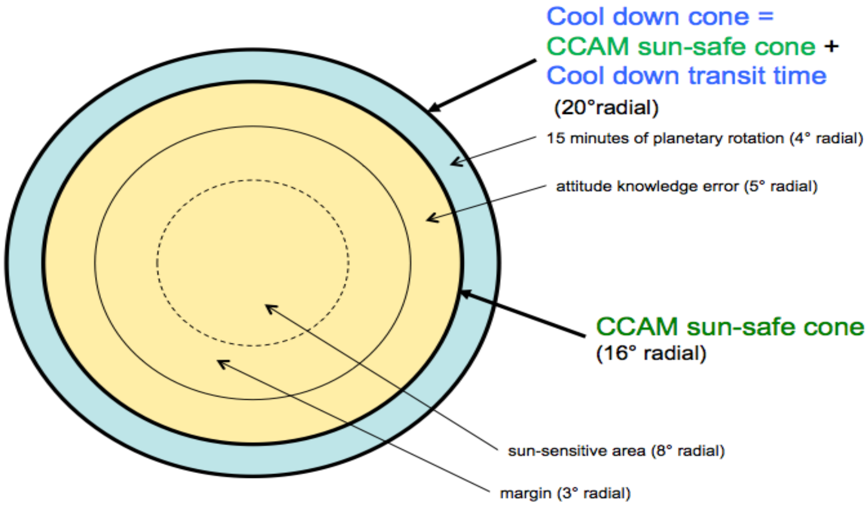


Figure 5: Definition of ChemCam Sun-Safe Cone and ChemCam Cooldown Cone, each contributor includes its own margins

2. **The allowable tracking time**, defined as the 3-minute maximum duration during which the RSM can track the Sun inside the Sun-Safe Cone. As long as this 3-minute duration is not expired, all RSM motions are allowed. When this duration is elapsed, the RSM cannot point inside the Cooldown Cone anymore. Passive transits of the Sun in the Sun-Safe Cone are allowed, but if an RSM motion is commanded, it must end outside the Cooldown Cone.

3. **The cooldown time**, defined as the 15-minute duration required before the Sun can re-enter the ChemCam Sun-Safe Cone, once the allowable tracking time is elapsed. Thus, if the Sun did not enter the ChemCam Sun-Safe Cone in the past 15 minutes, all RSM motions are allowed.

4. **The cooldown horizon**, defined as the elevation below the local level plane (0° astronomical elevation) under which ChemCam boresight must be pointed to ensure that the instrument is cooling. The planetary horizon is modelled at 4° below the local level plan to take into account the curvature of Mars, as seen from the altitude of the peak of Mount Sharp. Therefore, the cooldown horizon is defined at 20° below the local level plane, in order to ensure that the whole 16° half-angle Sun-safe Cone is below the planetary horizon.

An additional requirement for allowing RSM motions while ensuring ChemCam Sun-safety is that the rover attitude is deemed as well estimated by the rover flight software.

2.3 ChemCam observations in Sun-unsafe range

When ChemCam is in the Sun-unsafe range (i.e. when its focus stage is not in the 2 ±0.2 meters range), it cannot tolerate any exposure to the Sun. The Sun must not enter the 13° **ChemCam Sun-Unsafe Cone**, defined as explained below.

FOV Sizing Source	FOV Contribution
ChemCam Observation Sensitivity	5°
Angular Margin	3°
Maximum Attitude Error	5°
Total Sun-Unsafe Cone	**13°**

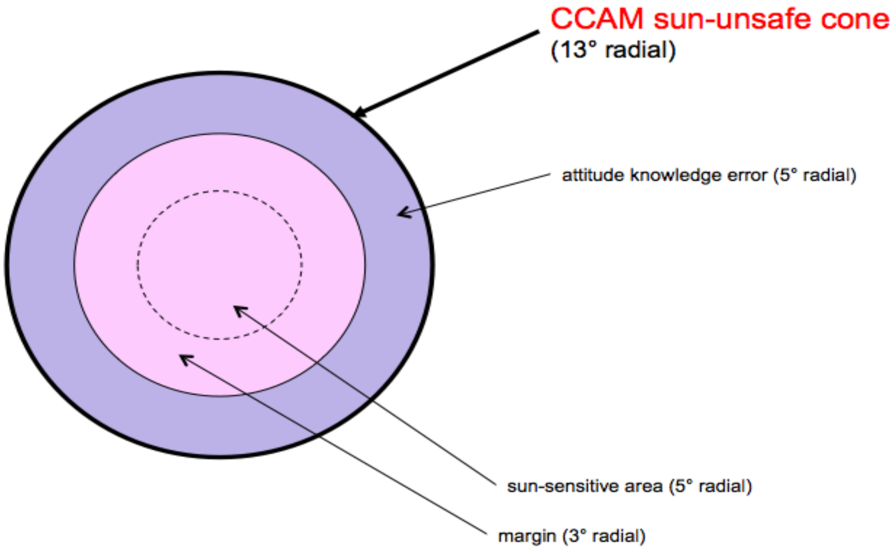


Figure 6: Definition of ChemCam Sun-Unsafe Cone

An additional margin of 4° is added by the rover flight software to account for the fault recovery time. This angular margin covers the event of an RSM anomaly that would leave ChemCam pointed in the sky, guaranteeing that at least 16 sols would be available to recover from such a situation, before the Sun could enter into the telescope field of view.

Similarly to the Cooldown Horizon for the Sun-Safe Cone, the **Sun-Safe horizon** defines the elevation under which ChemCam boresight can be safely pointed. This maximum elevation is 17° below the local level plane, which ensures that the whole Sun-Unsafe Cone of 13° is below the planetary horizon (4° below the local level plane).

The requirement of having a good quality for the rover attitude when pointing the RSM also applies when ChemCam is in the Sun-Unsafe range. In addition, the pointing with a Sun-unsafe focus position, must be compliant with the rules described in this section for the entire day, that is the mast cannot point in a location where the Sun will be in the next 24 hours.

2.4 Terrain Cones

A functionality named **Terrain Cones** has been introduced in the rover flight software to take into account the real local horizon instead of the planetary horizon. The motivation for this is to observe features such as buttes or hillsides that block the sun. Flight software's sun-safety logic checking has no way to know about such features and would normally reject the observations.

The Terrain Cones are placed by the MSL operations team over the terrain features of scientific interest, using a specific set of commands that is sent to the rover. A Terrain Cone is defined via the coordinates of its center and its half-angle. Several Terrain Cones can be combined to cover larger areas. This functionality must be used with care, as it suspends the flight software sun-safety logic checking.

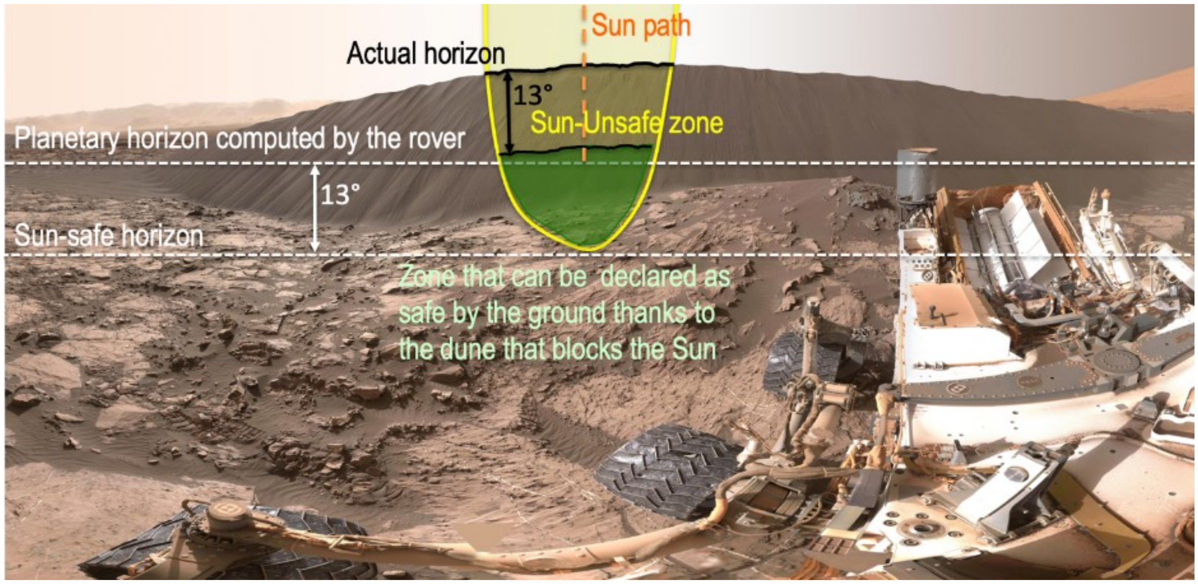


Figure 7: Example of use for Terrain Cones: the green area is safe for ChemCam observations as being 13° below the actual horizon. The ground has to declare the area as safe because the rover flight software has no way to know the actual horizon. "Namib Dune" panorama acquired on Sol 1197. Credits: NASA/JPL-Caltech/MSSS

3. Sun-safety in operations

3.1 Sun-safety as an operational constraint

As exposed in the previous section, the rover flight software Sun-safety module guarantees that ChemCam is not endangered by Sun exposure. This protection is achieved via a complex set of rules, that depend on several parameters such as the time of observation, the rover attitude or the focus position of ChemCam. The MSL operations team has the responsibility to design activities that are Sun-safe i.e. that are compliant with those sun-safety rules and will hence be allowed to proceed by the rover flight software. The goal is not to waste valuable time on Mars with activities that can be predicted to fail.

Consequently, each observation that points the RSM near or in the sky has to be cleared beforehand from the Sun-safety point of view, to ensure that it will succeed. This is ensured by the operations engineers in charge of programming the remote sensing instruments but also by the scientists in charge of selecting remote science targets and activities constitutive of the rover plans. Sun-safety constraints have been integrated in the operational procedures of the different science and engineering roles involved.

3.2 Strategic and tactical processes for Sun-safety checks

As detailed in [5], MSL operations are divided into strategic and tactical planning processes:

- The **strategic planning process** covers the next 10 to 100 sols - a sol being a solar day on Mars. Its goal is to develop a high level science investigation plan, including measurement objectives and a traverse route to meet those objectives. The strategic planning process also aims at preparing and validating new or complex activities.

  From the Sun-safety perspective, the strategical process is dedicated to build new activities that could potentially pose Sun-safety concerns; involved activities are atmospheric or Sun observations. Here is a list of activities that have been strategically approved for ChemCam Sun-safety:
  - ChemCam atmospheric measurements such as passive spectroscopy of the sky
  - MastCam Tau measurements: opacity measurements that acquire images of the Sun
  - MastCam Sunset and Sunrise movies
  - Rover Sun-find and attitude updates procedures, using Navcam to point at the Sun
  - Navcam supra-horizon movies
  - Navcam / MastCam Phobos/Deimos transits imaging
  - …

  Those strategically approved activities are defined by template activities with associated Sun-safety requirements such as the Sun position at the time of observation or the maximum activity duration.

- The **tactical planning process** aims at programming the next sol - or the next couple of sols - based on the latest data available from the rover telemetry. The daily tactical planning ends with the set of rover commands for the next sol plan being sent to Mars.

  Tactical planning involves Sun-safety checks for all cameras mounted on the RSM: for each plan, ChemCam, MastCam and Navcam tactical teams have to make sure their activities are cleared for Sun-safety. For activities that have been strategically validated, they can be instanciated on a given sol, and the tactical team must then verify that the Sun-safety requirements are met.

  Examples of Sun-safety tactical checks are provided in the next paragraph.

3.3 Examples of Sun-safe activities tactical implementation

All screenshots in this paragraph are from the MSLICE tool developed by California Institute of Technology / Jet Propulsion Laboratory. It provides a visualization of the instruments footprints as well as a representation of the different safety cones described in section 2.

3.3.1 Navcam dust devil survey and supra-horizon movie

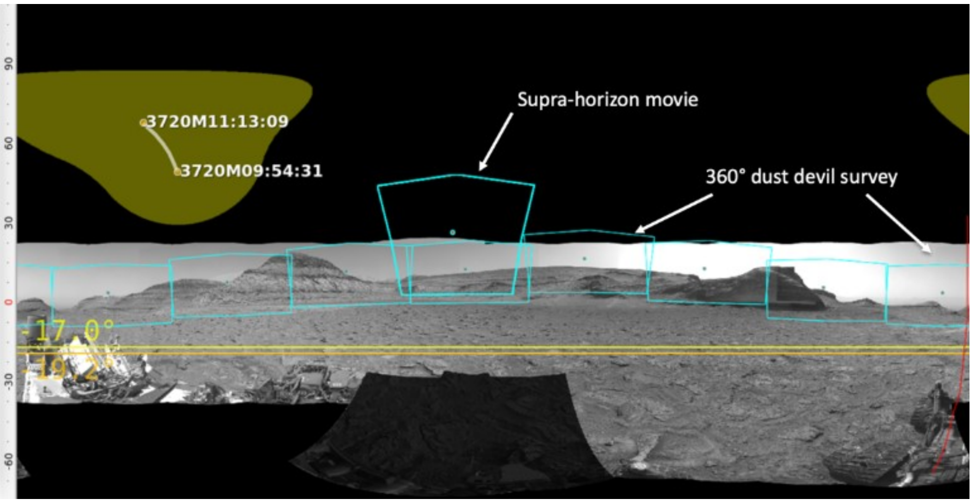


Figure 8: Sun-safety check for a Navcam 360° dust devil survey and a supra-horizon movie on Sol 3720.

In Figure 8, blue footprints indicate the frames acquired near the horizon during two Navcam observations, a supra-horizon movie (one pointing) and a 360° dust-devil survey (8 pointings). The yellow zone is the ChemCam cool-down cone around the Sun, expanded over the period of the observations, in other words the portion of the sky that might cause ChemCam warming during the span of those Navcam observations. Note that ChemCam focus stage is necessarily in Sun-safe position when the RSM is moved by other cameras than ChemCam (constraint enforced by the rover flight software). Both activities passed Sun-safety as the footprints stay away from the yellow zone.

When Navcam or MastCam is pointing inside the yellow zone, the observation must be strategically approved and meet the timing constraints exposed in section 3 (essentially do not track the Sun for more than 3 minutes).

3.3.2 ChemCam long- and short-distance observations

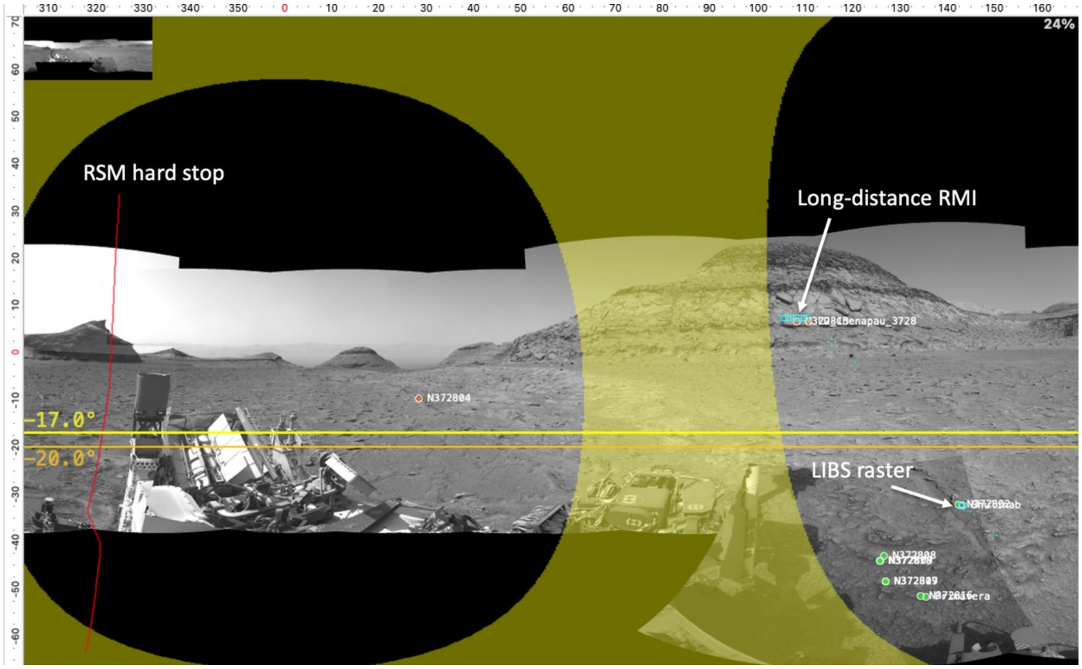


Figure 9: Sun-safety check for two ChemCam observations on Sol 3728: a long-distance RMI and a LIBS raster at short distance

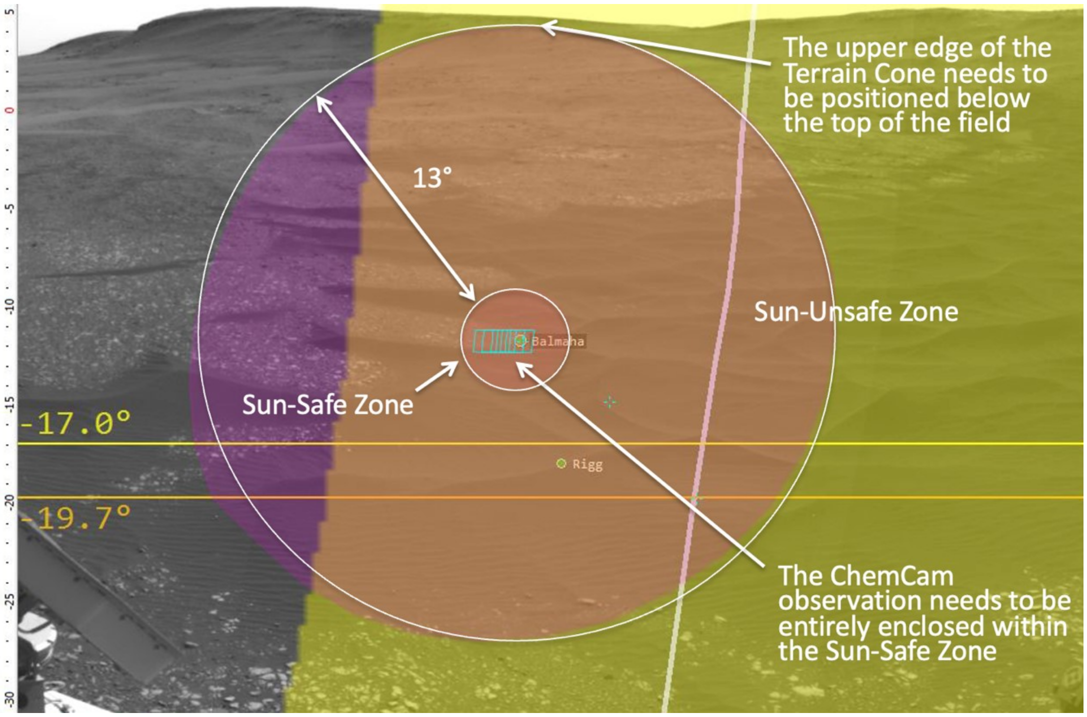
As in the previous paragraph, blue footprint represents science observation in Figure 9- here ChemCam LIBS and RMI observations. The yellow zone is represented over the entire sol duration and matches the checks performed by the flight software for Sun-safety. The long-distance imagery activity footprint is close to but outside the yellow zone.

The LIBS activity at short distance is below the Sun-safety horizon of -17° in local level and therefore passed Sun-safety.

A special attention must be paid to RSM motions taking place between activities: indeed, the flight software does not allow RSM motions to cross the yellow zone above the Sun-safety horizon if ChemCam focus stage is in the Sun-unsafe range. In such situation, ChemCam operations engineers have to command the focus stage in the Sun-range prior to the problematic RSM motion.

Note that the RSM hard stop constrains the RSM motions and its position relatively to the various observations must be taken into account when assessing the Sun-safety of RSM motions between observations. RSM hard stop location is represented in MSLICE (see Figure 9).

3.3.3 ChemCam Terrain Cones



The upper edge of the Terrain Cone needs to be positioned below the top of the field

The ChemCam observation needs to be entirely enclosed within the Sun-Safe Zone

Figure 10: Sun-safety check using a Terrain Cone for a ChemCam RMI observation on Sol 2402.

This RMI observation on Sol 2402 used a Terrain Cone feature in order to image a target in the yellow Sun-Unsafe zone above the Sun-safety horizon. The inner rose cone is the safe zone created by the Terrain Cone. In order to pass Sun-safety checks, the footprint of the ChemCam observation must be entirely enclosed within the inner cone, and the outer purple cone must be positioned below the top of the field. The outer cone is 13° larger than the inner cone, in order to comply with the margins associated to the Sun-unsafe cone described in paragraph 2.3.

4. Lessons learned

4.1 Operational processes improvements

The Sun-safety checks performed by the operations teams involves a number of geometrical constraints and durations considerations that were not always easy to assess in the first months of the mission. The Sun-safety process was then somewhat error-prone and time-consuming. However, after 10 years of operations, the science activities have been standardized and uplink procedures for Sun-safety have been improved, as well as the training of the new operators. Also, the Sun-safety module of the MSLICE tool has been upgraded to provide a higher level of automation when generating Sun-safety reports. These various improvements were part of a more global effort that led to shorten the operational timeline of about 50% over the years.

4.2 Sun-safety design for the Mars 2020 mission

The Mars 2020 mission is the latest of NASA's rovers that landed in Jezero crater on Mars in February 2021. The mission also has to deal with Sun-safety constraints since its Perseverance rover embarked SuperCam, the ChemCam successor instrument, with a similar optical concept using a Schmidt-Cassegrain telescope.

A first improvement to SuperCam was to modify the design of the secondary mirror baffle in order to reduce the absorbed heat by 30%. The thermal conductance of the mirror support was also increased by a factor 2 compared to ChemCam. Those changes make the instrument able to sustain a full sol of Sun-tracking when focused in the Sun-safe range. Please refer to [6] for more details. This essentially removed all Sun-safety operational constraints when SuperCam focus stage is in the Sun-safe range.

Besides, various angular margins have been reduced, based on the modified instrument design, better knowledge of the rover's attitude error and RSM pointing accuracy, and better estimation of various uncertainties, but also due to the flatter topography of Jezero crater compared to Gale crater. These modifications saved a total of about 7° of angular margin, lifting the Sun-safety constraints on significant areas around the rover. Also, the Mars 2020 operations processes have inherited from the operational improvements described in the previous paragraph.

5. Conclusions

ChemCam Sun-safety in operations processes arise from the two modes that are implemented into the rover flight software i.e. when ChemCam is focused in the Sun-safe range and when it is focused in the Sun-unsafe range. Those two modes are derived from the two types of risks posed by Sun-exposure to the ChemCam hardware. The Terrain Cones functionality was introduced to allow some additional flexibility when terrain features around the rover, such as buttes or dunes, block the sunlight.

A number of lessons have been learned from 10 years of managing the Sun-safety in operations with MSL: the Sun-safety operational process was improved to streamline operations. In addition, SuperCam, the ChemCam successor instrument, has benefited from an improved design that restricts surface activities less without increasing the hardware risks from Sun exposure.

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