SUPERCAM AUTOFOCUS MECHANISM: COTS EQUIPMENT DESIGN AND QUALIFICATION PROCESS FOR SPACE USE OF GROUND EQUIPMENTS

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ABSTRACT

The Mars 2020 will launch in July 2020 a single rover that will land and operate on the surface of mars. M2020 intends to conduct a Mars habitability investigation, with habitability defined as the "capacity of the environment to sustain life", i.e., the potential of a given environment to support life at some time, past or present.

SuperCam is one of the new French contributions to Mars Science Laboratory (MSL) instrument suite. The focus system of SuperCam is made of the secondary mirror of the telescope, mounted on the focus mechanism. Integrated in a compact opto-mechanical system, this mechanism is aimed to adjust the focus of the SuperCam telescope. SuperCam instrument functionality relies on an autofocus capability to precisely focus on the chosen target. The autofocus function is performed by this mechanism that translates the secondary mirror, with high repeatability, over the 15 mm stroke, and in the full applicable range of temperatures. Except the end-of-course sensors, this mechanism (provided by PI miCos) is exactly the same as the ChemCam one (Curiosity). Indeed, a ground COTS translation stage (PI miCos MT-40) was chosen and modified to meet the last mission requirements.

In the context of Mars 2020 mission, the same approach has been preferred: validate a ground COTS design by a qualification tests campaign.
This document will present:

- The COTS equipment design with a focus on the end-of-course sensors (Hall effect components)
- The qualification process followed (phases B/C)
- A feedback on space use of ground equipment

INTRODUCTION

The mission will focus on a roving, long-duration science laboratory that will provide a quantitative improvement in surface measurements and pave the way for future Martian surface and sample return missions. The assessment of habitability is to be made through multidisciplinary measurements related to biology, climatology, mineralogy, geology and geochemistry in terrain, which may include (depending on the site selected) sedimentary, hydrothermal and ancient deposits. The SuperCam instrument will provide powerful techniques to help the M2020 rover to reach these scientific goals.

SUPERCAM instrument concept

The SuperCam instrument is an evolution from the successful ChemCam instrument on MSL-Curiosity. In addition to the existing elemental capabilities (LIBS – Laser Induced Breakdown Spectroscopy), a new Raman spectroscopic analysis is implemented, coupled to an infrared spectrometer, and a microphone. To help context imaging, an improvement of the Remote Micro Imager (RMI) is done with a new color detector.

The SuperCam package consists of three separate major units – "Body Unit", "Mast Unit" and "Calibration Targets",which are further broken down into modular components. The Mast Unit is provided by IRAP (Toulouse, France), while LANL (Los Alamos, NM) is building the Body Unit. The IRAP and LANL portions are entirely separated mechanically, greatly simplifying interface controls as well as development across international boundaries. The University of Valladolid (Uva) in Spain is primarily responsible for the SuperCam on-board calibration target assembly.

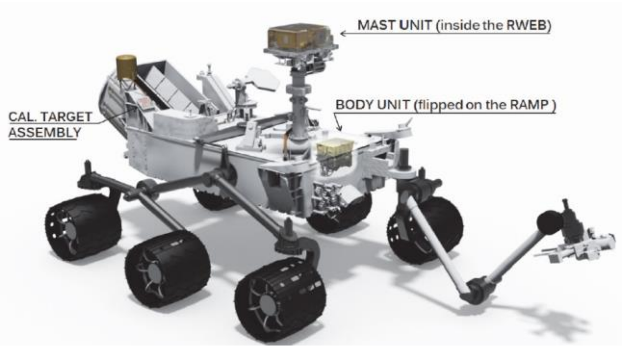


Figure 1 : CAD view of the Mars 2020 rover

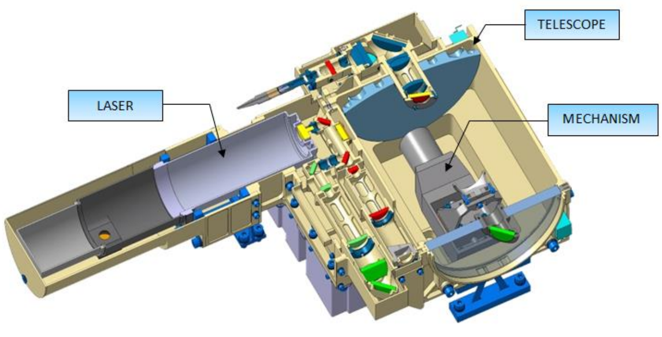


Figure 2 : Exploded view of SUPERCAM instrument

The Mast Unit (SCMU) consists of a telescope with a focusing stage, a pulsed laser and its associated electronics, an infrared spectrometer, a color CMOS micro-imager, and focusing capabilities.

The Body Unit (SCBU) consists of three spectrometers covering the UV, violet, visible and near-infrared ranges needed for LIBS.

In addition, a set of calibration (SCCT) targets mounted on the Rover will enable periodic calibration of the instrument.

1- SPECIFICATION

The performances specified for the autofocus mechanism of SuperCam are summarized in the table 1.

Function	Characteristics	SuperCam targets
Design	Total mass	< 300g
	Volume	110 x 55 x 30 mm^3
Power consumption	Normal mode	2.4 W
	Boost mode	3.2 W
Kinematic performances	Speed	10, 50, 100, 150 steps/s (= 12.5 to 187.5 µm/s)
	Translation range	15 mm
	Absolute position	30 µm
	Resolution	1.25 µm (powered)
		5 µm (unpowered)
	Autofocus precision (with repeatability)	< 5 µm
Interference of movements	Translation (out of translation axis)	50 µm
	Rotation (around travel axis)	2/3 ArcMin
	Stability	3 µm for 10s
Thermal environments	Cruise (UHV Storage)	50°C
	Non-operating	[-55°C ; +60°C]
	Operating	[-40°C ; +55°C]
Mechanical environments	Shocks	1400 g @ 1600Hz
	Random vibrations	All axis : 7.9 G rms
Life time	On ground	6 000 cycles
	On Mars (operational)	18 060cycles
	Operating life	Ground : 5 years Cruise : 10 months Mars : 1 Martian year
Sensors	Electrical travel range	> 13 mm
	Absolute precision of the stop position	10 µm

Table 1: Mechanism requirements

In order to cover the delta between the ChemCam and the SuperCam mechanisms requirements, the dedicated development plan was to accept and qualify the batch by tests in representative environments. In this way, all performances have been measured to check the conformance of each COTS models with the expected operating performances.

Using this technique, without dimensioning studies, the major risk is to fail during the acceptance tests or qualification tests sequences.

2- COTS AUTOFOCUS MECHANISM DESIGN

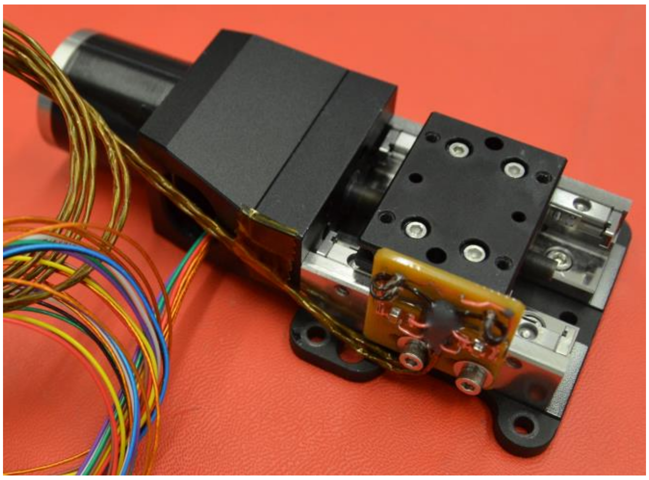


Figure 3 : SuperCam autofocus mechanism

Mechanical architecture

The « autofocus mechanism » assembly is made up of 4 subassemblies:

1- The motor stage
→ Phytron stepper motor : ZSS25-200-0.6A
2- The stage for guiding the screw in the fixed part
→ Stainless balls bearing
3- The movement conversion stage
→ Screw/nut system lubricated with Ultratherm 2000 and Dicronite ++
4- The stage for guiding the mobile part (slider) which ensures the straightness of the displacement
→ Guide rails and stainless steel roller cages

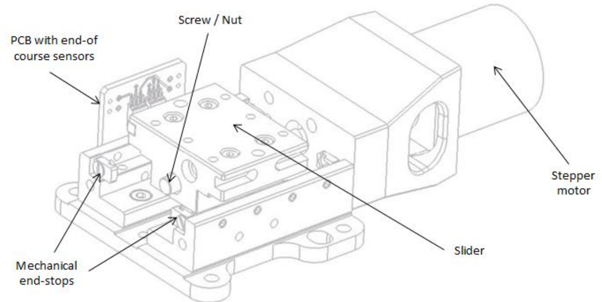


Figure 4 : Global view of the autofocus mechanism

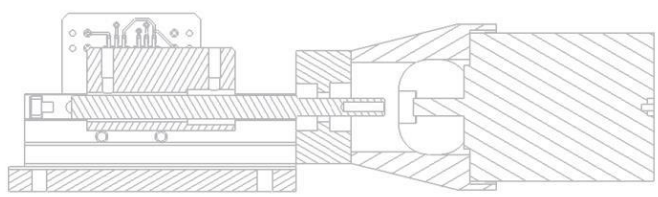


Figure 5 : Sectional view of the autofocus mechanism

Motorization

The motorization stage is based on a Phytron stepper motor (ZSS-25-200-0.6A). The main characteristics of the motor are presented below :
- Current rating : 600 mA (800 mA in boost mode)
- Angular step : 1.8 ° (i.e. 200 steps / revolution)
- Holding torque : 12 mN.m
- Detent torque : 2 mN.m
- Winding resistance (parallel connection) : 3.25 Ohms
- Winding inductance : 1.5 mH

End-of course sensors and magnets

a- Trade-off

As a reminder, the ChemCam mechanism was equipped with one electrical-stop comprised of an Infineon differential magnetoresistive sensor (FP-212-L-100-22) and a Permalloy pastille.

In the context of SuperCam, the need is a little bit different. In fact, two key functions are required :

- Safety function : prevent displacement in mechanical-stop for both moving directions
- Reset function : ensure one (or two) reference position(s) in case of motor steps counter loss

Given the impossibility of supplying the ChemCam sensor technology (end of production with no stock available), a trade-off was carried out. Thus, a few position sensor technologies have been considered. The main conclusions are listed in the table 2.

Finally, the choice fell on the Hall Effect sensors (Optek – OMH3075B). In fact, two main factors led to this choice :

- The contactless capacity in order to preserve the maximum motorization margins.
- The current qualification level in order to be compliant with the schedule constraints

In order to cover the need of electrical-stops in both directions, two sensors have been integrated on each mechanism of the batch. A dedicated PCB has been developed; it is shown on figure 6.

Figure 6 : PCB with the two end-of-course sensors

Sensor technology	**Positive side**	**Negative side**
Magnetoresistive Infineon FP-212-L-100-22	Contactless technology Chemcam feedback	Unavailability Measures impacted by temperature variations (at least in ChemCam configuration)
Magnetoresistive Sensitec GF708 or AL798	Contactless technology Martian rovers feedbacks (Curiosity, Opportunity) Precision Repeatability Measures not impacted by temperature variations	No qualification status in Europe Need to be entirely qualify (impact planning)
Hall effect Optek OMH-3075B	Contactless technology Space component European space program feedbacks Precision Repeatability	Measures impacted by temperature variations
Mechanical switches Panasonic AV4FU	PI miCos nominal design for ground application Easy implementing Low cost	Contact technology Complexity of integration Need to be entirely qualified (impact planning) Precision Repeatability
Reed switches	Contactless technology Easy implementing Low cost	Precision Repeatability Need to be entirely qualified (impact planning)
Strain gauges	Easy implementing	Contact technology Need to be entirely qualified (impact planning)
Absolute encoder (linear/multi turn)	Contactless technology Precision Repeatability	No spatialized component Need to be entirely developed (high cost) Need to be entirely qualified (impact planning)

Table 2 : Comparative table of envisaged sensors technologies

b- Magnets

In order to excite the sensors, customized magnets have been provided by Arnold Magnetics. The main characteristics are listed hereafter:

- Material : Recoma 28
- Parallelepiped shape : 2.5 mm x 2.5 mm x 4 mm
- Magnetizing
- Stabilized : 2 hours at 150°C

c- Design and measure principle

The electrical end-stops are based on two Hall Effect sensors (one per side) mounted on the lateral bench (fixed part) and two magnets glued on the slider (mobile part).

The output voltage of the Optek sensors change depending on the magnetic field :

- $V_{OUT} = V_{IN} = 3.3$ V
  if the sensor is exposed to the North Pole (in red)
- $V_{OUT} = 0$ V
  if the sensor is exposed to the South Pole (in blue)

This sensor is a bi-polar device. So, the output voltage stays constant while the sensitive area is not exposed to the opposite magnetic field.

As it is presented on the view, the sensor called “Close focus” is located on the “Infinite focus side” and the sensor called “Infinite focus” is located on the “Close focus side”.

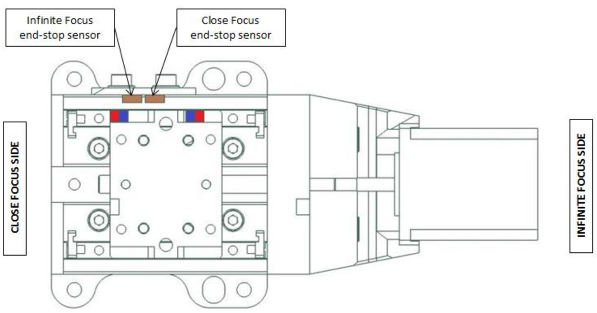


Figure 7 : Upper view of the mechanism with the magnets and sensors positioning

d- Electrical end-stops performances

These sensors are processed to Optek’s military screening program patterned after MIL-STD-883. These components have passed Radiation Hardness testing up to 350 Krad per MIL-STD-883 method and up to 150 Krad for ELDRS.

Throughout the supply, these factory tests have been required :

- Read/ Records 100% screening Group A, B, C
- PIND Test

To complete these tests (at components level), the CNES has performed a Destructive Physical Analysis in laboratory on 3 models.

After integration on autofocus mechanism, the sensors performances have been measured. First, the running-in phase (1000 end to ends) was a very good opportunity to switch-on / switch-off the electrical-stops. The absolute position of the slider (mobile part) is measured with an optical encoder (Codechamp, 21 bits).

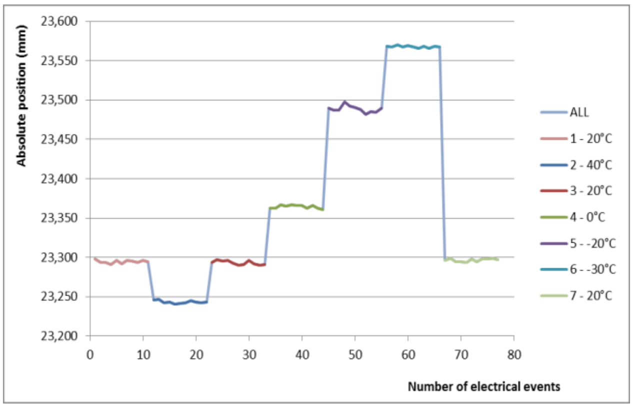
The table below presents the position repeatability measured at constant temperature (ambient room) for each electrical event.

Model		SN2	SN3	SN4	SN6
CLOSE FOCUS	ON	0,005 mm	0,006 mm	0,01 mm	0,007 mm
		99,3%	99,9%	98,9%	99,9%
	OFF	0,005 mm	0,005 mm	0,01 mm	0,007 mm
		97,8%	99,7%	96,8%	99,6%
INFINITE FOCUS	ON	0,006 mm	0,005 mm	0,01 mm	0,008 mm
		99,7%	99,9%	99,1%	99,9%
	OFF	0,006 mm	0,005 mm	0,007 mm	0,006 mm
		98,5%	99,6%	96,1%	99,6%

Table 3 : Standard deviations measured on 1000 samples

Note: Values in percent represent the effective sampling after aberrations suppression.

In a second time a characterization in thermal environment has been performed on a model.



Graph 1 : Absolute position for each Infinite focus switch-on in thermal environment

As observed, for a given thermal plateau, the repeatability is very fine (lower than 10µm). Nevertheless, this good repeatability strongly depends on the temperature stability.

But as the 3 measures done at 20C show reproducibility and precision the dispersion due to the thermal environment could be compensated for using a temperature table

3- ACCEPTANCE & QUALIFICATION

Logic for a batch acceptance campaign

As for the ChemCam autofocus mechanism development, it was planned to supply a lot of 5 flying autofocus mechanisms. This batch had to undergo an extended acceptance campaign including :

- Guidance quality measurements
- First Eigen mode research
- Bake out (60°C during 50 hours)
- Running-in test
- Reproducibility of absolute positions
- Thermal cycling (acceptance level)
- Motorization margins in thermal environment

This extended acceptance campaign had two main objectives :

- Validate the homogeneity of the batch.
- Assign serial numbers to each models of development after the complete screening

The testing showed many errors. The performances dispersion due to the manufacturing processes and the COTS integration procedures is more important than expected.

The first anomaly was established during the unpacking at CNES (just after the delivery). One model has several loose screws. It was immediately returned to the supplier but it raised the issue of the batch homogeneity. *Is that really an isolated issue? Which tightening torques has been applied for each model? For each screw?* In the COTS context, with an incomplete documentation and a limited traceability, it is very difficult to be convinced…Furthermore, the resonant frequencies research confirm this difficulty showing large differences between the models. One more model had to be refurbished by the supplier.

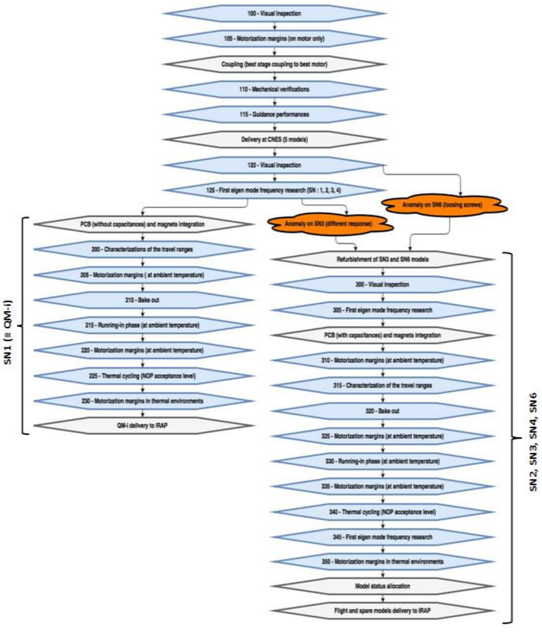


Figure 8 : Final acceptance test sequence

Finally, the initial acceptance tests sequence (which should be linear and identical for each mechanism models) had to be cut up to be performed in parallel as shown in figure 8.

Initially, assuming that the batch was homogeneous, the status allocation should be done with the performances measured during this campaign. But, several criteria like the refurbishment of one model or another have added complexity to this allocation.

Qualification tests sequence

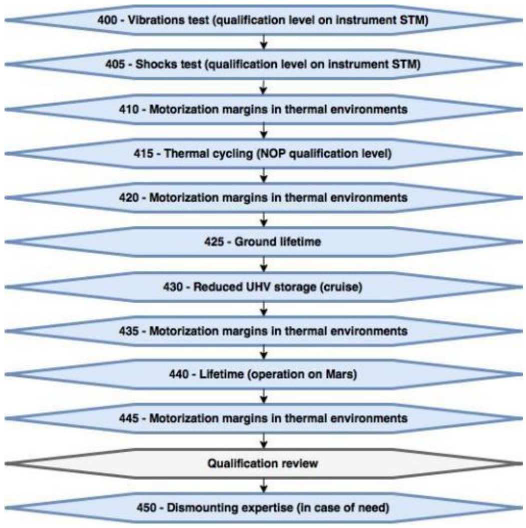


Figure 9 : Qualification test sequence in progress

4- SPACE-USE OF GROUND EQUIPMENT

Lessons learned from this development will contribute in improving our capacity to use ground equipment for space application. In fact, at first sight, it may be logical to note the time gain and the lower cost of this type of development. However, these benefits go hand in hand with a vulnerable position.

In the absence of specific design studies, there can be no assurance that the equipment will go through acceptance and qualification tests.

Furthermore, in this context, the lack of documentation, which is unconventional in space programs, is an additional difficulty. This limited documentation translates into a lack of visibility, and control on every process applied during the manufacturing and assembling phases. It has a direct impact on the batch homogeneity which seems in contradiction with the logic defined upstream.

Some « good health » tests (resonant frequencies research for example) allow to clearly identifying these dispersions. So, it is possible to refurbish each model on a case-by-case basis. But, once again, if the refurbishment closes all issues concerning the performances dispersions, what about the acceptance tests sequences dispersions between flight model, qualification model and engineering model?