CHEMCAM SCREW/NUT AUTOFOCUS MECHANISM: QUALIFICATION DATA AND GUIDELINES FOR SPACE-USE OF GROUND EQUIPMENTS

Y. Michel(1), E. Condé(1), D. Kouach(3), M. Simpfendoerfer(4),
Y. Parot(2), G. R. Orttner(2), M. Saccoccio(1) and S. Maurice(2)

(1) CNES, 18, avenue Edouard Belin, 31401 Toulouse cedex 9, France, yann.michel@cnes.fr.
(2) CESR, 9, avenue du Colonel Roche, 31028 Toulouse Cedex, France, sylvestre.maurice@cesr.fr
(3) OMP, 14, avenue Edouard Belin, 31400 Toulouse, France, driss.kouach@obs-mip.fr
(4) MICOS BmbH, Ftreiburger Str. 30, D-79427 Eschbach, Germany, martin.simpfendoerfer@micos-online.com

ABSTRACT

CHEMCAM is one of the 2 french contributions to Mars Science Laboratory (MSL) instruments suite. CHEMCAM instrument functionality rely on an autofocus capability to precisely focus on the chosen target (1-9m from rover). The autofocus function is performed by a mechanism that translates the secondary mirror, with high repeatability, over the 15 mm stroke, and in the full applicable range of temperatures. A ground COTS translation stage (MICOS® MT-40) has been chosen and modified to met mission requirements. This mechanism uses unusual components compared to what is chosen for high reliability space equipments in particular a screw/nut combination insuring the transmission function. It is designed to perform about 10.000 autofocus sequences during its lifetime.

This document presents both the development and qualification processes followed during phases B/C and lessons learned associated to space use of a ground COTS equipment.

1 INTRODUCTION

ChemCam (for CHEMical CAMera) is one of the 10 instruments suite on the MSL [1], a martian rover being built by Jet Propulsion Laboratory, for the next NASA mission to Mars (MSL 2011, Curiosity Rover). CHEMCAM is, with SAM (for Sample Analysis at Mars), the french contribution to MSL instruments. The mast unit sub-system set up is provided by CESR and CNES insures the prime contractorship for all French contributions to MSL. ChemCam will help determining which samples, within the vicinity of the MSL rover, are of enough interest to use contact and in-situ instruments for further characterization. Its package consists in two remote sensing instruments: a Laser-Induced Breakdown Spectrometer (LIBS) and a Remote Micro-Imager (RMI). Both instruments rely on an autofocus capability to precisely focus on the chosen target, located at distances from the rover comprised between 1 and 9 m for LIBS, and 2 m and infinity for RMI. The depth of field for LIBS and RMI are smaller than ±0.5 % of target distance to meet the science goals of the mission [2], [3]. An autonomous acquisition of focus has therefore been implemented to achieve such performances.

Focus is achieved by a translation mechanism which aims at translating the secondary mirror, with high precision and high repeatability, over the 15 mm required range, and in the full applicable range of temperatures (-40°C / +50°C). A MICOS® MT40 translation microstage has been chosen among several mechanisms designed for ground operations. This mechanism is made of a Phytron® 2-phases stepper motor which directly drives a steel M5/250µm leadscrew in a brass nut. Linear displacement is insured by a mobile plate guided on housing by rails guides with 45° crossed rollers.

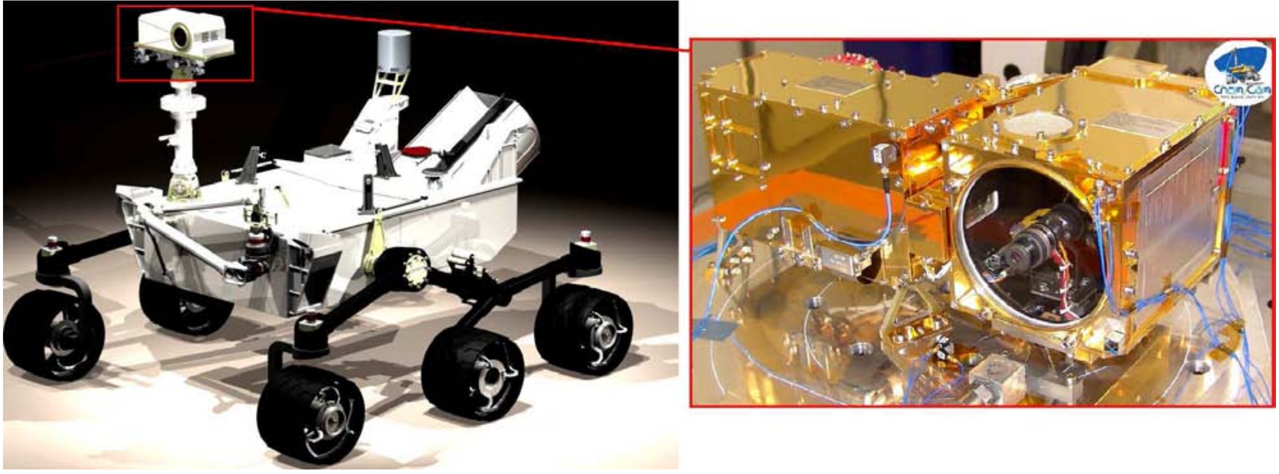

Figure 1 CAD view of NASA Curiosity rover and situation of CHEMCAM instrument on top of mast unit (copyright NASA/JPL/CALTECH) and picture of CHEMCAM flight model during vibration acceptance test.

Proc. '13th European Space Mechanisms and Tribology Symposium – ESMATS 2009', Vienna, Austria
23–25 September 2009 (ESA SP-670, July 2009)

The first part of this paper is dedicated to the qualification sequence including lifetime and environment and associated performances. An EM / QM /FM development sequence has been applied at subsystem level. In this part, resistive torque due to screw/nut combination (and wear-out due to sliding phenomenon) and its evolution during lifetime will be discussed as well as improvements performed at system level in order to meet positioning specification (backlash compensation procedure during autofocus).

The second part of this paper describes the difficulties linked to the use of standard ground equipment for space applications and gives some guidelines to avoid usual issues due to space processes particularity and inability of most "ground equipment" suppliers to face these constraints. These issues mainly concern quality processes, traceability and particularities due to space thermal and mechanical environments which often require design changes and induce going out of their fields of competence and experience.

2 SPECIFICATION & DESIGN DESCRIPTION

2.1 Specifications / Performances

The performances specified for the refocusing mechanism of CHEMCAM telescope are listed in table1.

2.2 Standard equipment evolution

The EM/QM/FM development strategy allowed design changes during mechanism development. For Engineering Model, two MICOS® MT-40 translation stages were provisioned : one "standard" stage and one "climate" stage able to undergo thermal environment (due to increased lateral and angular backlashes) :

- **MT-40 "Standard"** stage met optical requirements in terms of linearity, rotation and translation out of translation axis. It was used for EM instrument development and calibration.
- **MT-40 "Climate"** stage was used for a thermal lifetime test and underwent mechanical environment (3 axes random vibrations). It did not meet optical specification in terms of displacement linearity but it allowed assessing mechanism endurance for mission lifetime. The thermal lifetime test consisted in moving mobile plate from close focus to infinite focus and way back. 27.062 cycles were performed for temperature range [-40°C ; +55°C] under dry nitrogen.

Table 1 Refocusing Mechanism characteristics

Function	Specification	Data
Design	Total Mass	272.7 grams
	Volume	110 x 55 x 30 mm^3
Power consumption	Normal Mode	2.4 W
	Boost Mode	3.2 W
Kinematics Performances for CHEMCAM application	Driving frequency / speed	10 , 50, 100 and 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 (A/F) 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 10 s
Thermal requirements	Cruise (UHV) / storage	50°C /
	Non operating	[-55°C; +55°C]
	Operating	[-35°C;+35°C]
Mechanical Environment	Shocks (Rover release)	Max 4000 g @ 5 kHz
	Random vibrations [20 – 2000 Hz]	X axis : 10.8 G_{RMS} Y axis : 11.7 G_{RMS} Z axis : 11.8 G_{RMS}
Life time	On Ground (under Air at 22°C)	8.000 A/F (incl. margins) ~ 130 x 10^6 steps ~ 4.16 x 10^5 screw rotations
	On Mars (operational) [-40°C;+35°C]	20.266 A/F (incl. margins) ~ 330 x 10^6 steps ~ 1.05 x 10^6 screw rotations
	Operating Life	Ground : 5 years Cruise : 1 year Mars : 2 terrestrial years

In addition to non conformance of "Climate" stage to optical specifications, several weaknesses have been identified. These weaknesses mainly concerned endstops for mobile plate and roller cages and end of course sensors. For these reasons, MT-40 stage's design has been changed in collaboration with MICOS®. All translation stages including the one used on instrument EQM and QM/FM mechanisms were produced in accordance with this new design. All design changes are detailed below :

- **Thermal compensated design** : Incompatibility of MT-40 "standard" stage to thermal environment originated from relative expansion of aluminium Housing and mobile plate and Stainless steel rails guides leading to lateral backlash reduction up to 10 µm. The design change concerned mechanical architecture with the objective of reducing backlashes sensitivity to thermal environment. It consisted in replacing housing by two lateral pieces (stainless steel) and an aluminium base as illustrated on figure 3.

- **Mobile plate and roller cages Endstops :** Due to an anomaly encountered on EM during vibration test, endstops have been changed. Linear roller cages slipped from rails contact during Z axis random test. Attempt to move the cages back in the contact using stepper motor led to the loss of two rollers due to bending and slipping of cages on housing. Additional "claw" like endstops were added and mounted on rail guides as illustrated on figure 3. Roller cages are locked inside the claw and slip back in the contact when the mobile plate moves. Such design change has been validated during vibration test on subsystem (acceptance and qualification).
- **End of course sensor :** Two limit switches prevent damage from accidental over travel on MT-40 "Standard" stage. This design was found unconvenient for space use in terms of reliability and technology. These sensors were replaced by a unique end of course sensor made of a differential magnetoresitive sensor coupled to a Permalloy pellet glued on the mobile plate. The sensor is made of INFINEON FP 212 L 100-22 qualified on SMECm mechanism of SPIRE instrument. The precision capability of this sensing system is about +/-20 µm with associated electronics over the wide range of temperature.

2.3 EQM/QM/FM enhanced design description

2.3.1 Motorization

Mechanism motorization is insured by a PHYTRON® VSS 25-200-0.6 HV 2 phases stepper motor. The nominal holding torque (at 0,6 A) is 13 mN.m and the détente torque is 2 mN.m.

2.3.2 Transmission and guiding devices

Phytron® motor is coupled to screw/nut system with a flexible coupling device. The leadscrew is a M4 x 0.25 made of non stainless steel and the nut is made of Brass. Both are polished and lapped and the longitudinal backlash is 22-30 µm at 22°C. The leadscrew is coated with WS_2 on a CrN substrate (Dicronite-PlusPlus®). The screw/nut system is not preloaded in order to increase mechanism lifetime, longitudinal backlash is compensated using an autofocus procedure detailed in §2.4. Mobile plate guiding on housing is performed by rail guides with 45° crossed roller assembly to increase lateral and vertical stiffnesses.

2.3.3 Lubrication

Rail guides and screw/nut couples are lubricated using Lubcon® Ultratherm 2000 based on a perfluorized polyether oil for thermal stability respecting ECSS-Q-70-02 A for outgassing aspects. Ultratherm 2000 is coupled to WS_2 for screw/nut combination according to MICOS® experience.

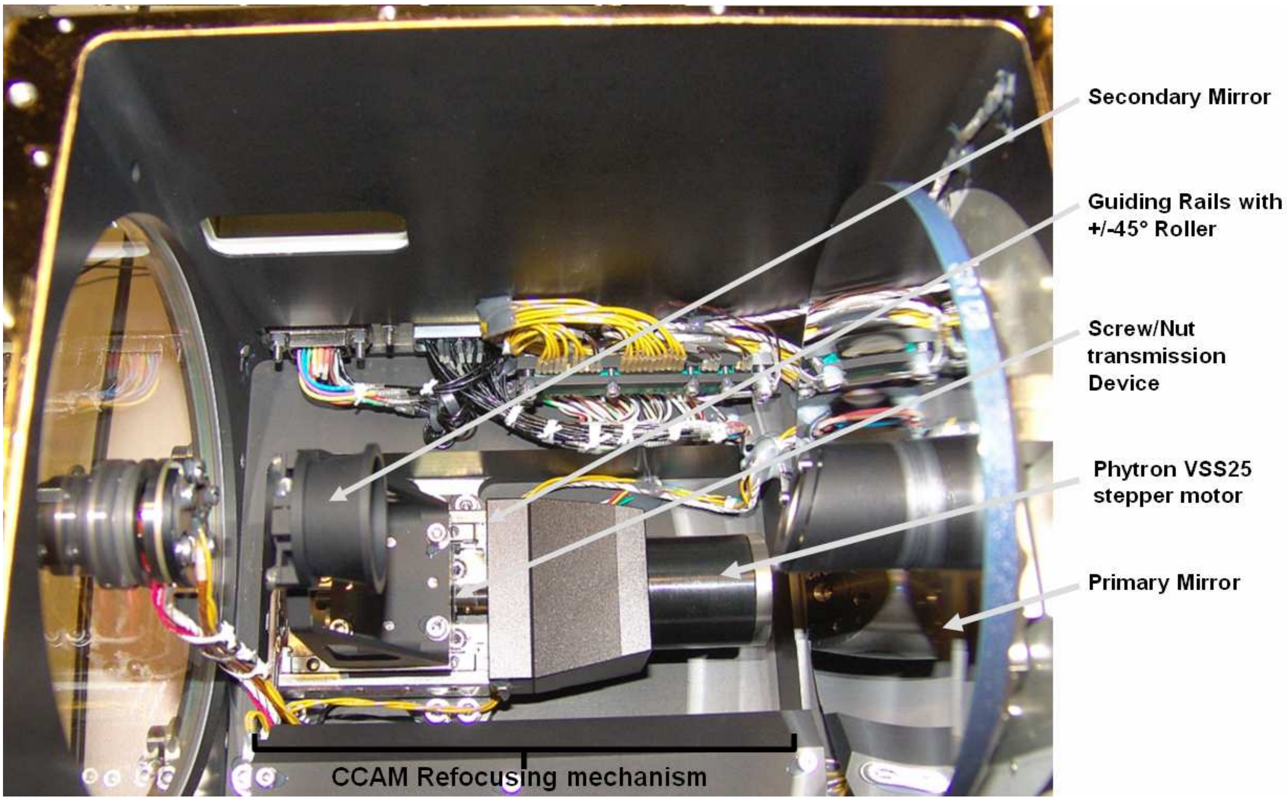

Figure 2 FM Refocusing Mechanism inside CHEMCAM Optical Box (OBOX)

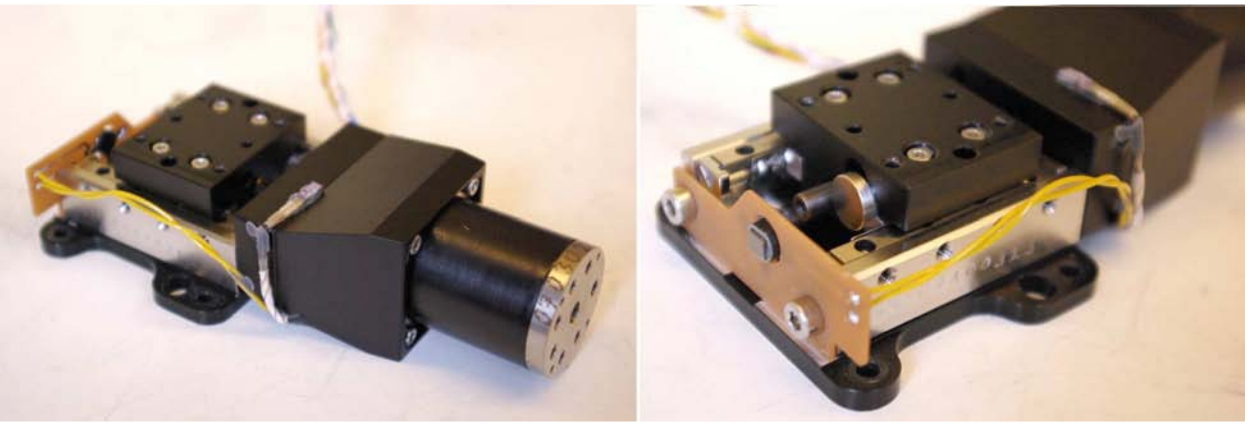

Figure 3 Views of QM mechanism and details on end of course sensor and roller cages

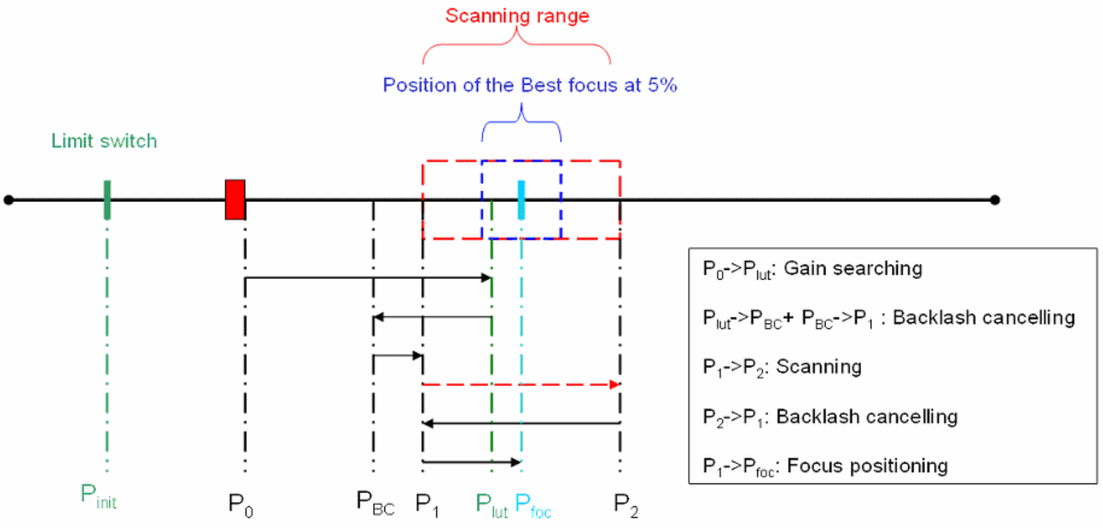

Figure 4 Autofocus procedure uses for CHEMCAM refocusing mechanism

2.4 Mispositioning causes & A/F procedure

Mispositioning of mobile plate might originate from 3 main root causes listed below. Figure 5 illustrates these errors, it is obtained by measuring absolute mobile plate position and by comparing it to the theoretical displacement (1.25 µm for 1 motor step) :

- Precision of end of course sensor (+/-20µm) used as reference if steps count is lost by electronics.
- Longitudinal backlash of leadscrew/nut combination up to 30 µm.
- Geometrical irregularities of screw/nut teethes appearing on unidirectional characterization of mechanism (cf. figure 5) leading to “longitudinal runout” effects with ~ 15 µm C-C amplitude.
- Global deviation of position along the 15 mm course of the mechanism due to screw/nut defects (up to 50 µm, cf. figure 5).
- Autofocus algorithm error while assessing best focus point (maximum & signal symmetry).

In order to respect autofocus precision requirements (<5 µm as repeatable as possible) and due to the absence of preloaded on screw/nut combination, an autofocus procedure has been defined to compensate mispositioning causes listed above. This procedure is completely relative making it insensitive to sensor precision and geometrical irregularities of screw/nut device as long as screw/nut defects are repeatable. Longitudinal backlash is compensated by covering symmetrical displacement around best focus point as presented in figure 4 : best focus point (number of steps) is calculated during scanning phase and final positioning is performed with the displacement direction (pair number of direction changes necessary for backlash compensation).

This procedure showed very high precision and repeatability as illustrated in §3.3.2 though that compensated backlash varies with scanning range and temperature due to grease viscosity and associated effect on resistive torque (full compensation below -20°C and almost non compensation at 20°C and above).

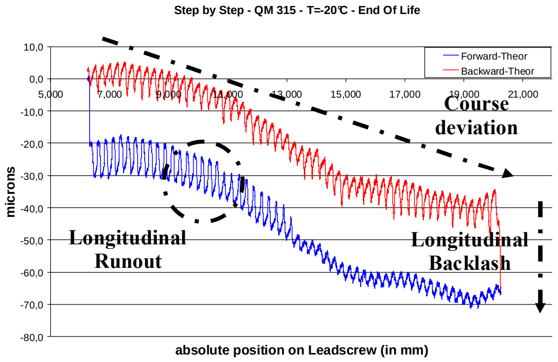

Figure 5 Characterisation curve : measured absolute position compared to theoretical displacement

3 QUALIFICATION PROCESS

3.1 Qualification test sequence & Test bench

To insure QM to FM representativity, a “FM” batch consisting of 4 mechanisms was procured and a batch qualification process was decided : 1 FM, 2 QMs (subsystem and instrument EQM) and 1 SPARE.

Among the FM batch, the first QM is dedicated to instrument EQM and follow instrument qualification process including thermal and mechanical tests as well as instrument calibration. The second QM is dedicated to subsystem qualification including life time and mechanical tests. The QM test sequence is detailed in flow chart below.

Diagram 1

Refocusing QM mechanism
Functional tests
Thermal cycling
Functional tests
Probe release shocks & Random vibration test (on Instrument STM)
Functional tests
Ground life time (8000 A/F)
Functional tests
Cruise : UHV storage
Functional tests
Martian life time (20266 A/F)
Functional tests
Long storage phase (6 months) under UHV
Functional tests
Dismounting and Expertise

During characterization and life time phases on QM, in order to assess mobile plate translation and autofocus performances, the refocusing mechanism has been coupled to a CODECHAMP® 21bits absolute linear encoder (developed for IASI corner cube mechanisms, cf. [4]). Encoder’s precision is below 1µm.

3.2 Vibration & Shocks

Both instrument and subsystem QMs were subjected to qualification shocks and random vibrations. High level sine vibrations were found non necessary by JPL (quasi static loads covered by random). Mechanism team had to face with two major problems concerning mechanical qualification:

- **Motor / guiding I/F :** For random vibrations, QM qualification levels were calculated from instrument EQM measurements but transition from flexible (on instrument) to stiff (shaker) interface was hard to achieve without over estimating qualification levels. This assumption led to mobile plate locking on FM design due to sliding of motor / guiding stage interface. After investigation, sliding originates from MICOS® assembly procedure and settings with relatively low torque screw clampings. Thanks to EQM heritage on flexible I/F, it has been decided to preserve MICOS® procedure knowledge instead of design change and QM mechanism underwent vibrations on instrument STM structure. Instrument qualification levels were adapted in order to compensate structural STM/FM differences and to inject identical G_{RMS} levels at mechanism I/F and on frequency bands including mechanisms Eigen modes.
- **Differences between stages from same batch :** Among 4 mechanisms from FM batch, some had significantly different dynamic responses especially for mobile plate’s modes. This behavior is attributed to non preloaded leadscrew/nut combination (backlash) and to 45° crossed rollers assembly. Eigenmodes shifted up to 200 Hz for one model which was left out and then reassembled and resetted by MICOS®. Reassembly consisted in modifying mobile plate / housing alignment and permitted to find back the mechanisms batch’s dynamic behavior.

3.3 Lifetime

The EM mechanism was tested during a lifetime test made of 28266 autofocuses (including ECSS margins). This lifetime corresponds to about 1.47 millions screw rotations inside the 5 mm long Brass nut. Autofocus procedure used for qualification was identical to procedure detailed on figure 4 with a 4 mm wide scanning interval (worst case). Focus points were randomly chosen along available course. Motor driving frequencies were 150 Hz for T > -20°C and 100 Hz otherwise in order have acceptable motorization margins (cf. § 3.3.1). Motorization margins and autofocus performances were checked all along lifetime testing over the complete temperature range.

3.3.1 Motorization margins

During phase B, resistive torque was measured on EM during and after lifetime test and motorization margins complied with ECSS standards at 10 Hz driving frequency (MM > 5 @ -40°C). During Phase C, FM batch showed higher resistive torque all along its lifetime. This torque is mainly due to screw/nut combination: it represents from 35% to 90% of the resistive torque depending on driving frequency and temperature ([-40°C; +55°C]). At this time no explanation has been found for this behavior's change ; the most valuable hypothesis concerns screw/nut manufacturing and coating processes.

For the whole QM lifetime, an open loop command was used and no step were missed for 150 Hz and 100 Hz driving frequency over the full temperature range. Motorization margins were measured by identifying minimal motor current allowing full course for the go & back displacement without step missing. Results are plotted on figure 5 and 6 for beginning and end of life respectively. Resistive torque includes the whole mechanism's electromechanical and tribological components (motor détente torque, spindle bearing and screw/nut device resistive torques).

Figure 5 illustrates typical effects of Ultratherm 2000 viscosity increase with decreasing temperature at screw/nut sliding interface. Sliding velocity at teethes heads varies from 0.6 mm/s to 9.5 mm/s for 10 to 150 Hz driving frequencies. Mechanism's behavior seemed to be insensitive to driving frequency for T > 0°C. At cold temperatures, resistive torque is highly temperature dependant and is significantly higher than EM one.

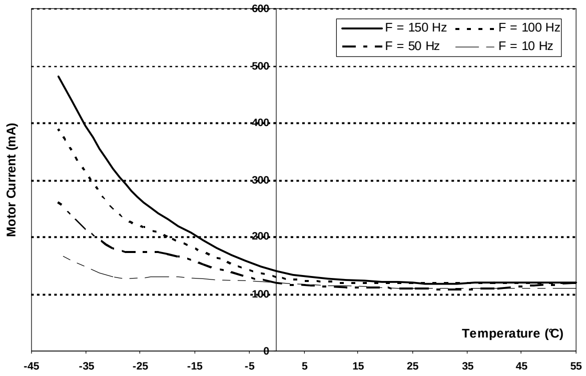

Figure 5 Minimal driving current before lifetest

As illustrated on figure 6, a significant evolution of resistive torque has been observed during lifetime. This evolution is characterized by a decrease of extreme viscous friction (-22% at 150 Hz & -40°C) and an increase of non viscous friction (+20% at 150 Hz & 25°C). At intermediate temperatures ([-25°C ; 10°C]), the behavior is different : the resistive torque is higher and viscous phenomena appeared for higher temperature (15-20°C at EoL instead of 5°C at BoL). All theses observations are attributed to grease removal from screw/nut contact after lifetime and to wear-out particles coming from both nut and screw. This is confirmed by optical observations on EM and QM showing Ultratherm grease charged with WS_2 particles giving its dark grey color as illustrated on figure 7 (Ultratherm 2000 initially white).

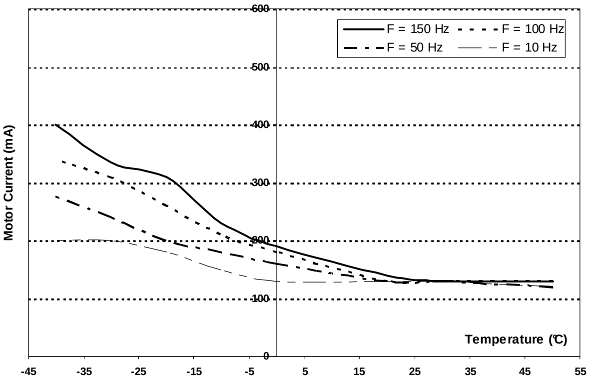

Figure 6 Minimal driving current after lifetest

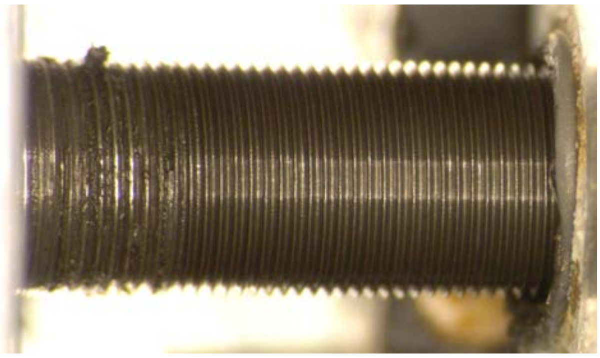

Figure 7 EM WS_2 coated leadscrew after lifetime

3.3.2 Autofocus Performances

During Phase B, autofocus procedure has been settled on EM especially concerning backlash canceling and influence of scanning interval. Autofocus performances along lifetime were only tested during Phase C on QM. Results are gathered in table 2 and on figure 8.

Table 2 Positioning error summary during lifetime

Positioning error	Ground lifetime	Mars lifetime	Error distribution	
< 1,25 µm	6864	17764	87.1%	**97.7% in specs.**
1,25-2,5 µm	811	1273	7,4%	
2,5-5 µm	246	645	3,16%	
5-10 µm	*57*	*220*	*0,98%*	***2.3% out of specs***
10-20 µm	*22*	*202*	*0,79%*	
20-30 µm	*0*	*162*	*0,57%*	

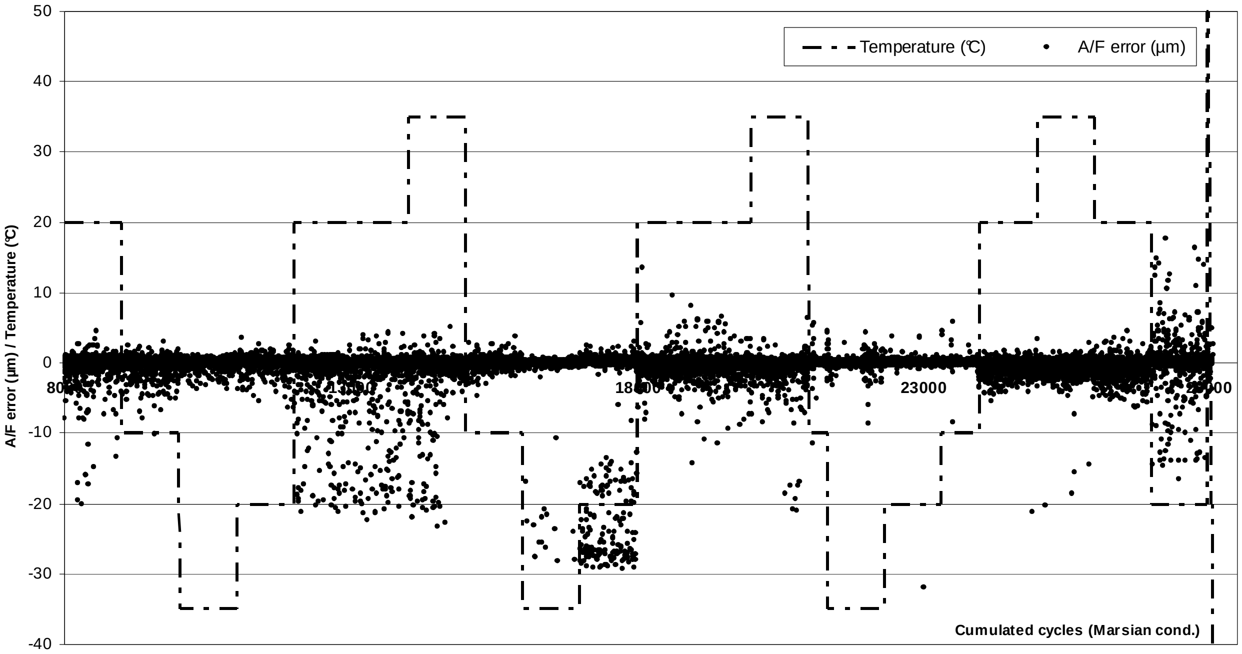

Figure 8 Autofocus error measured on QM during Martian lifetime (20266 A/F)

Table 2 underlines the good reliability and repeatability of mechanism for autofocus. Among 28266 autofocus, only 2.3% are out of critical specification (>5µm) and most of them are acceptable for science (specification depending on target's distance i.e. Mobile plate position).

Figure 7 gathers autofocus performances along the whole Martian lifetime. Two main observations shall be done :

- The graph underlines that out of specs. A/F error is not related to temperature. Errors seem to appear by phase (12.000 to 14.000 and 17.000 to 18.000 A/Fs). This is probably due wear out particles or small chips that need to be removed from the contact. No sensitive degradation of resistive torque has been observed during these phases.
- During cold phases, mechanism is more precise due to full backlash compensation related to resistive torque increase.

4 LESSONS LEARNED

4.1 Partnership with MICOS®

Even if MICOS® was an official contractor of CNES, the collaboration was more at a partnership level. Even though no brand new development was done, MICOS® was involved in the project development and accepted to manufacture MT-40 with CNES design proposal. Excellent teamwork between the parties has been achieved.

In such organization with modification of commercial on the shelf component (COTS), it is necessary to keep manufacturer involved. MICOS® knowledge was indeed necessary concerning manufacturing and stage's setting processes as well as for translation stage heritage even for ground applications.

For these reasons, a portion of the success must be attributed to the positive and interactive way of working of CNES and MICOS teams.

4.2 Space use of ground equipment

For CHEMCAM focus application no space-qualified alternative existed with respect to specification particularly in terms of volume, mass and precision performances. Moreover a specific development was not compatible with project planning and budget. This is the reason explaining the choice of a ground COTS alternative with standard screw/nut component usually avoided due to complex tribological sliding phenomena.

Nevertheless, particularities due to space, thermal and mechanical environments as well as the high reliability need may require some design changes (cf. § 2.2). This often induces the manufacturer to go out of their fields of competence and experience and a strong partnership and involvement of both space concerned and manufacturer teams. CHEMCAM refocusing mechanism development and qualification processes are a good illustrations particularly concerning mechanical environments and lifetime.

Finally, using COTS components includes significant risks particularly due to non space-qualified processes and to the lack of traceability. For CHEMCAM project, these lacks led to several anomalies during B/C phases. Sliding of motor/guiding I/F (§ 3.2) is a perfect example of an anomaly that could have been avoided by having more information on integration and setting processes.

4.3 Design rules and qualification process

For all reasons presented above, some precautions concerning design rules and qualification process must also be taken during phase B to successfully qualify a COTS.

Concerning CHEMCAM refocusing mechanism, role of phase B activities and corresponding design rules are particularly important when design changes are needed. EM must be submitted to an exhaustive set of evaluation tests and expertise including complete lifetime and vibrations in order to reach an equivalent to TRL5.

It is often considered by the community that the high motorisation margins and worst-case considerations applicable to space hardware development are too demanding and constraining. Experience on refocusing mechanism underlined that if these guidelines would not have been followed during EM testing (MM>6), FM batch would not have been compliant to specification (cf. 3.3.1), mainly due to wear at screw/nut interface.

In the same way, for COTS components a particular attention should be paid on mechanical environment specification and qualification strategy. As presented in § 3.2, motor/guiding sliding anomaly has been solved by taking care to not overestimate vibration levels with the will to preserve mechanism guiding settings and manufacturer heritage.

4.4 Performances improvements with development at system level

When specific development is not possible and when COTS components have been chosen, flexibility at system and electronics levels is necessary. It permits to implement new functionalities or to compensate limitations of COTS component. For CHEMCAM refocusing mechanism, autofocus procedure as well as end of course magnetoresitive sensor have been defined at phase B end. Both have been implemented and settled thanks to electronics and software flexibilities and both permit the mechanism to meet performances required.

5 CONCLUSIONS

The CHEMCAM refocusing mechanism is based on a MICOS® MT-40 standard translation stage architecture. This component on the shelf has been modified in order to respect stringent optical specification and Martian operating environment. Phases B/C including characterisation, modification and qualification were completed within a period of 2 years thanks to a close co-operation between CNES and MICOS®. The severe performance requirements were met with less than 5 µm positioning precision over a 15 mm operating stroke. Positioning, linearity of displacement and capability to underwent mechanical environments were demonstrated at both mechanism and CHEMCAM instrument levels.

Due to hard Mass/Volume requirements correlated to a relatively long stroke (15mm), a Screw/Nut technology has been chosen despite its complex tribological behaviour. The screw/nut combination showed good stability after about 1.47 millions screw rotations (28266 A/F) and high reliability after 2 lifetime tests performed on EM and FM batches.

CHEMCAM refocusing mechanism development was also very instructive for space use of ground component. It underlined the necessity to have a strong collaboration with manufacturer particularly when design changes are needed as well as a strict respect of design rules applied to space systems. Moreover, a particular care must be taken to critical phase B steps such as lifetime and vibrations.

6 ACKNOWLEDGMENTS

The authors gratefully acknowledge MICOS® Team members for their advice and involvement during phase B/C development : M. Simpfendoerfer, W. Meienburg and L. Amelung.

7 REFERENCES

[1] Saccocio et Al, CHEMCAM on MSL2009 : 1st laser induced breakdown spectrometer for space science, International Conference on Space Optics, 2008.

[2] Wiens et Al, 2005, 36th LPSC, #1580

[3] Maurice et Al, 2005, 36th LPSC, #1735

[4] Spanoudakis et Al, Design and production of the METOP satellite IASI corner cube mechanisms, 10th ESMATS, 24-26 September 2003, ESA SP-524.