MINIATURIZED ATOMIC FORCE MICROSCOPE FOR PLANETARY EXPLORATION

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ABSTRACT

The Atomic Force Microscope (AFM) has revealed itself as a reliable tool for characterizing surface topography with nanometer resolution. In principle, a sharp tip mounted on a cantilever is brought into close proximity of the sample surface. The forces acting between the sample and the tip slightly deflect the cantilever. Scanning across the surface while recording this deflection provides a topographic image of the sample.
As in most space experiments, performing microscopy measurements on a planetary mission requires a good trade-off between the experiment's weight and size and the quality and relevance of the measured data. A plain optical setup with acceptable size and weight for a space launch will provide images with limited resolution. Thus, atomic force microscopy with a well designed instrument can be complementary to an optical setup for increasing image resolution and getting higher scientific throughput.
At the first glance, high sensitivity and required interaction between the instrument and the operator render the AFM unsuitable for planetary missions. However, micro-fabrication technology combined with innovative design ideas allowed us to build an error tolerant system with functionality for addressing the above mentioned challenges.

DESCRIPTION OF MECA

The presented instrument is part of the Mars Environmental Compatibility Assessment Project (MECA) headed by the Jet Propulsion Laboratory (JPL). The purpose of this scientific payload is to assess harmful effects of the atmospheric dust on both robotic and human missions to the surface of mars [1].
Scientific data [2] from both Mars Pathfinder and Mars Global Surveyor indicate a vigorous recirculation of dust between the Martian surface and atmosphere. Although properties of the dust have been inferred from remote sensing, there has been no imaging of individual dust and soil particles to determine their size distribution and shape. Such information is essential in understanding the contribution of the particles to the Martian dynamics, and assessing the harmful effects of the dust on both robotic and human missions to the surface of Mars.
MECA contains a microscopy station to produce images of dust and soil particles. Mars Pathfinder data indicates that the mean particle size of Martian atmospheric dust is less than 2 micrometers. Hence MECA's microscopy station, in addition to an optical microscope capable of taking color and ultraviolet fluorescent images, includes the presented AFM to image far below optical resolution. The experiment is enclosed in a box and placed on the lander platform.

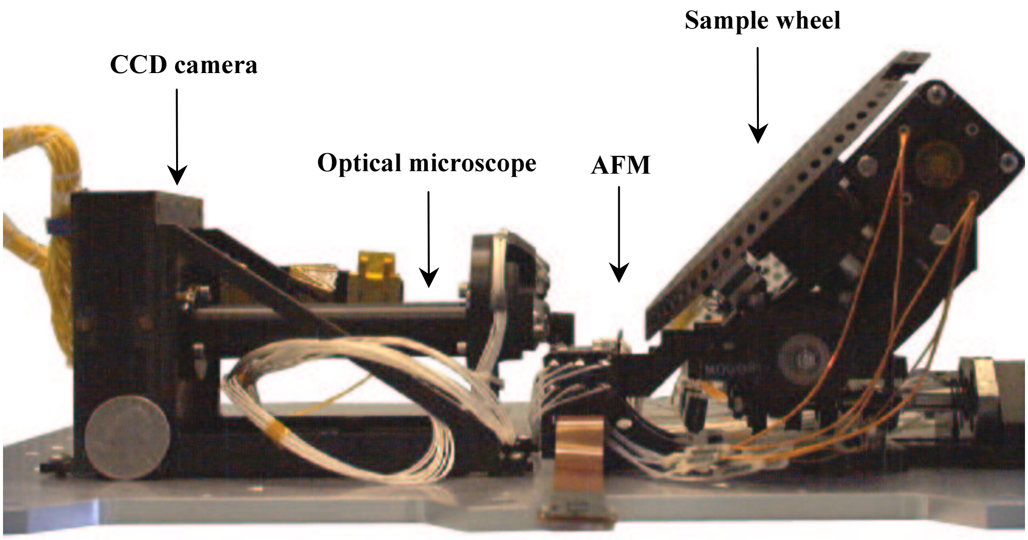

Figure 1: *Photograph of MECA's microscopy station with the cover removed.*

Delivery of the dust samples is achieved by an external robotic arm which is part of the lander's platform equipment. It will be capable of taking surface and subsurface samples. A sample handling wheel with 69 substrates is enclosed in the MECA box. A small slit located on the top of the box will reveal only a segment of the wheel. The dust delivered on the exposed substrates will be brought in front of the microscopes by performing a rotation and translation of the wheel. Since the composition of the dust is not precisely known, a set of 7 substrates with different hardness and adhesion properties (magnetic, conductive or non-conductive) will alternately populate the wheel. Figure 1 shows a photograph of the microscopy station with the described sample handling system.

In addition to the microscopy stage, MECA is equipped with other experiments incorporating chemical sensors for measuring PH, redox and conductivity of soil-water mixtures. An electrometer will be able to monitor electrical fields and tribo-electric charging during robotic arm operation. Adhesion and abrasion plates directly exposed to the Martian atmosphere and imaged by a camera fixed on the robotic arm will allow investigators to evaluate degradation of materials.

AFM WORKING PRINCIPLE

Like all other scanning probe microscopy (SPM) methods, AFM relies on a miniaturized probe scanned across the surface of a sample within very close distance to it. At each point on the sample, a certain physical signal is measured, and finally reconstructed in a computer point by point. The AFM uses a sharp tip at the end of a soft cantilever to probe the surface. The forces acting between the tip apex and the sample surface are detected by measuring the deflection of the cantilever. This is usually done by measuring the varying deflection angle of a laser beam on the cantilever.

In constant force mode, the bending of the cantilever is kept at a constant value while scanning over the surface. This is done by the scanner which in addition to performing the X and Y motion, controls and measures the Z deflection by a closed loop system. In most cases, the scanning principle relies on piezo-electric deformation of a tube on which high voltages are applied.

Alternately, to the constant force mode, the cantilever is excited at its resonance frequency. The resonance is detuned when exposed to the force gradient above the sample surface. This signal produced by the deflected laser beam can be used for imaging the topography of the sample in a comparable way as the lever bending in the constant force mode. This technique is sometimes called tapping mode [3] as the tip apex is in intermittent contact with the sample. It has the advantage that lateral forces between the tip and the sample are minimized.

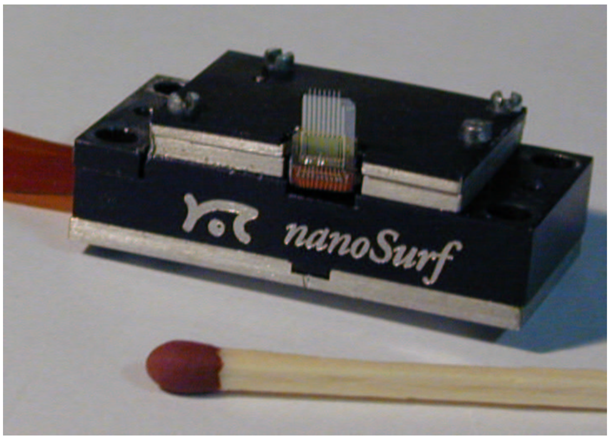

***Figure 2**: Front view of the electro-magnetic scanner with mounted AFM chip. Wire-bonded connections link the silicon chip to the flex-print that comes out on the side of the scanner.*

INSTRUMENT DESCRIPTION

The instrument consists of three distinctive parts: A micro-fabricated AFM sensor chip with eight cantilevers, an electromagnetic scanner and the controller electronics. The AFM chip is mounted on the moving part of the electromagnetic scanner which provides the X and Y motion and controls the vertical Z-motion (figure 2). All necessary connections to drive the scanner and to read the signals on the sensor chip are wired to the electronic board through a flex-print.

CHIP DESIGN

Maximum functionality was transferred to the micro-fabricated silicon chip of the AFM (Figure 3). First, a stress sensor is integrated into the micro-fabricated silicon cantilever. Second, means for exchanging blunt tips or broken cantilevers is provided through the use of a cantilever array. Third, diamond was incorporated as a low-wear material for selected tips in the array. Through this concentration of functionality into the micro-fabricated component of the instrument, constraints could be relaxed for the other mechanical subsystems.

The cantilever deflection is measured by means of implanted piezoresistors in a Wheatstone bridge configuration [4]. A special reference resistor is incorporated on an ultra-short cantilever for compensating thermal drifts. This reference cantilever is protected against mechanical damage by a surrounding, rigid safety bar. The use of piezo-resistive detection instead of laser beam deflection is an important gain of weight, space and ease of operation since no optical alignment is needed.

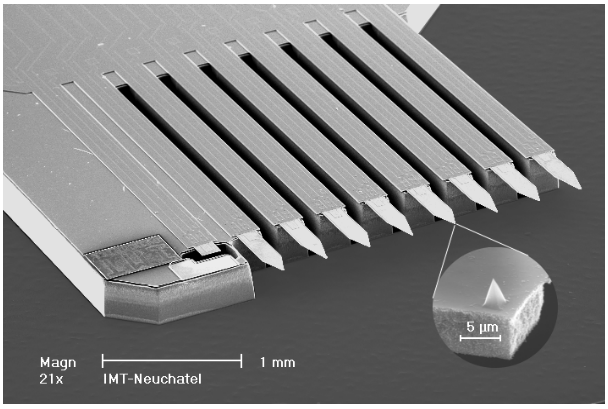

Figure 3: *SEM image of the AFM chip. 8 cantilevers and tips are located at the edge of support beams. Integrated piezo-resistors for deflection sensing have been implanted onto each cantilever. A reference resistor implanted on an ultra-short cantilever and surrounded by a safety bar will compensate thermal drifts.*

Electrical isolation between the resistors and the cantilevers is achieved by reverse biasing the pn-junction formed between the p-type resistors and the n-type bulk of the cantilever. This limits, to some extent, the range of usable tip-potential which can only be applied via the cantilever. It is expected that in the dry Martian atmosphere, electrostatic forces between the sample and the tip will be present. The ability to change the tip potential is therefore important to, at least partially, compensate for these forces and, hence, identify them.

Broken tips will be permanently removed by means of a cleaving tool. Therefore the AFM-chip features eight cantilevers for redundancy. The piezoresistors on these cantilevers are contacted by wire-bonding and can be individually addressed via an external multiplexer.

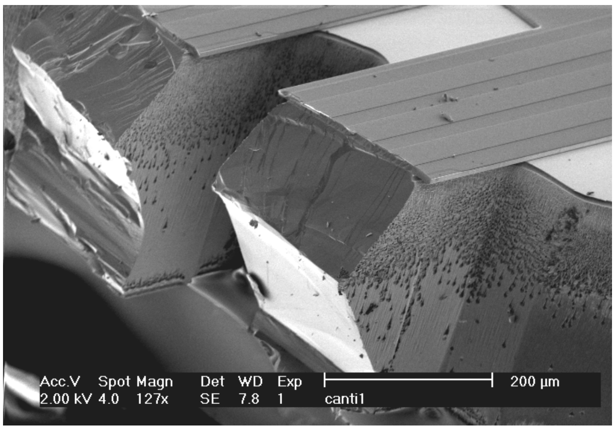

Figure 4. *SEM image of the cleaving edges produced when breaking off the thick support beams for a cantilever exchange. The electrical paths for contacting the piezoresistors are visible on top of each beam..*

The AFM-chip is mounted on the scanner with two tilt angles relative to the substrate plane to ensure that only one tip at a time is in the lowest, imaging position. The cantilever tips are alternately equipped with monolithic silicon tips and CVD molded diamond tips.

The whole chip has a width of 2.6 mm. A simple breaking of the cantilevers for exchanging blunt tips will not be sufficient as the edge of the chip at the first cantilever would touch the sample when measuring with the last few cantilevers. Therefore, the latter reside on rigid support beams rather than on the bulk of the chip. It is this support beam that is cleaved-off for cantilever removal. Figure 4 shows a SEM image of the cleaving edge produced when breaking the support beams.

The space between two support beams, which have the full wafer thickness, is about 90µm. Therefore, the standard KOH etching technique cannot be used for bulk-machining the AFM-chip and must be replaced by anisotropic, deep reactive ion etching (DRIE) [5].

SCANNER DESIGN

The key properties for the AFM scanner are, as for the silicon chip, small size, low power consumption and shock resistance. Earth-bound AFM designs normally utilize piezo-ceramic actuators for this purpose. Piezo elements which deliver enough stroke are rather bulky or brittle. Driving voltages of over 100V are typically needed for this scanning technique.

Within our design three electromagnetic actuators placed in a triangular configuration are employed for moving the sensor array in three dimensions. Each actuator consists of an electromagnetic coil and a spring-suspended permanent magnet (Figure 5). The coils are driven by current sources. Passing a current through a coil will attract or repel the magnet and move the platform in a linear manner. The low driving voltages of less than 15V avoid arcing within the Martian atmosphere (~ 7mbar CO_2). The robust electromagnetic scanner weights 15g and has an overall size of 12mm x 18mm x 24mm.

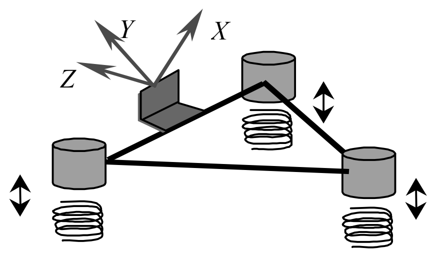

Figure 5: *Schematic view of the scanning principle. 3 magnets are placed in a triangular configuration and attached to a spring-loaded platform. A coil is placed under each magnet. By supplying the right currents to the coils, one can describe a linear motion in x, y and z at the sensor array position.*

ELECTRONICS DESIGN

The electronics consist of modules to address the different functional tasks of the AFM. An amplifying circuit is used to measure the resistivity change of the piezoresistor integrated on the cantilever. A multiplexer allows switching between cantilevers. The amplified deflection signal is converted to numeric information. It is used for the digital feedback circuit for constant force operation in static mode. The scanner motion is also digitally controlled in order to easily adjust the scan-size and orientation. Three DAC (digital to analog converter) circuits convert this information and drive the current sources for the scan-coils. For dynamic mode operation, a direct digital synthesizer (DDS) is used as a frequency generator to vibrate the cantilever. To detect the resonance frequency of a cantilever, a phase locked loop circuit (PLL) is used. All logic circuits are realized in two field programmable gate arrays (FPGA). The heart of the electronics is a dedicated microcomputer system. On power-up, the required measurement software is automatically downloaded from the lander computer. All communication between the controller and the lander computer is done through a serial interface. This architecture simplifies interaction with the lander and assures a great autonomy of the AFM: the lander simply request the AFM to take an image.

On Mars the solar radiation and bombardment with heavy ions is much less shielded than on Earth. If a heavy ion hits a register cell, the stored information is likely to be falsified. Such data corruption is called single event upset (SEU). To secure the data in such a case, a triple voting circuit has been implemented (Figure 6). Each data bit is stored in 3 independent registers and checked by a voting cell. The output of the voting cell always reflects the majority of its inputs. All important register cells in the programmable logic chips are implemented in this way. With such a design rule the failure rate can be reduced by a factor between 1’000 and 10’000.

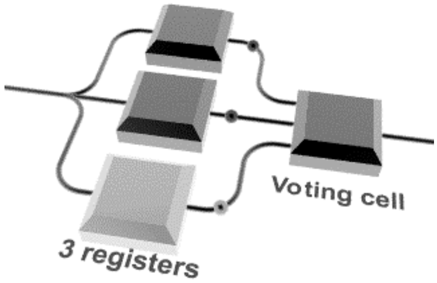

Figure 6: *Illustration of the triple voting scheme. Even if one of the three register cells has a falsified bit induced by a heavy ion impact, the voting cell will still transfer the correct information..*

A more severe, hardware failure due to irradiation is called single event latch-up (SEL). It can occur in certain CMOS chips, if a conducting path is opened between a power line and ground by a sudden ionization due to heavy ion impact. A high current will flow through this path and destroy the CMOS chip by overheating. To prevent these SEL from harming the electronics, a protection circuit has been implemented. It constantly measures the current consumption on all power lines and immediately shuts down the power if the current increases too much. A short time later, the power is switched on again and the board reboots to its normal function.

AUTONOMY OF THE AFM

Commands to operate the AFM can be sent to Mars only once every day. No direct interaction with the instrument is possible since the delay is of about 8 minutes. This restriction significantly influences the measuring protocol and the software that runs the instrument. Autonomous operation concepts had to be developed to meet these requirements.

The command dictionary of the AFM consists of several block level commands. Basic initializing sequences and health checks for contact and tapping mode prepare the instrument for an approach. Imaging commands specify a series of arguments like the image-size, the scan-speed and several feedback-loop settings. During imaging, the status of each scan-line is analyzed to assure good quality of the image.

A high-level command will be implemented to permit a smarter imaging. A pre-scan sequence maximizes the image-size to stay within the dynamic Z-range of the scanner. As the topography of the sample is not known, this procedure will prevent a tip crash when scanning a too large area. A first image will then be taken with the determined scan-size. A smart-zoom sequence will analyze the information of the first image by using the JPEG compression algorithm already present on the lander computer. Choosing the least compressible sub-area as target for the next image will prevent from zooming into a sub-area with no information. The smart-zoom sub-routine can be repeated several times and a set of sub-sequent images will be generated.

The development of the software is based on a good knowledge of the instrument under different conditions. Several error cases have been encountered during characterization. Fault detection and possible recoveries have been implemented in the software to face these problems

SCANNING TECHNIQUES

The most challenging issue is to perform AFM measurements of loose particles. The lateral tip to particle interaction might be too high to define the particle structure without pushing them around.

Later, during the actual mission, the Martian dust will be poured onto the substrates, leaving them attached just by surface adhesion forces. The dry, cold atmosphere on Mars will contribute to the fact that these forces will be very small. Since the composition of the dust is not precisely known, a variety of substrates with different hardness and adhesion properties (magnetic, conductive or non-conductive) will be used in the flight system. The AFM tip can be set to a specific potential relative to the sample to eventually compensate electrostatic forces.
The main factor to assure good scientific data consists in a safe measuring technique. The scan speed and the feedback parameters play an important role in avoiding particle displacement. On the substrate side, a soft and sticky surface like silicone or a polymer-coated nickel plate can help to fix the particles. Unfortunately, these material properties will be less pronounced under the dry and cold atmospheric conditions on Mars.
Since it occurs quite frequently that the tip is contaminated with particles, and that the actual image quality is deteriorated by tip convolution, it is useful to reverse-image the tip by using a tip-calibration sample. The tip curvatures of the calibration tips is much smaller than the curvature of the particle on the AFM tip, hence, the particle itself will be imaged several times when scanning over the calibration tips (Figure 7). Since such a calibration sample consists of a matrix of tips, a blunt calibration tip will be easily detected by comparing it to neighbouring features. The period of the tip matrix is well known and gives a direct size calibration of the repeated features. Thus, tip-contamination turns to our advantage and the repeated reverse-imaging of a single particle will help consolidating the scientific data.

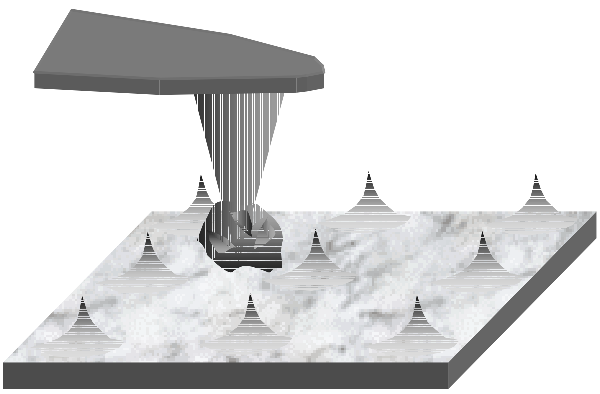

Figure 7: *Schematic principle of the reverse imaging technique. The use of an array of sharp tips as a measuring sample will produce an AFM image with repeated topography of the particle sticking on the AFM tip since it has a bigger curvature than the calibration tips.*

MEASUREMENTS

A first set of measurements of a calibration grid helped to characterize the scanning behaviour of the instrument. The scanner has a maximum X-Y range of 50 µm a vertical range of 14 µm.. Figure 8 shows a full-scan image of a calibration grid with 10 µm pitch. Figure 9 is a subsequent image of the feature in the middle of Figure 8.

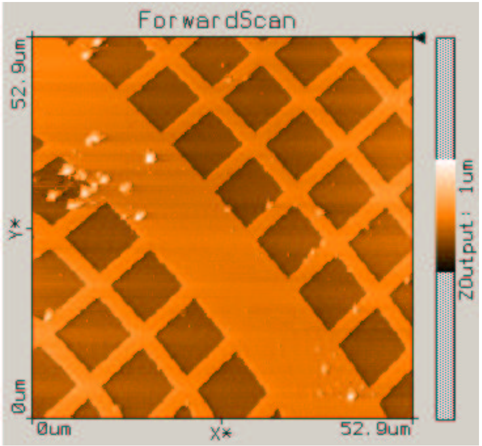

Figure 8: *AFM image of a 10 µm calibration grid with 200 nm step height.*

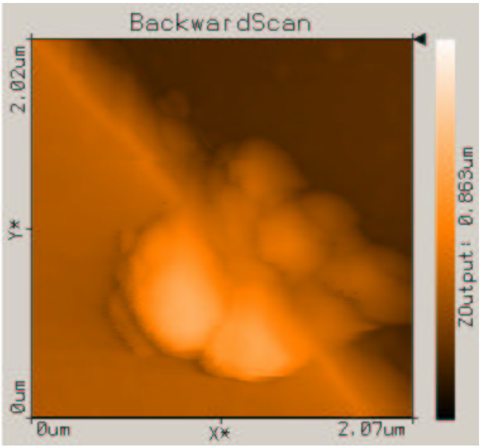

Figure 9: *Subsequent AFM image of the feature in the middle of Figure 8.*

Quartz particles have been measured using the different techniques described in the previous section. Figure 10 shows an AFM image taken with a clean tip in tapping mode. The scan-speed of the tip over the sample needs to be around 5 µm/s to avoid displacement of the particles on the substrate. Thus a full scan image recorded forwards and backwards would take 1 hour and 20 minutes. Figure 11 shows an AFM image of a tip calibration sample taken with a quartz-contaminated tip. As described in Figure7, the particle sticking on the AFM tip is reverse-imaged several times. The fuzziness and reduced height of some features on the image results from blunt tips of the calibration sample.

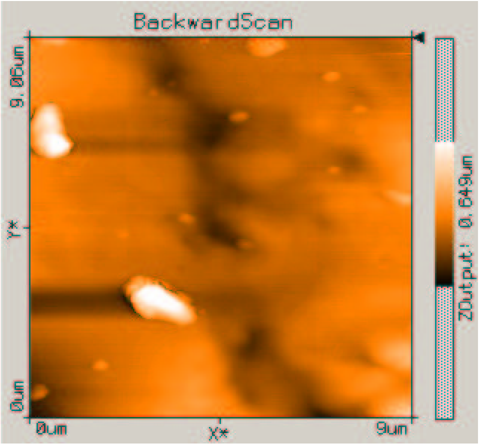

Figure 10: *AFM image of quartz particles taken in tapping mode with a clean and sharp AFM tip.*

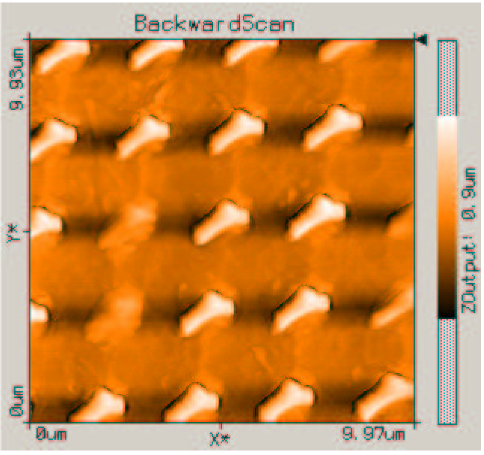

Figure 11: *AFM image of a tip calibration sample taken with a quartz contaminated tip. The fuzziness and reduced height of 2 repeated features on the image results from blunt tips of the calibration sample.*

NEXT FLIGHT OPPORTUNITIES

The instrument was originally designed for a Mars mission headed by NASA and scheduled for a launch in April 2001. Unexpected design and management failures during two Mars missions in 1999 induced a drastic review of NASA's robotic exploration program. The landing technique used by Mars Polar Lander (MPL) in 1999 was at the origin of possible failures that might have provoked the loss of the mission. Since the 2001 mission was based on the same design as MPL, and the reliability of the whole design was questioned, no lander was sent to Mars in 2001. The scientific payloads selected to fly with this mission have been put on a waiting list, together with the experiments that were part of MPL and could never produce scientific data. Newly designed missions are scheduled for 2003, 5 and 7. NASA proposes to develop and to launch a long-range, long-duration mobile science laboratory that will be a major leap in surface measurements [6]. The instrument presented in this paper would then be a precious tool to gain information on size distribution, hardness and shape of the Martian dust and soil.

CONCLUSIONS

The described AFM instrument went through thermal cycling tests at low pressure and passed all the specified vibration and shock tests to be space qualified.
The measurements obtained during characterization are of great importance for planning the AFM investigations on Mars. If the particles on Mars behave the same way as the Mars-equivalent quartz particles that we investigated, conclusions on measurement techniques and necessary scanning times can be drawn as follows.
Once the tip has been contaminated with particles, the use of the reverse-imaging technique on a tip calibration sample will be of great help to increase the amount of relevant scientific data. The presence of a repeated structure with known period will give reliable information on the size of the feature. Tip artefacts due to worn tips of the calibration sample will be easily detected by comparison with neighbouring features.
In a future work, investigations of different families of quartz (α-quartz, cristobalite) that are formed under particular thermal conditions will be performed.

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