MOLE CARRIED SENSOR PACKAGE

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ABSTRACT

From 2003 to mid 2006 Galileo Avionica, leader of a team of European Research Institutes and Universities, conducted an ESA founded study for the design, development, manufacturing and testing of a Mole Carried Sensor Package (MCSP) for planetary exploration. The MCSP system is thought to be mounted on a Lander with the purpose to deploy a mobile penetrometer, or “mole”, carrying a payload of sensors for sub-surface measurements.

The developed Mole is actually divided in two separate sections, the tractor mole and the trailed mole, which are connected with a short flexible cable. Upon proper command, the moles are released and can start their journey through the planetary soil powered and controlled by the Lander through a 3÷5 m long flat cable which carries power and signal lines. The advantage of a two mole systems is that, leaving unchanged the tractor mole, the trailed mole can be reconfigured upon different mission scientific objectives.

The MCSP prototype testing began in July 2005 and went to an end in March 2006 after a successful test campaign including mole deployment and low-temperature tests in vacuum.

1. INTRODUCTION

Future planetary surface exploration aims to undertake several physical and chemical measurements. Some require sub-surface penetration to bring the sensors underground (e.g. for thermal flux investigations, search for water films on soil grains). A possible device to achieve such result is a Mobile Penetrometer (MP) or “Mole”. It is a relatively simple device, able to penetrate slowly but at very low power; it may be instrumented with sensors, and brings them in contact with the subsurface soil.

In its simplest implementation, the Mole appears externally as a slender cylinder with a conical tip. The tubular body encloses a shock mechanism, composed of a hammer, a main spring and an actuator; this assembly is itself sliding and lightly compressed near to an anvil, behind the tip. The main spring, compressed then released, drives the hammer against the anvil and the assembly rebounds. Internal shocks, repeated every few seconds, are slowly propelling the Mole in the soil, requiring a low average power. A Mole is normally linked to an external power source via a tether, which also transmits signals to the surface, and allows retrieval by pull-out.

The Mole is deployed from the surface, normally from a lander, by additional Deployment Devices (DD); launch

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locks, insertion support, and tether winch can also be foreseen if required; moreover electronics are required for both the Mole itself and the additional devices. The whole assembly (Mole + DD) constitutes a "Mole system"; when carrying a payload (P/L) of sensors, the Mole is called an "Instrumented Mole" (IM), and the entire system is called an "Instrumented Mole System" (IMS).

This study was aimed at the development, design and test of a functional breadboard model of an IMS and at investigating the feasibility of using the IM as a P/L carrier.

2. SYSTEM REQUIREMENTS

The main requirements that have most importantly driven the design of the IMS are summarized here below:

- Functional requirements:
  - ✔ The ISM shall be compatible with the reference planetary mission (a night landing on Mercury) which would use a lander called the "Mercury Surface Element" (MSE).
  - ✔ After its insertion in the planetary regolith, the Mole shall be capable to penetrate the regolith itself by means of an internal electro-mechanical hammer that has to provide a shock energy of at least 0.1 J every 6 seconds.
  - ✔ During the penetration, the Sensor package (SP) shall acquire at least the Heat Flow, the Electrical characteristics, the Mineralogy and the composition of soil material and make a Borehole imaging.
  - ✔ The Tethering Device shall include a tether magazine (without any mobile part) housing the tether and a tether deployment sensor allowing to measure the length of the tether deployed to the IM.
- Performance requirements:
  - ✔ The IM shall be able to penetrate the planetary regolith at a depth of no less than 3 m (with a goal of 5 m) in 5 hours, assuming a soil whose estimated physical properties are provided in sec. 6.4 and Appendix 2 of [1]. Particularly, the Bulk Density and Porosity of the Mercury surface, the most relevant parameters affecting the IM penetration, are defined in sec. 6.4.2 of [1] and ranges from 1.3 kg/dm^3 (typically for the first 2 cm of surface) to 1.93 kg/dm^3 for depth > 60cm. Grain size is in the range 30 to 120 µm.
  - ✔ The IM shall be able to penetrate in the planetary regolith when the angle between the MSE base and the planetary surface ranges from 0° to 20°.
  - ✔ The IMS shall measure the IM depth & attitude with an error better than 50 mm & 5°.
- Physical characteristics:
  - ✔ The IMS shall fit within the available P/L volume inside the MSE which, based on earlier studies of a low-cost lander for a similar mission, is estimated as a cylindrical envelope with a 20 cm diameter base and a 20 cm height.
  - ✔ The total IMS mass shall not exceed 1000 g.
  - ✔ During penetration the IMS average power consumption shall not exceed 3 W; while not penetrating, the average power shall not exceed 0.3W.
- Environmental requirements:
  - ✔ The mole has to be locked (also its internal moving parts) to withstand both the launch loads and the landing shocks.
  - ✔ Operating temperature range: -190°C to +10°C;
  - ✔ Not operating temperature range: -190°C to +70°C.
- Scientific objectives:
  - ✔ During the penetration, the Heat flow and Physical Properties Package (HP3) shall at least determine the following feature of the soil:
    - Heat Flow (from Mole temperature distribution, regolith thermal conductivity and density)
    - Electrical characteristics
    - Mineralogy
    - Composition

3. CONCEPT SELECTION

The selection of the most suited concept for the IMS implementation was done considering two possible sizing for the hammering section and making a trade-off among different approaches of the single body mole and the double body mole.

Two different sizes of available motor-reducer components (namely 19 and 31 mm ext. diameters) were considered and the moles preliminary designed showed two possible overall sizing: a mole 25 mm diameter and 245 mm length and a mole 35 mm diameter and 275 mm length, with a larger mass for the second mole and no practical benefit in terms of length. The diameter of 25 mm (later in the project increased to 26 mm) has been considered as preferred for the hammering section mainly because of mass reason. For the payload section of the mole a reference length of 165 mm and a diameter of 26 mm was considered for the trade-off on concept selection.

Different approaches for the implementation of a single body mole were considered, as shown in Figure 1 (in which the "hammering section" is depicted in red while the HP3 "scientific section" is depicted in blue):

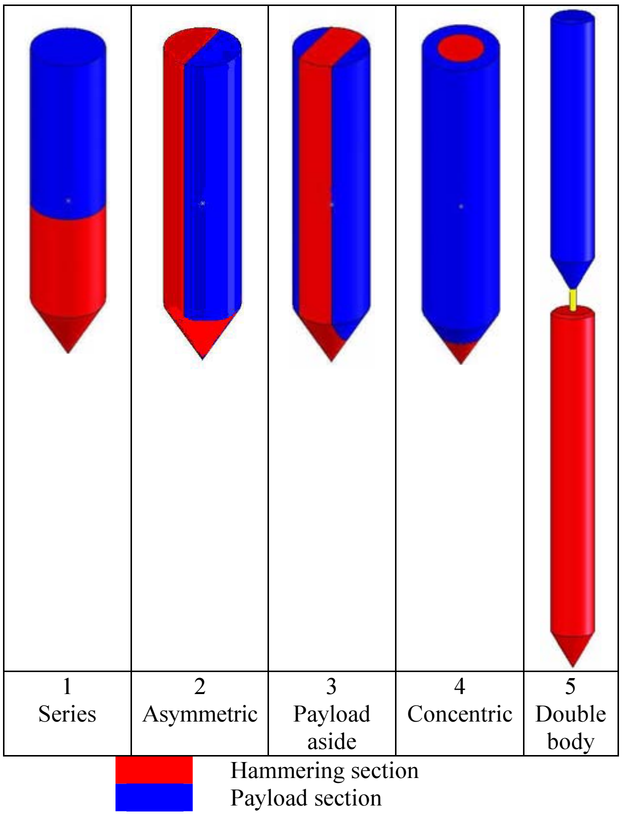


Figure 1: Mole Architectural approaches

1. Series Type Mole: the front part is dedicated to the hammering section, while the HP3 is hosted in the rear part.
2. Asymmetric Type Mole: hammering and HP3 are hosted along the length of the Mole.
3. Payload aside Type Mole: the HP3 is hosted on two opposite sides of the Mole body; with respect to concept N°2, this allows a partial increase of the thrusting action by exploiting the asymmetrical shape of the mole portion allocated to the hammering section itself.
4. Concentric Type Mole: the hammering section is hosted in the central core of the Mole, surrounded by the HP3.

Sketch N°5 of Figure 1 shows instead a Double Body Mole, or trailed mole concept, in which the hammering and HP3 are each hosted into a dedicated body; for the trade-off its penetration performance was assumed to be equal to the one of a series type mole having the same volume.

A trade-off among the different concepts was performed, assuming as criteria:

- Impact in mole length (relative weight of 0.25)
- Mass (relative weight of 0.20)
- Ease of sensor package accommodation (relative weight of 0.20)
- Ease of stowing and deployment (relative weight of 0.15)
- Penetration performances (relative weight of 0.12)
- Modularity of concept (relative weight of 0.08)

The results of the trade-off proposed to select the Double body Mole concept for further development and testing in the contract.

4. DEVELOPED CONFIGURATION

The developed configuration of the IMS and its main elements are shown in Figure 2.

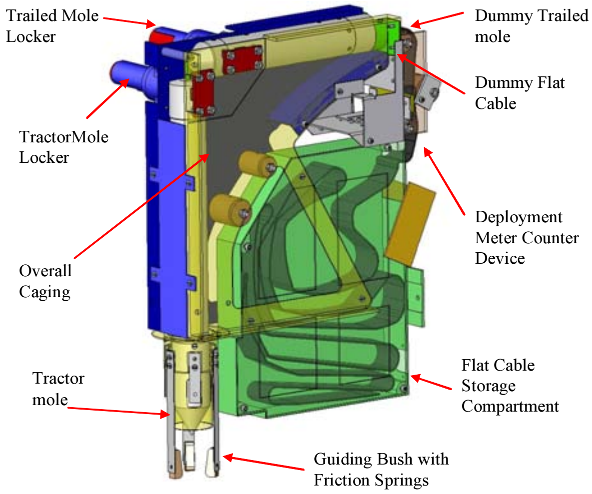


Figure 2: IMS overall view (305 x 238 x 112 mm)

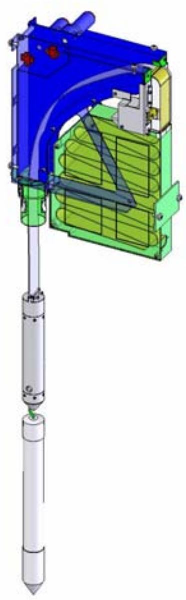


Figure 3 IMS deployed view (not representative for flat cable features)

The tractor mole is connected to the trailed mole by a 3 mm diameter short cable which brings internally the electrical connections necessary to operate the mole actuator. The trailed section is connected to the overall caging of the IMS by means of a dummy flat cable carrying the electrical connection lines to support both hammering section actuator, sensors (navigation, temperature) and other electrical parts (resistors) placed inside the trailed section. The flat cable storage compartment allows the accommodation of a flat cable up to a length of 5 m.
The mass of the entire breadboard system is 1690 g, but a flight equivalent is estimated to be around 1300 g.

The main elements of the systems are briefly described in the following paragraphs.

4.1 Tractor Mole

For the hammering mechanism of the Tractor Mole a roller-screw type design was chosen. This design envisages an actuator whose rotary motion is translated into a longitudinal motion and compresses the hammering mechanism main spring (the so-called "force spring"). This entire mechanism, complete with the actuator and the hammer mass itself, is free to move inside the Mole external cylindrical housing to which is connected only by another spring (the so-called "brake spring"). Figure 4 shows two exploded views of the Tractor Mole, while the mechanism's functions along a single hammering cycle is sketched in Figure 5.

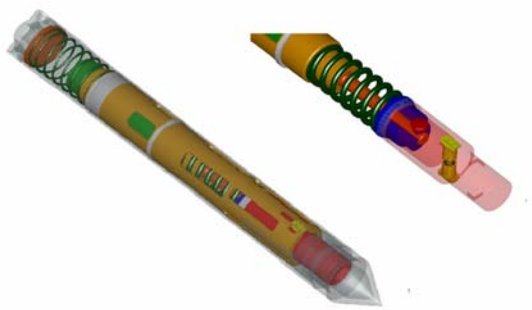


Figure 4 Exploded views of the Tractor Mole

To produce the propulsive shock, the actuator unit drives a roller-screw mechanism along a cylindrical cam which has a screw-like surface for about 350°. In the remaining 10°, the cam has a vertical slit which causes the "force spring" to be rapidly released once the roller reaches this position.
Upon this release, the hammer on one hand and the "suppressor" (actuator + roller-screw mechanism shaft + structure surrounding the hammer) on the other hand are accelerated into opposite directions. The lighter of the two masses (the hammer) impacts against the Mole housing front tip from the inside (position d in Figure 5) and the useable fraction of the shock energy causes a displacement and compression of the soil near the Mole tip to effect penetration. The heavier "suppressor" instead moves backwards inside the housing, then dragging the hammer after it has completed its forward shock. During this motion, the suppressor compresses the "brake spring" and transfers a force to the housing which attempts to push the Mole out of the soil again. With appropriate sizing, the force of suppressor's backwards motion is compensated by the friction of the soil with the Mole housing.

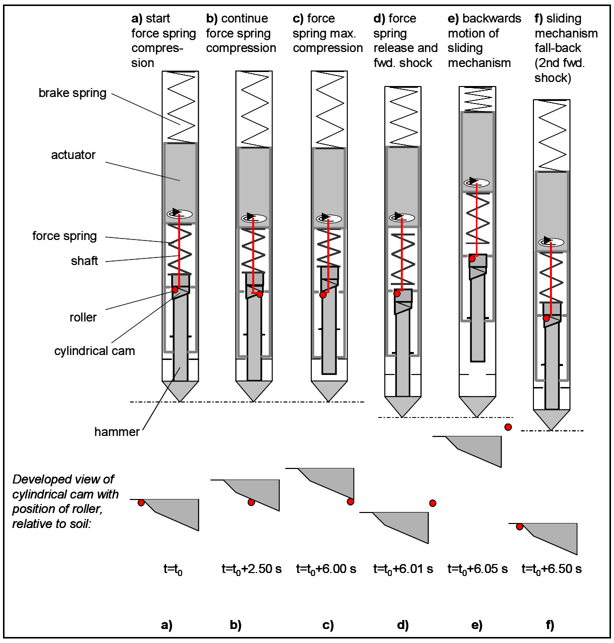


Figure 5 Schematics of hammering mechanism sequence during a single shock cycle

After the "suppressor" has reached the maximum backwards travel position, it returns to the forward end of the housing and impacts against the front tip, thus imparting a second forward shock to the Mole housing (position f) in Figure 5).
The final result of the entire cycle is thus a net forward motion of the Mole into the soil due to the two forward shocks.

One of the key design drivers is the need to brake the "suppressor" by the "brake spring" before it impacts the rear end of the Mole, otherwise shocks would be transferred to the housing in the reverse direction as well, which would be detrimental to forward soil penetration.
The duration of the shock cycle is dominated by the time required to compress the "force spring" by the actuator, and for the MCSP design it is about 6.5s. Power required for the hammering mechanism is constant (i.e., does not increase with depth reached) and is of the order of just 1.3 W.

The Mole incorporates also launch & landing lock to hold the sliding hammering mechanism relative to the Mole housing and turn the Mole into a single rigid item until it has to be firstly operated after landing. These locks are automatically released by hammering mechanism actuator rotation during its first operation, making a dedicated release actuator unnecessary.
Table 1 list some of the key parameters in the Hammering Mole design, while Table 2 shows the mass break-down of the system.

Table 1 Hammering Mole key parameters

Actuator mass	101 g
Spring stroke	7.0 mm
Maximum drive torque during shock cycle (including a 50 % margin)	0.7 Nm
Hammering frequency	6.5 s / shock
Length	251 mm

Table 2 Hammering Mole mass budget

Part	***Mass (g)***
Hammer elements	113
Suppressor (including actuator)	206
Housing	116
Total	**435**

4.2 Dummy Trailed Mole

Instead of a fully sensored trailed mole, a dummy model was used with one 2-channels accelerometer used as inclinometer, one longitudinal accelerometer, one temperature sensor and three resistors to simulate heat dissipation. A 3D view of the model is shown in Figure 6.

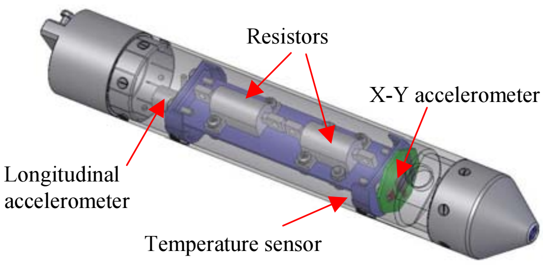


Figure 6 Trailed Mole dummy model

4.3 Cables

The two moles (traction and trailed) are interconnected mechanically and electrically by means of a short and round circular cable made by an external stainless steel sleeve (flexible but capable to withstand longitudinal traction load) enclosing four isolated wires.

The entire system was then connected to the IMS structure through a flat cable. For the breadboard model a dummy flat cable was realized by integrating together side by side an array of 16 wires (AWG 28 teflon insulated) and one miniaturised coaxial cable (for one of the accelerometers). The whole array is protected with a first layer of Teflon tape. A paper tape with black and white marking every centimeter for cable deployment optical measurement was put on this Teflon tape for its whole length, and then s second layer of Teflon tape cover the entire assembly. The resulting cable had 24 mm width and 1.9 mm thickness. A picture of the dummy flat cable is shown in Figure 7.

Figure 7 Picture of dummy flat cable

4.4 Other features

A guiding bush was implemented to guide the tractor mole (and the trailed mole) during the advancing action. It uses six friction springs acting on the tractor mole body to support mole advancing during the deployment phase.

The launch locks are implemented by 2 devices working as pin-pullers. Particularly, the traction mole was centred and kept in place by the friction springs in its forward part, while engaged and kept pressed by one pin-puller in the rear part; the trailed mole was instead engaged and kept pressed by one pin-puller in its forward part, while centred by a supporting circular bush in the rear part.

The deployment length is measured by counting the marks on the flat cable through a specifically manufactured optical counter (made by a diode emitter and a phototransistor detector) with drive electronics.

The entire IMS is hosted inside a sustaining structure made of carbon fibre and primarily divided into two main parts: the Glider assembly and the Flat cable storage. All parts form a self standing mechanical frame capable to provide all deployment and initial mole guiding functionalities and to support the launch induced loads.

5. BREADBOARD TESTS

An IMS breadboard prototype was built and tested to assess the operational and functional capabilities of the concept.

5.1 IMS functional testing at ambient

The functional testing in ambient conditions allowed the verification of both the deployment of the moles and the capability to penetrate the soil.

The IMS, with the tractor mole and the trailed mole locked as for the launch/landing condition, was placed above a 2900 mm high container filled soil simulant with the long springs at 25 mm from to the top surface of the soil simulant. Figure 8 shows the complete test setup, while Figure 9 gives a more detailed view on the IMS device. The test was conducted in vertical to check a gravity component along the mole vertical axis. A single borehole was made along three test sessions for an overall depth of 2165 mm and the main records are summarised in Table 3.

Figure 10 shows the transitions recorded by the mole deployment counter and stored in the data collection system during the first session (marks on the flat cable 10 mm black, 10 mm white). It is clear the good accuracy of the penetration depth counter, in line with the real measurement performed after mole recovery.

Table 3 Summary of soil penetration test results

Test n.	***I***	***II***	***III***	***Total***
Test duration (s)	2309	14884	9364	26557
True reached depth (mm)	365	1310	490	2165
Average speed (mm/min)	9.6	5.2	3.1	4.9
Measured depth (mm)	370	1300	480	2150

Figure 8 Test setup

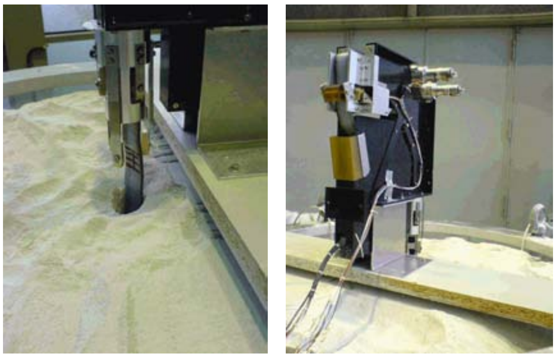
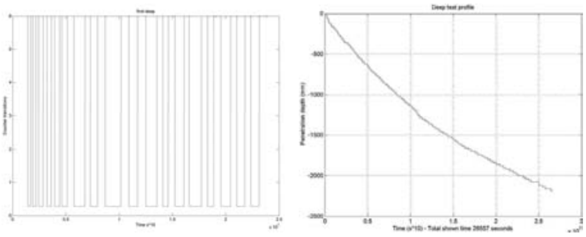


Figure 9 The soil penetration test



Deployment counter transitions

Total depth 2165 mm

Figure 10 Recorded data

During the test sessions the outputs of the accelerometers were continuously recorded and then analyzed to calculate the deviation angle with respect to vertical axis, whose maximum value was below 2°÷3°. The apparent noise that seemed to affect the accelerometer information was caused by the longitudinal shocks which propagate on the accelerometers transversal axis. Figure 11 shows an example of spikes separated by the hammering period and background noise (equivalent to less than 0.1°).

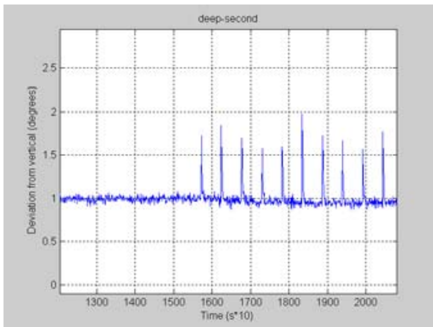


Figure 11 Noise on vertical angle measurement

5.2 Functional testing in simulated reduced gravity

This test allows the verification of the deployment of the moles and of the penetration into the soil in simulated reduced gravity condition.

The test was conducted at 70° inclination from vertical (β=20°) to simulate a gravity component along the mole axis similar to Mercury environment. A sketch of the test setup is shown in Figure 12, while a real view is given in Figure 13. The test has been carried out through 4 sessions, for a total deployment length of 1380 mm.

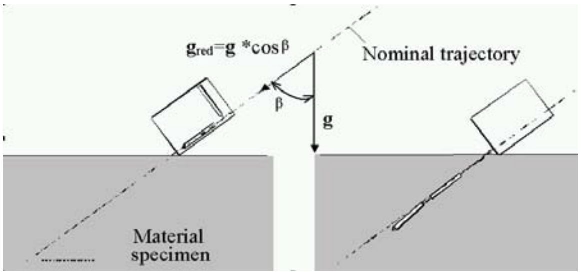


Figure 12 Simulated reduced gravity test

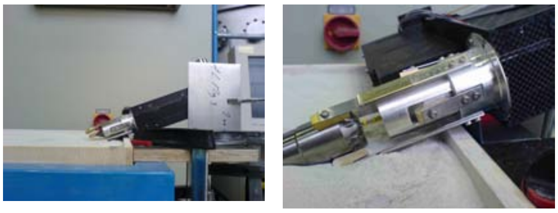


Figure 13 IMS during simulated reduced gravity test

5.3 Thermal vacuum tests

5.3.1 Pre-Verification In Thermal Vacuum Condition

The scope of this test was to check the functionality of the tractor mole hammering device. Before the test, the tractor mole motor was substituted with one capable to operate in low temperature, while heaters were installed in the tractor mole. During the test, tractor mole mechanism was turned on at approximately –150°C (tractor mole housing temperature, with actuator heater activated) and hammering was found nominal (about both frequency and current). The test was carried on up to approximately 2100 mole shocks.

5.3.2 Thermal Vacuum Test

The scope of this test was to verify the mole deployment and soil penetration in thermal vacuum condition at low temperature. The test set up included a sample container equipped with a breakable membrane to contain the soil simulant and prevent its propagation in thermal vacuum pump. The test set up had the IMS suspended above the container with the trailed mole locked as for launch condition.

The test was conducted along three days and the following activities done:

- Setup installation and start vacuum procedure.
- Unlocking of the moles at ambient temperature, resulting in forward movement by some cm partly perforating the membrane above the soil container, and then start cooling procedure;
- Operational test at T = -128.2°C, P < 10^{-3} mBar, Tsoil=-146°C, and hammering behaviour found nominal (on both frequency and current); moles motion observed to be uneven, with phases of elastic bouncing in the structure, interrupted by period of moles net forward motion; the test was carried on up to about 1400 shocks delivered, then was intentionally stopped; the total moles forward motion into soil was estimated equal to few cm.
- Warm-up, with tractor mole operation repeated at approximately -90°C, -60°C, and -30°C and hammering behaviour found nominal.

Prior to open the chamber, at an ambient temperature condition, the system was switched on again and operated normally.
Investigation performed with additional testing made at ambient pressure / temperature and in thermal chamber at –40°C at ambient pressure indicated possible causes of the uneven motion at low temp & low pressure:

- force resistance for dummy flat cable extraction increases up to 60% from ambient temperature to –40°C.
- force needed for penetration increases from 11 to 17 N at ambient to 17 to 23 N at –40°C.
- detachment of teflon tape which was applied to some parts of the CF structure to reduce friction.

5.4 Vibration tests

The vibration tests were conducted to verify the mechanical resistance of the IMS structure and mechanisms during the launch phase. Before the tests all the screws were checked and some epoxy glue was put on the screw heads to lock them. The moles were locked by pin pullers, while a dedicated vibration test support was used to sustain the IMS during the tests.

Four kinds of test were applied:

- Sine vibration test

Frequency (Hz)	*Input level*	*Sweep rate*
5-20	20 mm P-P	2 oct./min
20-100	20 g	2 oct./min

- Random vibration test

Frequency(Hz)	*Input level*	*Duration*
20-100	+3 dB/oct	120 sec
100-200	0,3 g2/Hz	120 sec
200-2000	-6 dB/oct	120 sec

- Resonant survey: 0.5g/5-2000 Hz, 2 oct./min
- Shock test: 10 shocks @ 50g (the desired acceleration level could not indeed be reached due to the characteristic of the shaker, and the test

sequence was thus modified from one single shock at high level to more shocks at lower level).

For each of the axes shown in Figure 14 the following sequence was used:

1. Resonant Survey
2. Sinusoidal test
3. Resonant Survey
4. Electrical test
5. Random test
6. Resonant Survey
7. Electrical test
8. Shock test
9. Resonant Survey
10. Electrical test

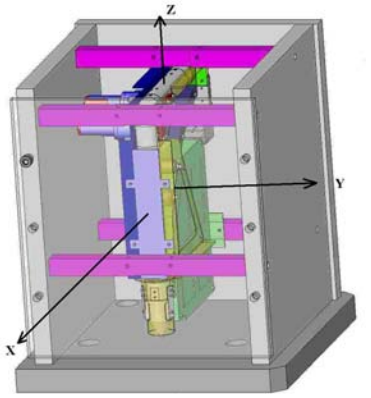


Figure 14 Vibration tests reference axes

The electrical tests were performed to monitor the status of the devices inside the IMS by checking the value of the DC resistances of the devices. The resonant surveys were also performed to check the mechanical behaviour of the structure. Four accelerometers were mounted on the structure: one for each axis plus one representing the control/feedback signal, each time aligned with the shaking axis. The acquisition of the longitudinal accelerometer inside the trailed mole was also performed.

During the test entire vibration test campaign no major problem raised: all the checks (either resonant survey or electrical tests) were successful and no loose parts/nuts were found during the visual inspection performed while switching from one axis to the next one. The validity of the locking concept were proved even if during the test along the X-axis it was found that the tractor mole could slightly slide if pushed with force: the tractor mole was indeed kept into position also during the strong vibrations along the other axes, leaving the sliding as a side effect.

5.5 Functional tests after vibration tests

This test was intended to functionally prove that the IMS is capable to correctly perform an entire operative sequence, from tractor mole internal mechanism unlocking to penetration into the soil. The test was continued for about 13 minutes till the nose of the tractor mole was almost touching the bottom of the soil simulant container. The depth reached was 170 mm. The markers impressed on the tractor mole body during advancement are clearly visible in Figure 15. At the end of this functional test the whole system worked correctly.

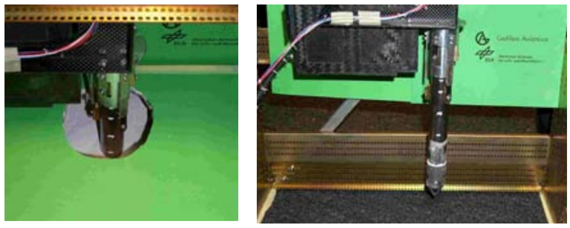


Figure 15 The tractor mole in the soil at the end of the test (left) and extracted from the soil (right)

6. CONCLUSIONS

The project allowed developing and validating an innovative concept of mole system for investigations into planetary soil regolith. During the development several technological issues were tackled and solved; the IMS prototype was extensively tested on both functional and environmental aspects, and all tests were passed without major inconveniences. The assembly tractor plus trailed mole is capable to penetrate the soil with appropriate advancing speed and the concepts of stowage and deployment have been proved.

Tests underlined the following aspects as the ones which deserve some further attention for possible future applications:

- flat cable characteristics: the dummy used in the prototype was much heavier and stiffer to pull than the one foreseen for FM;
- connection link between the two moles: cable solution proved to be effective, but lifetime improvement may be required;
- use of DC brushless motor for the tractor mole: in this case a local electronics is required, which must be carefully strengthened in order to avoid possible damages due to local highly dynamic environment;
- shape and position of the deployment springs.

The trailing concept appeared to be effective and was proven as a valid approach for mole systems operating in regolith when stowage size limitation does not allow installing a single longer mole.

7. REFERENCES

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2. *Instrumented Mole System Final Report*, GA Doc. n. MCSP-SA-GA-014, rev.A, 04 August 2006