MERCURY MOLE N°: 7399

Mole-Carried Sensor Package For Mercury Sub-Surface Measurements

ESTEC/Contract N° 17555/03/NL/CH

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ACRONIMI E ABBREVIAZIONI / ACRONYMS AND ABBREVIATIONS

CPA	Conductivity, Permittivity, and Attenuation
DACTIL	Depth, Accelerometry and TILt suite
DD	Deployment Device
DEN	Densitometer
FEE	Front End Electronics
GT	Guiding Tube
HP3	Heat flow and Physical Properties Package
IM	Instrumented Mole
IMS	Instrumented Mole System
IMSE	IMS Electronics
LET	Linear Energy Transfer
MCSP	Mole Carried Sensor Package
MP	Mobile Penetrometer
MPO	Mercury Planetary Orbiter
MSE	Mercury Surface Element
PSD	Power Spectral Density
RMS	Root Mean Square
RQTS	Requirements
SOW	Statement Of Work
SP	Sensor Package
SRS	Shock Response Spectrum
SSA/DT	Small Sample Acquisition Tool
TC	Telecommand
TD	Tethering Device
TEM	Thermal Excitation and Measurement suite
TM	Telemetry
XRS	X-Ray Spectrometer

1. INTRODUCTION

This document is the Executive Summary of the activities performed under ESTEC/Contract N° 17555/03/NL/CH named Mole Carried Sensor Package.

The aim of the activity was to develop and test an Instrumented Mole System (IMS) - i.e. a system able to deploy a mobile penetrometer carrying a payload of sensors for sub-surface measurements – to be mounted on a Planetary Lander.

This IMS could potentially be used on future planetary missions such as those for the exploration of the surface of Mercury or on other planets.

With respect to other mole systems developed so far (e.g. original Mole developed by Vniitransmash in ESA SSA/DT contract, Mole with Sampling Mechanism developed by DLR under ESA contract, Pluto Mole for Beagle 2 mission) the present one is characterised by a much greater volume (and mass) dedicated to the scientific package with respect to the system overall volume and mass and a by a more powerful hammering mechanism.

After the review of the preliminary requirement included in the SOW, for the IMS implementation different types of single body moles (i.e. a single case including both the hammering section and the scientific section) and double body moles have been considered and traded. The decision was to develop a double body mole system composed by a *tractor mole* (which houses the hammering section) and a *trailed mole* (which houses the scientific experiment section) connected by a short cable. This allows the accommodation of the moles disposed at 90 degrees each other in a compact lightweight structure, so minimising the storage volume. The lightweight structure has also a storage compartment for a long flat cable (3-5 meters) which is used to provide the moles with electrical power and data for their operation.

Two mechanism of the pin-puller type are used to keep the moles constrained for launch and landing. No active deployment mechanism was necessary being the deployment achieved by the reaction to the hammering shocks provided by sets of springs included in the guiding tube.

Upon completion of the detailed design phase, a breadboard of the IMS has been manufactured including the following main parts:

- Overall structure (made in carbon fibre)
- Tractor mole
- Dummy trailed mole, including accelerometer on the 3 axes and a temperature sensor
- Dummy flat cable
- Guiding tube and deployment springs
- Mechanisms to secure the moles at launch and landing
- Deployment counter to measure the mole advancing into the soil

The breadboard has been extensively tested in its main constituent part individually and in integrated mode. Once integrated deep soil penetration tests, simulated reduced gravity tests, thermal vacuum/climatic chamber tests and vibration test have been performed with good results.

In the following chapters a short summary of all the activities performed is presented.

1.1 INDUSTRIAL TEAM

The work performed in this contract has been carried out by the following industrial team

Galileo Avionica, Prime contractor, responsible for the system definition and development (but for the tractor mole) and testing (with DLR Koeln)

DLR Koeln, Subcontractor responsible for the development of the tractor mole and testing of the tractor mole and of the integrated system (with Galileo Avionica)

University of Muenster, Subcontractor for the overall Scientific Payload assessment, the HP3 and the permittivity probe preliminary definition and the thermal analysis.

University of Leicester, subcontractor of University of Muenster, responsible for the X-Ray fluorescence spectrometer (XRS) preliminary definition.

Kayser-Threde, subcontractor of University of Muenster, responsible for the Raman spectrometer preliminary definition.

Space – X, subcontractor of University of Muenster, responsible for the camera preliminary definition.

Note: the activity of University of Muenster was taken in charge by DLR Berlin after the conclusion of the payload assessment.

1.2 APPLICABLE DOCUMENTS

[AD 1] SOW of "Mole-carried Sensor Package for Mercury Sub-Surface Measurements", TOS-MMM/2001/196, Is.1 Rev.0, 14-02-2003

[AD 2] IMS General Assembly, GA Doc. n. MCSP-MD-GA-007-000

[AD 3] IMS Instrumented Mole Dummy Model, GA Doc. n. MCSP-MD-GA-007-002-000

[AD 4] IMS Instrumented Mole Dummy Model, GA Doc. n. MCSP-MD-GA-007-015-000

1.3 REFERENCE DOCUMENTS

[RD 1] Instrumented Mole System Requirements Specification; GA Doc. n. MCSP-RQ-GA-001

[RD 2] Instrumented Mole System Verification Test Plan; GA Doc. n. MCSP-PL-GA-009

[RD 3] Launch Lock Conceptual Trade-off, GA Doc. n. MCSP-SD-GA-008

[RD 4] Concept and performance of Instrumented Mole, DLR Doc. n. BC-AR-005 WP100-DOC-3

[RD 5] V.V. Gromov, A.V. Miskevich, E.N. Yudkin, H. Kochan, P. Coste & E. Re (1997). The Mobile Penetrometer - A "Mole" for Sub-Surface Soil Investigation. Proceedings of the 7th European Space Mechanisms & Tribology Symposium, ESTEC, Noordwijk, The Netherlands. ESA SP-410.

[RD 6] Comparison between single body and double body moles, GA Doc n. MCSP-SA-GA-005

[RD 7] R. Nadalini, MCSP Tractor Mole Thermal Mathematical Model Description Document, MCSP-TN-MOLE-07-IFP Issue 0.5, June 13, 2005

[RD 8] AEA Technology: Space Tribology Handbook.

[RD 9] L. Richter, V.V. Gromov, E. Re (2006). MSM – Mole with Sampling Mechanism. Final Report of ESTEC Contract No. 39595/99/NL/WK(SC).

[RD 10] HP3 Description Document Issue 3.0, HP3-TN-PACK-01-DLR, October 14, 2005.

2. SYSTEM DEFINITION AND REQUIREMENTS

2.1 SYSTEM DEFINITION

The original definition of the Instrumented Mole System, as from the SOW, foresees a system based on a mobile penetrometer carrying a payload of sensors for Mercury sub-surface measurements. As shown in Figure 2-1 the IMS consists of the following items:

- Instrumented Mole (IM), in turn split into:
  1. Mobile Penetrometer (MP) also called Mole which is a slender tubular device, with an internal electro-mechanical hammer to propel it into the ground;
  2. Sensor Package (SP), made of sensors and electronics to perform in-situ physical and chemical property measurements of the soil and to provide measurements of the parameters related to the IM navigation
- Guiding Tube (GT): that is the mechanical housing for the IM when it is stored and includes the devices to support the mole initial advancement in the soil
- Tethering Device (TD), a tether to exchange power/data with the powering the IM
- Deployment Device (DD): to deploy to soil the Guiding Tube plus Mole.
- IMS Electronics (IMSE), for power conditioning and distribution of the MSE power bus and exchange of TsC/TLMs with the IM sensors sensor package.

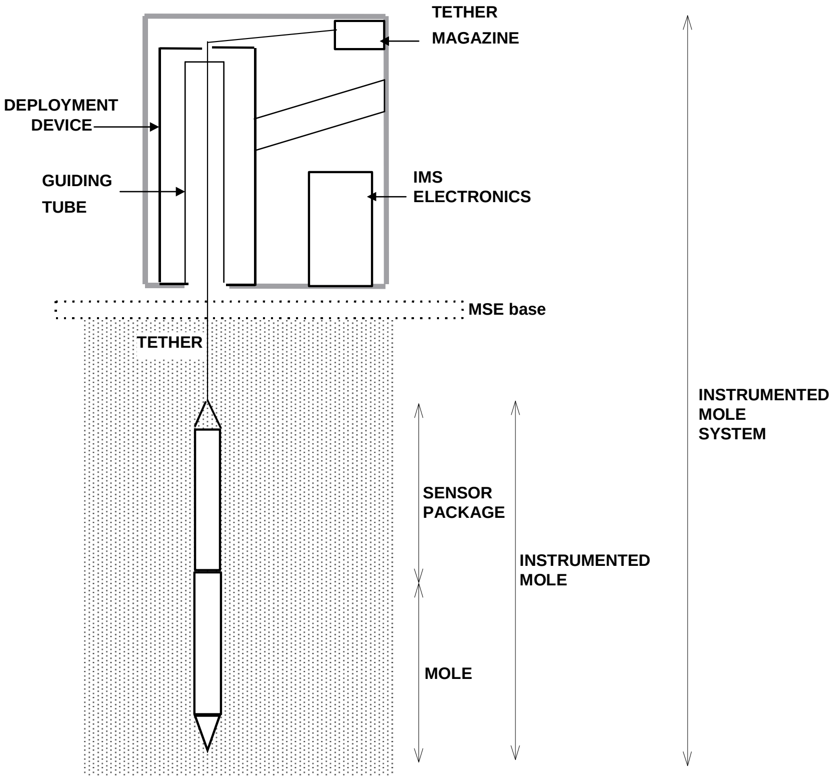


Figure 2-1 Main components of the IMS

2.2 MAIN REQUIREMENTS FOR THE MOLE SYSTEM

The main requirements set for the IMS can be briefly summarised as follows:

§ After its insertion in the planetary regolith by the combined action of the DD and GT, 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 sec.

§ Depth of penetration into regolith: 3 meters in 5 hours time, 5 meters goal.

§ The mole has to be locked (also its internal moving parts) to withstand both the launch loads and the landing shocks.

§ The mole has to include sensors to allow the determination of the mole position (accuracy > ± 50 mm) and to allow attitude measurement (accuracy > ± 5°).

§ IMS total envelope < 500 cm3 within a cylinder of 200mm diameter x 200mm height.

§ Total IMS mass < 1000 g.

§ IMS average/peak power consumption during penetration < 3 W/<4W; average power consumption < 0.3 W when the IMS is not penetrating.

§ Operating temperature range: -190°C to +10°C (compatible with the "night landing scenario“); not operating temperature range: -190°C to +70°C.

2.3 SCIENCE PACKAGE OBJECTIVE AND ASSESSMENT

Primary goal of the sensor package is Heat Flow determination, derived from the following measurements:

- Temperature distribution along the Mole path
- Thermal conductivity of regolith material
- Density of regolithSecondary objectives of the sensor package are:

o Determination of regolith electrical characteristics
o Mineralogy and composition of soil material/spectroscopy
o Borehole Imaging

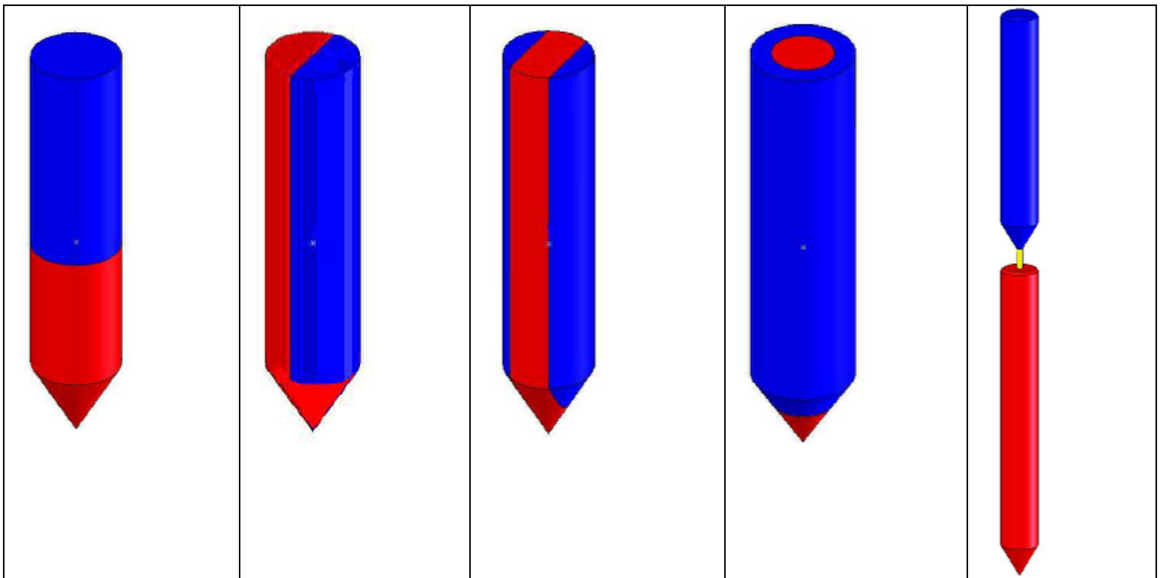
Sensor package assessment

The scientific goals of the Heat flow and Physical Properties Package (HP3) to measure the heat flow on Mercury were classified as mandatory. Moreover, the stratigraphy, maturity, and composition of the Hermean regolith can be obtained along with searching for frozen volatiles such as water ice and sulfur possibly intermingled with the regolith. This package is the present baseline configuration and includes the Thermal Excitation and Measurement suite (TEM), the Densitometer (DEN), and the Depth, Accelerometry and TILt suite (DACTIL) sensors.
Since HP3, with its estimated mass of 300 g (plus margins), uses up all the allocated mass budget, there are, at present, no available resources to accommodate further sensors. To include other instruments, either the resources used by HP3 need to be optimised and reduced, or the overall quantity (including, mass, power, volume and available mole length) needs to be increased. HP3 is presently under development in a parallel contract assigned by ESA to DLR. Berlin.

3. IMS 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 design 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 3-1 (in that figure the “hammering section” is depicted in red while the “scientific section” is depicted in blue):
1) *Series Type Mole* with the front part dedicated to the hammering section.
2) *Asymmetric Type Mole* for accommodation in length of the hammering section.
3) P*ayload on mole lateral sides* which may allow, with respect to concept N°2, a partial increase of the thrusting action by exploiting the asymmetrical shape of the mole portion allocated to the hammering section itself.
4) C*oncentric mole*.
Sketch N°5 shows instead a *Double body mole*, or trailed mole concept; for the trade-off its penetration performance was assumed to be equal to the one of a series type mole having the same volume.



1) Series	2) Asymmetric	3) Payload aside	4) Concentric	Double body

Hammering section
Payload section

Figure 3-1 Possible approaches for single body moles

A trade-off among the different concepts was performed, assuming as criteria the following parameters and weights:

- 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 trade-off is summarised in the here after Table 3-1.

		Single Body								Trailed mole	
		N°1 (series)		N°2 (asymmetric)		N°3 (P/L on lateral sides)		N°4 (concentric)			
	relative weight	Score	W. S.	Score	W. S.	Score	W. S.	Score	W. S.	Score	W. S.
impact in mole length	0,25	-3,00	-0,75	2,00	0,50	2,00	0,50	2,00	0,50	1,00	0,25
mass	0,20	0,00	0,00	-1,00	-0,20	-1,00	-0,20	-1,00	-0,20	0,00	0,00
ease of sensor package accommodation	0,20	3,00	0,60	1,00	0,20	-1,00	-0,20	-1,00	-0,20	2,00	0,40
ease of stowing and deployment	0,15	2,00	0,30	2,00	0,30	2,00	0,30	2,00	0,30	0,00	0,00
penetration performances	0,12	1,00	0,12	-2,00	-0,24	2,00	0,24	2,00	0,24	1,00	0,12
modularity of concept	0,08	2,00	0,16	0,00	0,00	0,00	0,00	-2,00	-0,16	2,00	0,16
total weighted score ---->			**0,43**		**0,56**		**0,64**		**0,48**		**0,93**

Table 3-1: Trade-off summary

Based on the considerations presented it was proposed the trailed concept for further development and testing in the contract.

4. IMS CONFIGURATION FOR THE PRESENT DEVELOPMENT

The IMS overall view is shown in Figure 4-1 where the main elements are evidenced:

- tractor mole,
- dummy trailed mole,
- dummy flat cable,
- overall caging (with flat cable storage compartment),
- guiding bush with friction springs,
- deployment meter counting device,
- devices for locking of the tractor and trailed moles for launch and landing.

The tractor mole is connected to the trailed mole via a short cable of diameter 3 mm 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 deployment sequence is reported in Figure 4-2.

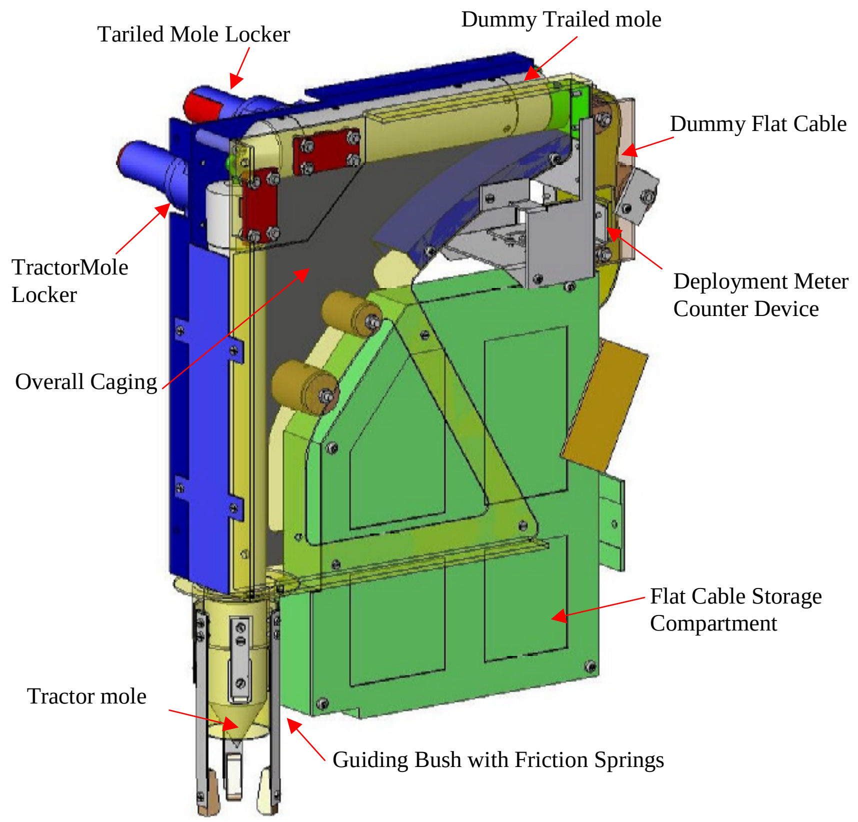


Figure 4-1 IMS overall view

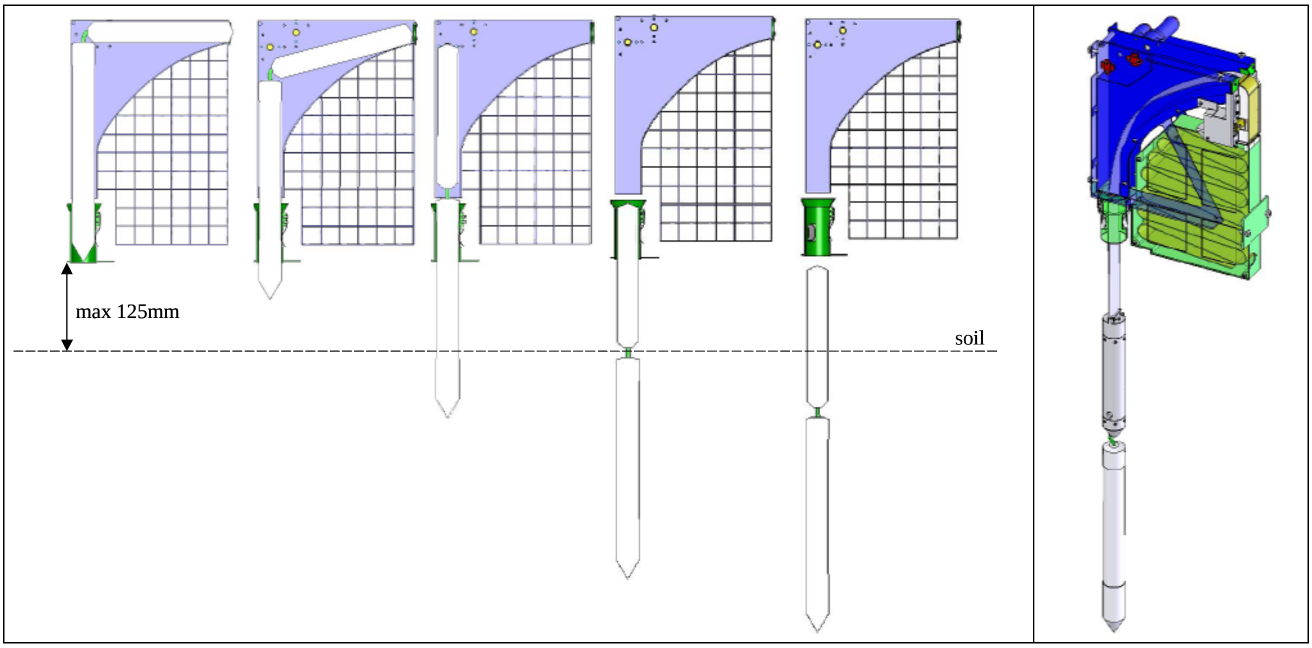


Figure 4-2 Deployment sequence

4.1 TRACTOR MOLE

As described in [RD 4] as a result of trade-off, a roller-screw type design was chosen for the hammering mechanism of the Tractor Mole of the IM. Figure 4-3 shows exploded views of the Tractor Mole. In this design scheme for the mechanism, the rotary motion of the actuator is translated into a longitudinal motion for compression of the hammering mechanism main spring (so-called 'force spring'). This mechanism, complete with the actuator and the hammer mass itself, is suspended on a so-called 'brake spring' within the Mole external cylindrical housing and is free to slide in it.

The actuator unit drives the roller-screw mechanism shaft which has a conical roller attached perpendicularly to it, see Figure 4-4. This roller moves along a screw-shaped surface on a part called the cylindrical cam which in turn is part of the hammer that is retracted against the force spring during shaft rotation. The screw-like surface of the cylindrical cam spans a circumferential angle of around 350°. Along a 10° stretch of circumference the cam exhibits a vertical slit which causes the force spring to rapidly expand as the roller is pushed down the slit. Figure 4-5 schematically depicts the mechanism's functions during a single hammering cycle.

Upon release of the force spring, the hammer on the one hand and the actuator unit with the roller-screw mechanism shaft and structure surrounding the hammer – collectively referred to as 'suppressor' - are accelerated into opposite directions with different terminal velocities due to the different sizes of masses involved. The lighter of the two masses (the hammer) impacts against the Mole housing front tip from the inside (position d) in Figure 4-5). A part of this energy is dissipated in the internal shock process whereas the useable fraction of the shock energy causes a displacement and compression of the soil near the Mole tip to effect penetration. The 'suppressor', being the heavier of the two masses of the sliding hammering mechanism, commences a backwards-directed motion inside the housing - i.e., away from the tip - with lower initial velocity than the lighter hammer, and drags it along with it after the hammer has completed its forward shock, due to a stop between the hammer and its guiding structure belonging to the roller-screw mechanism. During this motion, the suppressor compresses a second spring ('brake spring') between itself and the housing back end (position e) in Figure 4-5), transferring a force to the housing which attempts to push the Mole out of the soil again. Another force contribution in this direction originates from friction between the suppressor and the housing.

However, with appropriate sizing, these forces during backwards motion of the sliding hammering mechanism will be smaller than the friction of the soil with the Mole housing. This allows Mole net forward motion into the soil with each shock without requiring reactive forces to be provided by external mechanisms.

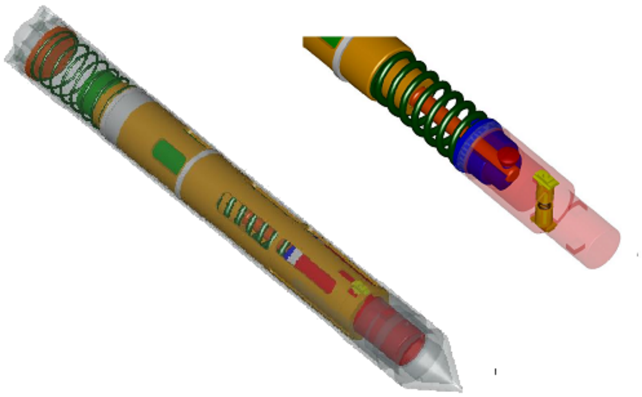


Figure 4-3 Exploded views of the Tractor Mole

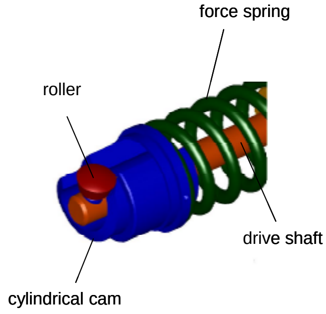


Figure 4-4 Geometry of screw-shaped surface of cylindrical cam, with roller engaged on it.

The design ensures that the suppressor during its backwards travel inside the housing never contacts the housing back end during hammering shock cycles; otherwise shocks would be transferred to the housing in the reverse direction as well, which would be detrimental to forward soil penetration. The measure to prevent such a contact with the back end is an appropriate choice of the length of the Mole housing (ensuring that the suppressor is fully decelerated due to resistive forces with the housing wall, combined with the gravity force component) and the introduction of the brake spring for limiting the required length of housing.
After the sliding mechanism has reached the maximum backwards travel position, it returns to the forward end of the housing, either under the action of gravity - depending on Mole orientation with respect to the gravity vector - or under the action of the expanding brake spring, or both.

At the conclusion of this forward motion, the sliding hammering mechanism impacts against the front tip, imparting a second forward shock to the Mole housing (position f) in Figure 4-5). During a single shock cycle - being defined as one compression and release of the force spring followed by the described shock dynamics - two shocks are thus delivered in the direction of forward penetration and both contribute to the ground penetration process. The duration of the shock cycle is dominated by the time required for compression of the force spring by the actuator, and for the IM design is some 6.5 sec.
Power required for the hammering mechanism is constant (i.e., does not increase with depth reached), of the order of just 1.3 W and it is only a function of mechanism design (stiffness of force spring and specified shock frequency). For hammering, the actuator is constantly turning in a single direction.

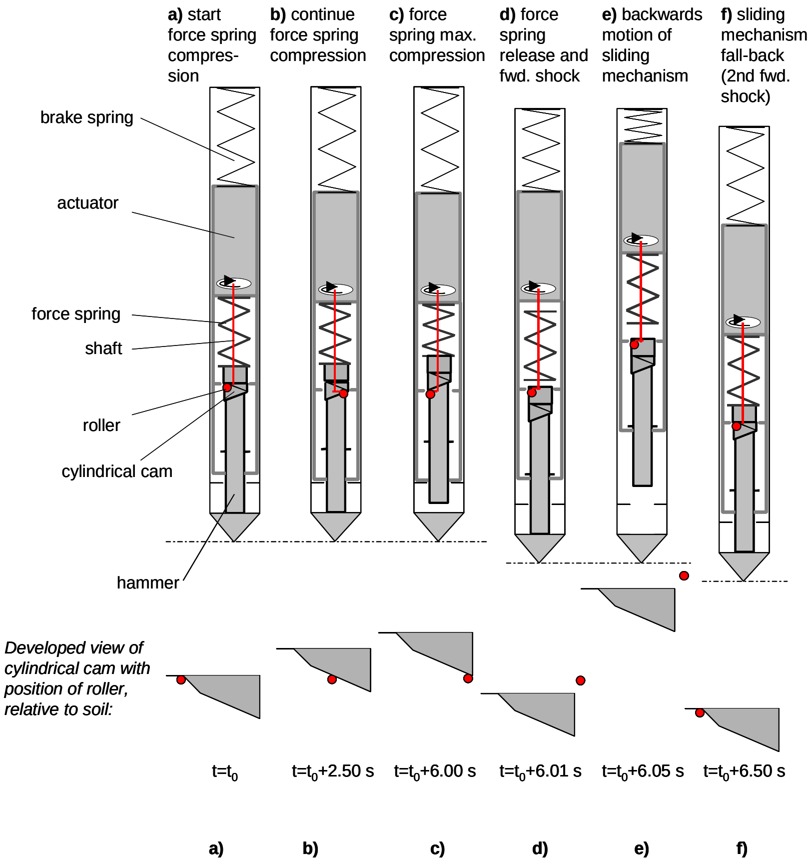


Figure 4-5 Schematics of MP sliding hammering mechanism with operating sequence during a single shock cycle.

Figure 4-6 and Figure 4-7 show assembly drawings of the Tractor Mole, identifying the parts. The main housing of the Mole (part 1) attaches to the housing tip (part 2) and an intermediate 'front' housing (part 3) via threads which also was the solution adopted in the previous Mole developments, easing assembly and integration. Hammer impact occurs onto the Mole tip part representing the anvil. Sliding bushes (parts 8 & 9) serve as bearings for the sliding hammering mechanism relative to the housing as was the case for the PLUTO Mole flight development to reduce number of parts and increase reliability.

Two lateral recess holes positioned 180° apart are contained in the back cover (part 4) to serve as the interface for restraining pins being part of pin pullers in the IM support assembly. In the IMS design baseline, only one pin puller would be utilized to secure the Tractor Mole during launch and landing. The unused recess hole in the Breadboard back cover part can be closed by a removable filler.

The sliding hammering mechanism, employing the roller-screw concept to compress the force spring prior to each shock, resulted from a sizing driven by availability constraints regarding brushless DC motors with integrated electronics. Whereas the mechanism in functionality bears a strong resemblance to that of the MP-1 Mole of the SSA/DT contract [RD 5], it is sized differently - as a result of different choice of motor and Mole diameter - and it features several design enhancements which are:

- stiffer drive shaft through hollow design and larger diameter (in part afforded by larger Mole diameter)

- more favourable design of roller attachment to drive shaft through separate axle (laterally threaded into shaft) and use of bush between roller and axle
- rotationally compliant drive shaft coupling to gearbox output shaft providing reduced loads on roller during transition to release of compressed force spring
- use of a brushless motor, providing higher reliability of mechanism especially for operations in high vacuum.

These enhancements are novel also with respect to the MSM/PLUTO designs.
As opposed to the MP-1 Mole design but similar to the PLUTO Mole flight design, the IM Mole section incorporates a launch and landing lock ('transfer lock') which on the one hand holds the sliding hammering mechanism relative to the Mole housing and on the other hand ties the hammer to its support structure, essentially turning the Mole into a single rigid item until it is to be first operated after landing. As the main feature of this lock, it is released by exploiting the hammering mechanism actuator rotation during first operation, making a dedicated release actuator unnecessary for this function as well as any breach through the Mole housing. Electrical lines to supply the motor and an actuator heater inside the Mole are incorporated into a flexprint cable that is routed in the central cavity of the brake spring (part 34) on which the sliding hammering mechanism is suspended, and thus is routinely bent during hammering. This is different from what was done in the previous Mole designs which had the motor supply wires attached along the brake spring, being not viable for the IMS because of the larger required number of lines leading to the sliding mechanism.
The steel braiding of the cable connecting the MP to the MPC is clamped to the Mole back cover, as in the MSM/PLUTO designs.
The electrical routing from the interconnecting cable entering the MP back end to the internal flexprint cable is realized via a connector to ease integration and maintenance activities. This was done similarly in the PLUTO Mole flight design.

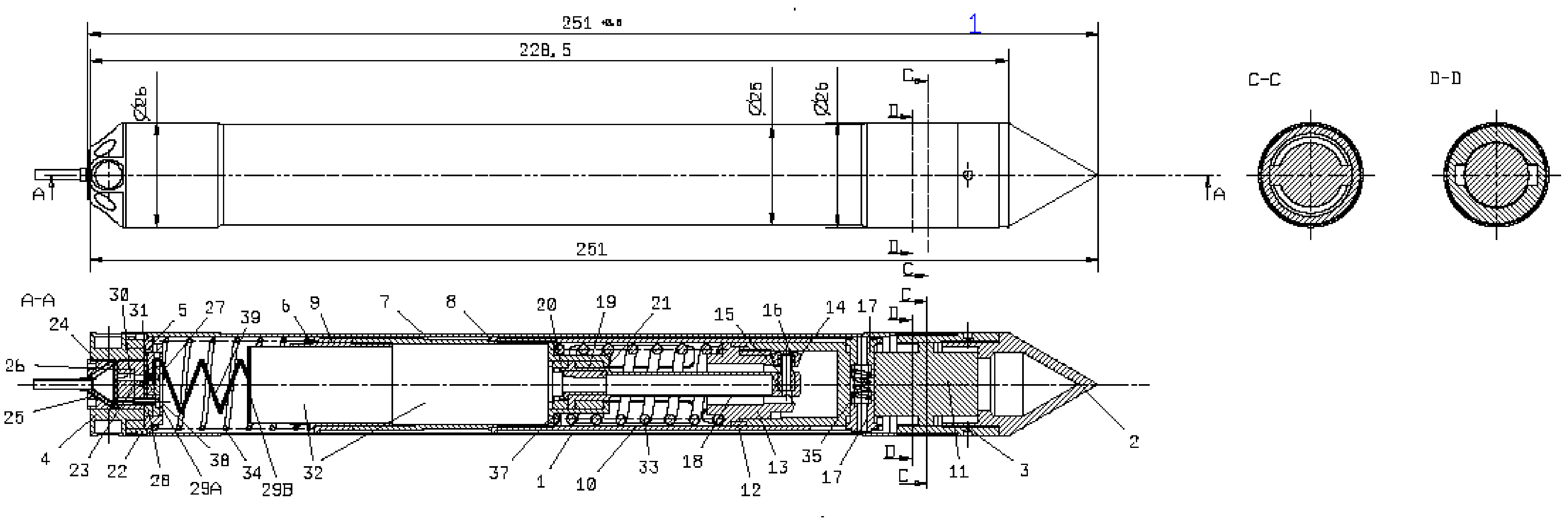


Figure 4-6 Assembly Drawing of Tractor Mole

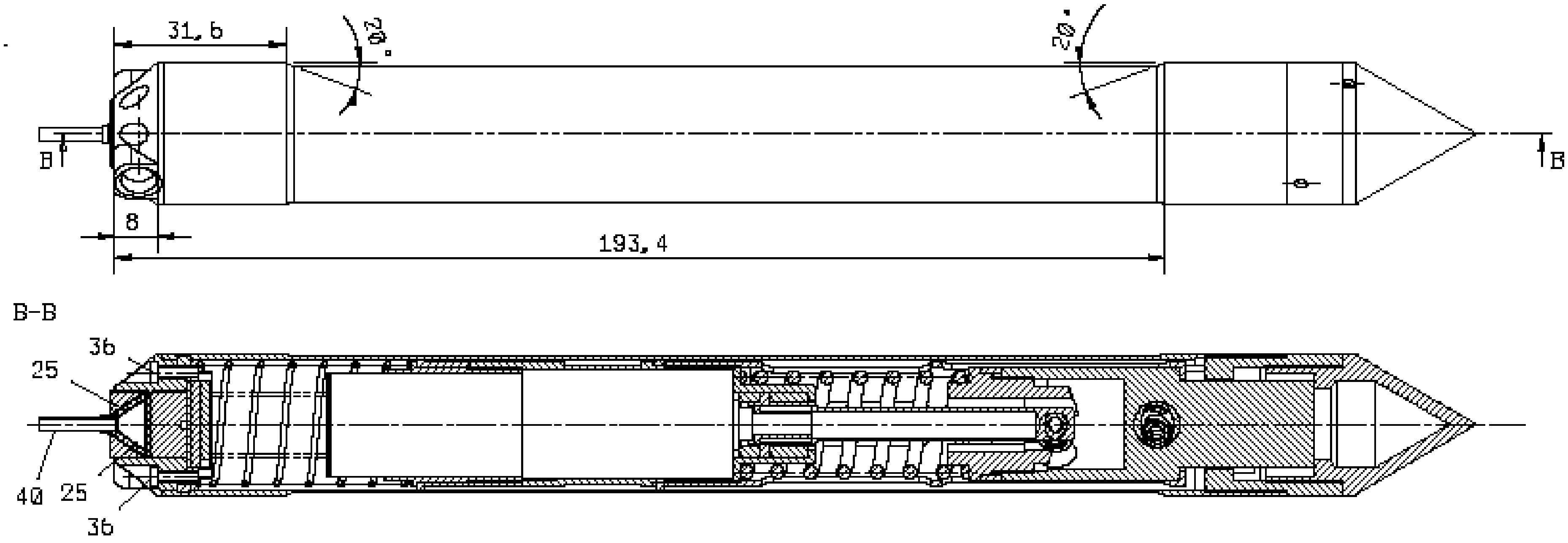


Figure 4-7 Assembly Drawing of Tractor Mole (2nd view)

Tractor mole design summary

Table 4-1 summarizes key parameters of the design of the Tractor Mole, as well as gives a mass budget.

Motor	Faulhaber 1935 S 012 BRE
Gear	Faulhaber 20/1 planetary gear
Actuator mass	101 g
Spring	Gutekunst G108123; spring rate 11.6 N/mm
Spring stroke	7.0 mm
Maximum drive torque during shock cycle (inclusive a 50 % margin)	0.700 Nm
Hammering frequency	1 shock per 6.5 s
Mass of Mole section	
Mass of hammer elements	113 g
Mass of suppressor (includes actuator)	206 g
Mass of housing	116 g
Total	435 g
Length	251 mm

Table 4-1 IM Mole section key design parameters

Tractor Mole predictive performances

Soil penetration performance of electro-mechanical Moles can be predicted by a modified theory of pile driving inherited from geotechnics; this was accomplished already during the MSM/PLUTO Mole developments. In the theory, checked against Mole penetration test data, the useful energy per shock cycle delivered by the hammering mechanism is equated to the work done by the soil resistive forces along the Mole permanent forward motion for the shock cycle considered. Useful energy ($E_{soil,p}$) is obtained by considering energy transfers within the hammering mechanism, as a function of Mole design parameters.
For the MP Breadboard design produced as part of the IMS activity, an Esoil,p of 0.135 Nm is obtained.
The equations of incremental IM motion during soil penetration [RD 9] were then solved, with the following assumptions:

- reference Mercury regolith
- Mercury gravity
- the MP-MPC assembly is modelled as a single cylindrical body of 26 mm diameter and 416 mm length (including front cone)
- $E_{soil,p}$=0.135 Nm
- hammering period: 6.4 s
- a drag force incurred by pay-out of the tether from its supply compartment of 10 N was assumed (based on measurements on the H/W)
- both sets of friction springs in the IM Launch Tube were assumed to incur a drag force of 7.0 N (based on measurements on the H/W), with a contribution per set of 3.5 N
- mass of MPC: 300 g.

Figure 4-8 shows the resultant predicted soil penetration profile of the IM (i.e., the combined train of Tractor Mole and Trailed Mole) for the Mercury application.

The cumulative hammering duration needed to advance to a depth of 3 m in the reference application thus is 199 minutes, and to reach a depth of 5 m a cumulative duration of 561 minutes is required. This corresponds to 1,866 and 5,260 mechanism shock cycles, respectively and exceeds the requirements given in [AD 1] and [RD 1].

The following observations and caveats apply:

- there still is a positive slope of the depth vs. time curve at the considered end depth of 5 m, i.e. the IM system could conceivably penetrate significantly deeper in the assumed soil profile
- predictions were derived with an assumed length of the Trailed Mole of about 160 mm and an assumed Trailed Mole mass of 300 g; with a longer and more massive Trailed Mole, performance will deteriorate for an unchanged Tractor Mole design (note, the Trailed Mole as valid for the HP3 instrument package is expected to have a length of 350 mm [RD 10]).

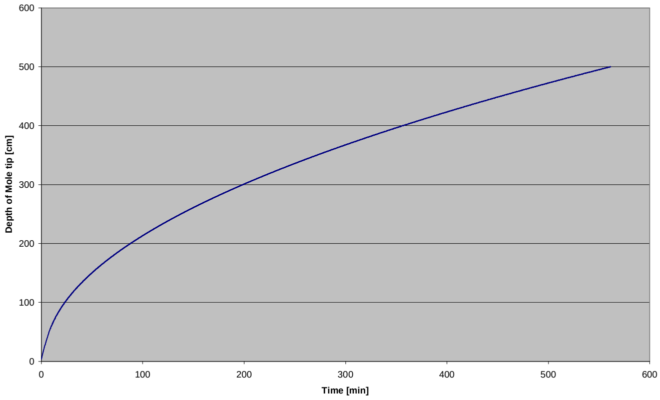


Figure 4-8 Predicted soil penetration profile of the Tractor Mole-Trailed Mole train in reference Mercury regolith at Mercury gravity, accounting for tether pay-out drag and friction spring drag, and assuming a Trailed Mole of 160 mm length and of 300 g mass

4.2 DUMMY TRAILED MOLE

The trailed mole dummy is a cylindrical container with the objective to simulate the real trailed sensor package. Inside the container (see Figure 4-9) there are sensors and other components as follows:

- N°1 two-channel transversal accelerometer (used as inclinometer), model ADXL 320 by Analog Devices
- N°1 longitudinal accelerometer for mole axial acceleration measurement, model 4374 by Breuel & Kjaer
- N° 1 temperature sensor PT100
- N° 3 220 ohm resistors in parallel to simulate internal power dissipation.

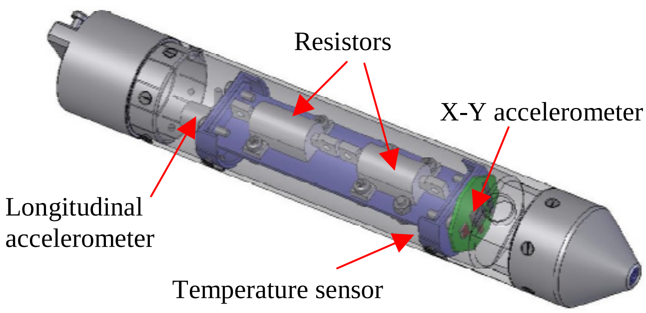


Figure 4-9 Dummy trailed mole

4.3 MOLES INTERCONNECTION CABLE AND FLAT CABLE

Moles interconnection cable

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 cable is the type HT2807TF HS 4 (by Axon Cable GmbH).

Dummy flat cable

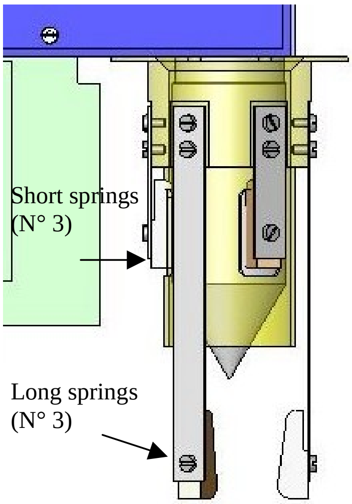
The dummy flat cable is realized by integrating together side by side an array of 16 wires (AWG 28 teflon insulated) and one miniaturised coaxial cable (for the piezoelectric 4374 B&K accelerometer). The whole array is protected with a first layer of Teflon tape. A paper tape with black and white marking every centimeter for cable deployment measurement is put on this Teflon tape for its whole length. A second layer of Teflon tape cover the flat cable. A picture of the dummy flat cable is shown in Figure 4-10; the main physical characteristics are: length = 3000 mm, width = 24 mm; overall thickness: approximately 1.9 mm.

Figure 4-10 Picture of dummy flat cable

The dummy flat cable so manufactured resulted much stiffer than the envisaged FM cable (still under development in an ESA parallel contract). This caused some problems during thermal vacuum tests (as explained in dedicated chapter) at very low temperature were the stiffness of the cable was significantly increasing.

4.4 GUIDING BUSH

The guiding bush has the function to guide the tractor mole (and the trailed mole) during the advancing action. Six friction springs are foreseen acting on the tractor mole body to support mole advancing (during the deployment phase) as shown in Figure 4-11.



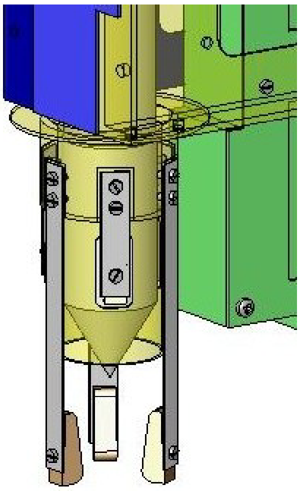
Manufactured guiding tube and springs

Figure 4-11 Guiding bush and springs

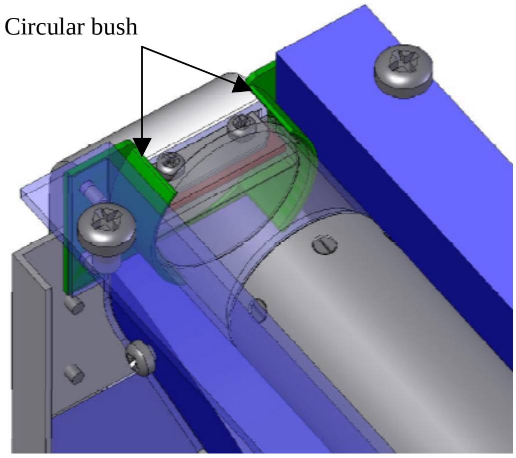
4.5 LAUNCH LOCKS

The method to lock at launch the two moles has been discussed and traded in RD3.
The launch lock is implemented by 2 devices working as pin-pullers. More specifically: at launch configuration the following is implemented:

- the traction mole is centred and kept in place by the friction springs in its forward part (see Figure 4-12 a); while in the rear part it is engaged and kept pressed by one pin-puller (see, Figure 4-13 left);
- the trailed section in the rear part is simply centred by a supporting circular bush (see Figure 4-12 b) while in its forward part is engaged and kept pressed by one pin-puller (see Figure 4-13, right);

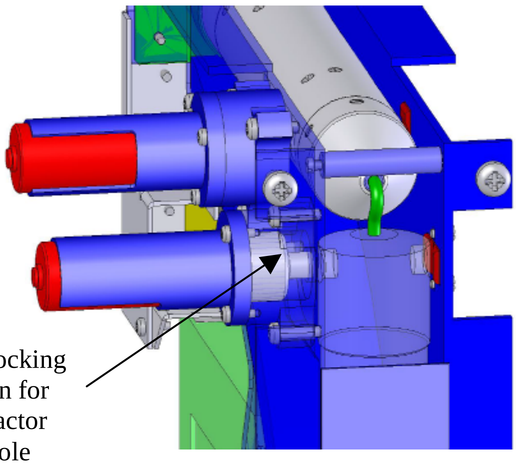


a) front part of the tractor mole kept in place by the short friction springs inside the guiding tube



b) rear part of the trailed mole kept in place by supporting circular bush

Figure 4-12 Details on holding points on the forward part of the traction mole and the rear part of the trailed mole



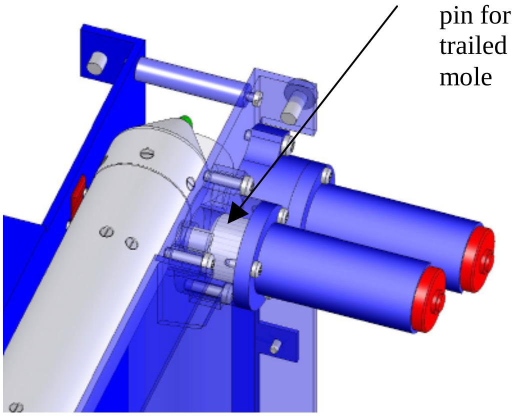


Figure 4-13 Details on holding points on the forward part of the traction mole and the rear part of the trailed mole

4.6 DEPLOYMENT LENGTH MEASUREMENT

The deployment length is measured by implementing an incremental measure of the markings on the flat cable (black and white marking alternates every centimeter as previously described in chapter 4.3) utilising an optical counter head and drive electronics specifically manufactured.
The optical counter is schematised in Figure 4-14 and is realized by combining:

- a diode emitter (Optek OP133W) of 5 mW irradiated power in an angle of +/- 25°
- a fototransistor detector (Optek OP 803SL) with a field of view of +/- 14°.

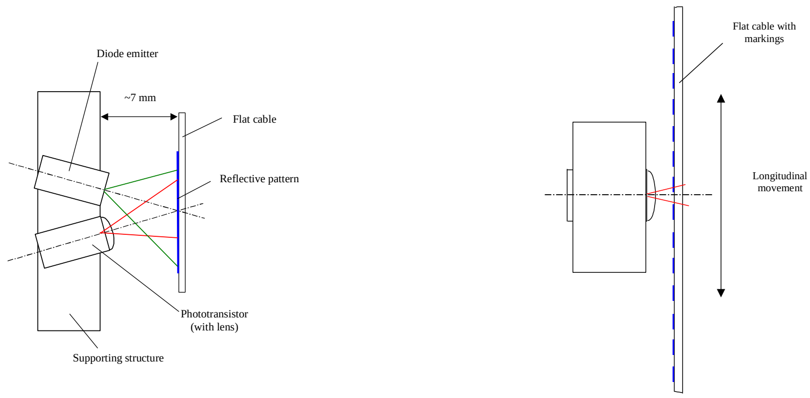


Figure 4-14 Schematics of optical counter head (not to scale)

The driving electronics for the optical counter (see Figure 4-15) implements the following functions:

- supply of the photodiode emitter;
- supply of the phototransistor and acquisition of the generated signal;
- amplification and filtering of the acquired signal;
- implementation of the square wave output based on comparator with hysteresis.

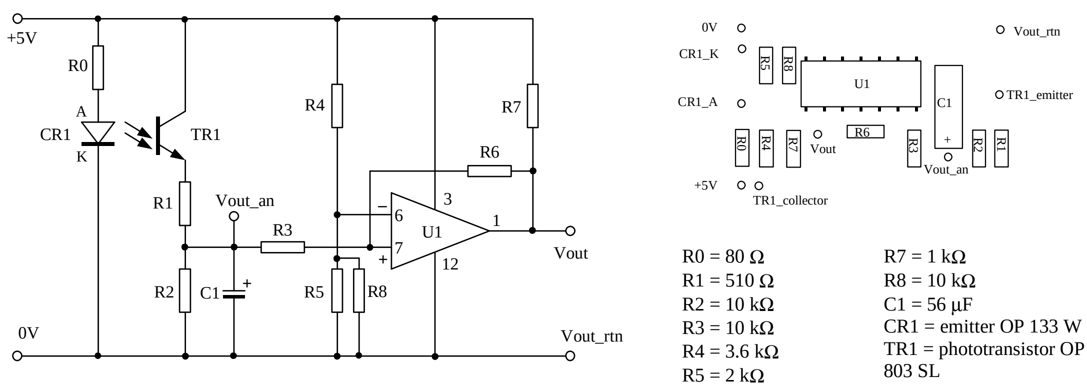


Figure 4-15 Deployment counter electrical schematics

4.7 CAGING

The caging (see Figure 4-16) is made of carbon fibre and comprises two main parts: Glider assembly and Flat cable storage.

All parts are connected together and to the items previously described in order to form a self standing mechanical frame capable to provide all deployment and initial mole guiding functionalities and to support the launch induced loads.

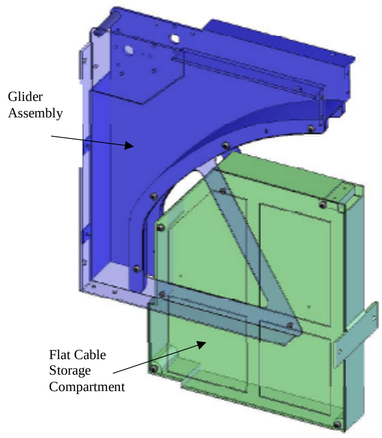


Figure 4-16 IMS Caging

4.8 IMS MASS BUDGET

The total design estimated IMS mass budget is shown in Table 4-2 were two masses are shown:

- the mass of the prototype assuming to utilise Carbon Fibre for the main structural parts,
- the mass of the FM, assuming to utilise Carbon Fibre for the main structural parts, with a first optimisation for mass reduction and assuming the development of specific flight components for the cable and the deployment sensor.

General Assy ITEM NO.	PART NUMBER	QTY.	IMS prototype made in CF [g]	Flight [g]
1	Glider_Assembly	1	295	240
2	Trailed Mole Section (total)	1	250	250
3	Tractor Mole Section (total)	1	435	435
4	GuidingBushAssembly (total)	1	49	27
6	TrailingCable	1	5	5
7	HoldDown_InstrumentBack	1	8	8
9	FlatCableSensor	1	267	117
10	FlatCableStorage	1	164	117
14	FlatCable	1	200	100
5, 8, 11, 13	Other Mechanical Parts	1	17	17
	TOTAL (excluding Lander Base Electronics, connectors, harness)		1690	1316
	Lander Base Electronics(NA for prototype)	1		40
	Connectors and harness (NA for prototype)	1		10
	TOTAL envisaged for Flight Model			1366

Table 4-2 IMS Mass Budget

5. IMS BREADBOARD TEST RESULTS

The breadboard of the IMS developed in the contract is shown in the picture of Figure 5-1, taken at the beginning of the integrated system test campaign. In can be noted the presence of only three (short) friction springs, being the other three (long) added during the tests campaign, before the performance of the deployment and soil penetration test.

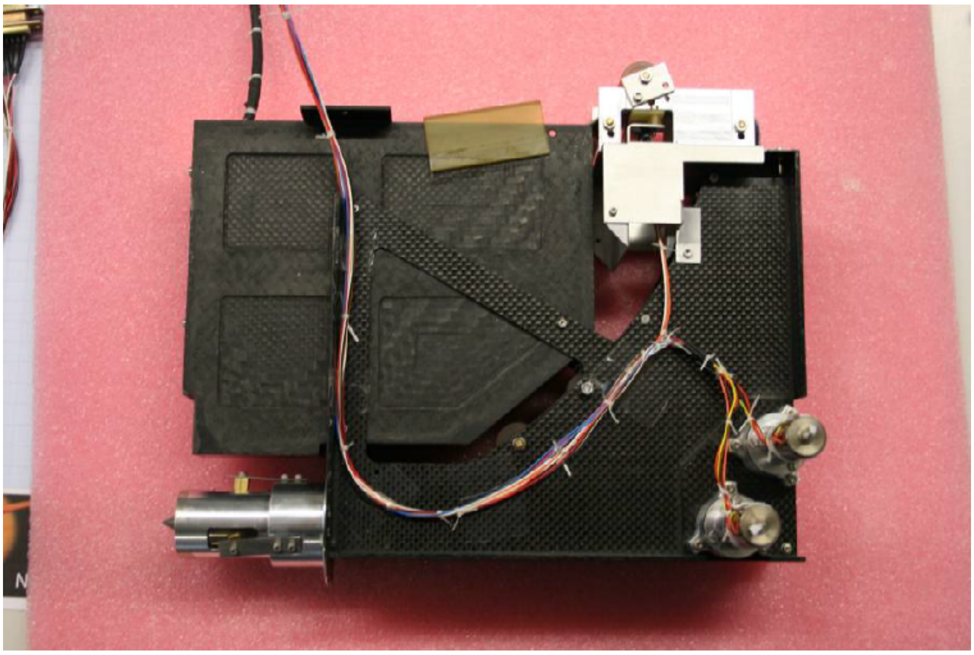


Figure 5-1 Photo of the IMS breadboard at start of the integrated system test campaign

The measured mass of the breadboard is 1628 g (in line with the expected 1690 g).

5.1 IMS TEST PLAN

Different tests have been performed, initially on single items to prove their effectiveness before integration within the IMS and then on the Integrated Mole System.

Main test on single items include the following:

- Test of the accelerometer package included in the trailed mole
- Test of the deployment system

Main test on IMS items include the following:

- Functional test
- Simulated Reduced Gravity Test
- Thermal vacuum Test
- Vibration Test

In this Executive Summary only the tests at integrated IMS are summarised.

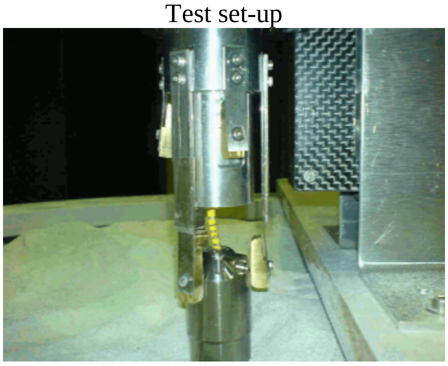
5.2 IMS FUNCTIONAL TESTING AT AMBIENT

The functional testing at ambient allows the verification of both the deployment of the moles and the capability to penetrate the soil. The container of the soil simulant was 2900 millimetres

height and the IMS was placed above the container such as to have a distance of 25 mm from long springs to the top surface of the soil simulant. The test was conducted in vertical to check a gravity component along the mole vertical axis.
Three test sessions were performed and the main records are summarised in Table 5-1. The values of telemetry of the hammer mechanism at the beginning of the test are the following: V = 8.5 V, I = 0.1 A, 1 strike every 5.0 seconds. Figure 5-2 shows some pictures taken during and at the end of the tests.


Test set-up


Tractor mole entering the soil


Tractor mole leaving the guiding tube long springs


Tractor mole has left the long springs, trailed mole is approaching them


Trailed mole is abandoning the long springs


Particular of the IMS flat cable at the end of test

Figure 5-2 Some pictures taken during the soil penetration test

	First session	Second session	Third session	Sessions I+II+III

Date	21-12-05	22-12-05	22-12-05	
Time frame (hours:minutes)	17:16 to 17:55	8:07 to 12:15	13:15 to 15:51	
Total time (seconds)	2309	14884	9364	26557
True reached depth (mm)	365	1310	490	2165
Average speed (mm/minute)	9.6	5.2	3.1	4.9
Measured depth (counts)	18.5→370 mm	65→130 mm	24→480 mm	215 mm ±20 mm

Table 5-1 Summary of soil penetration test results

Figure 5-3 shows the penetration depth as a function of time, obtained from the processing of the records of the deployment counter.

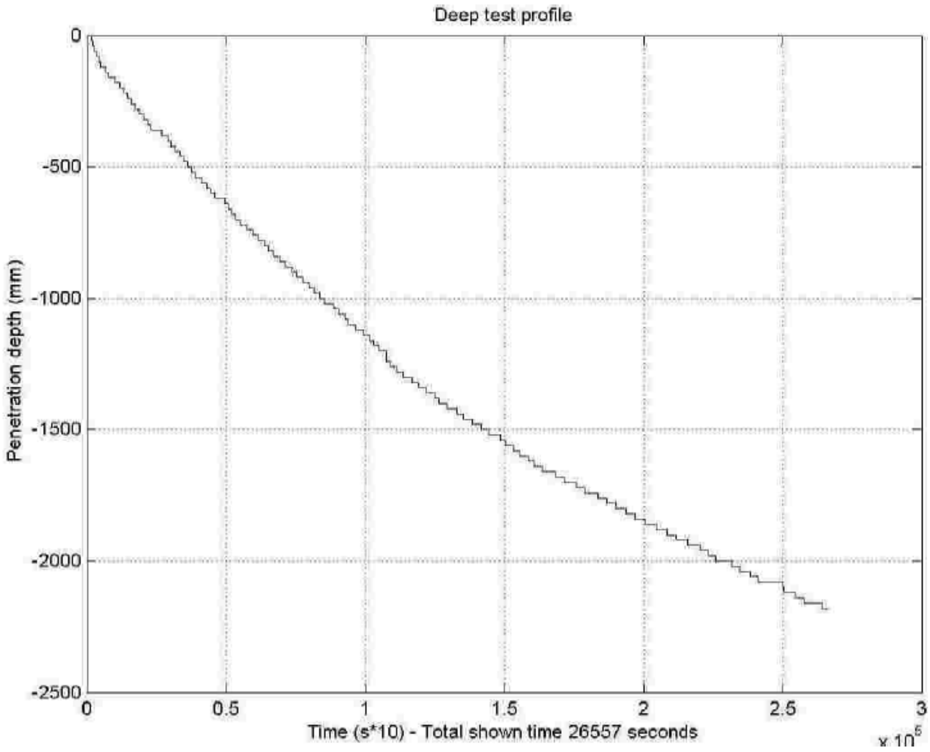
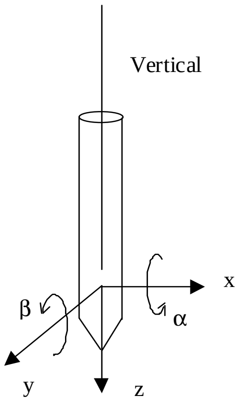


Figure 5-3 Total depth 216.5 cm sum of session I, session II and session III

During the test session the outputs of the accelerometers were continuously recorded and then analysed to calculate the deviation angle with respect to vertical. In Figure 5-4 the output of the accelerometers (scaled in g values) are shown, as an example, for the second session.



Definition of angles

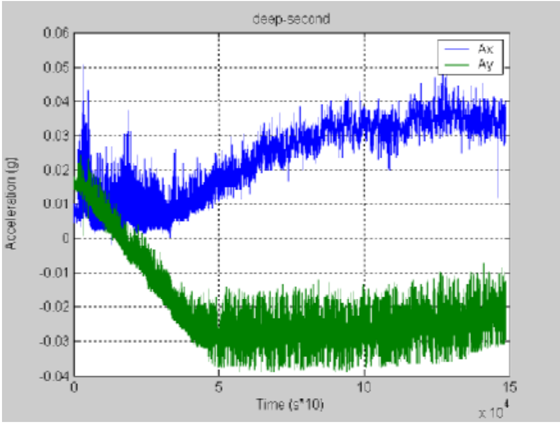
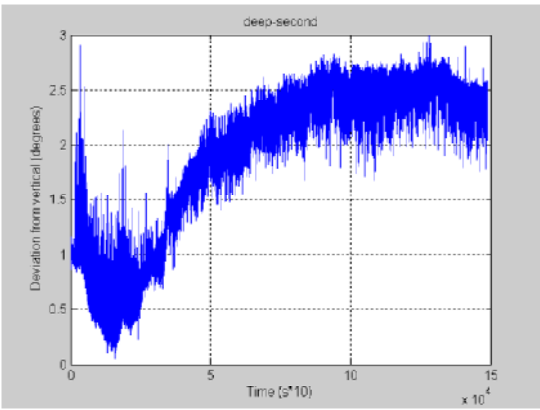
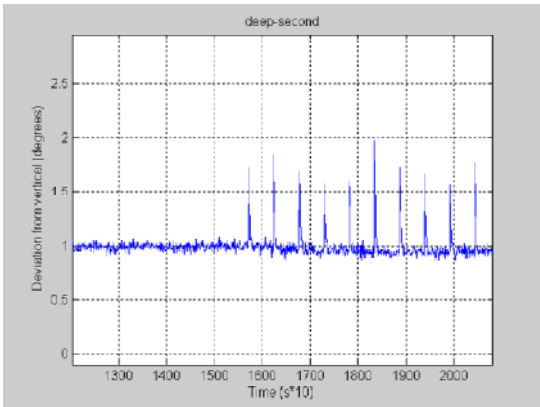


Figure 5-4 Accelerometer outputs vs time, scaled in g values (session II)

The data are then processed to extract the angular deviation from the vertical regardless in which direction this deviation tales place and the results (always for session II) are shown in Figure 5-5. It appeared that during the whole deep penetration test the maximum deviation from vertical was below 2-3 degrees.



Full record



Details of first part of recording

Figure 5-5 Computed deviation angle wrt vertical (during session II)

5.3 FUNCTIONAL TESTING IN SIMULATED REDUCED GRAVITY

Test at 70° inclination

The test was conducted at 70 degrees inclination from vertical (β=20°) to simulate a gravity component along the mole axis similar to Mercury environment, as shown in Figure 5-6.

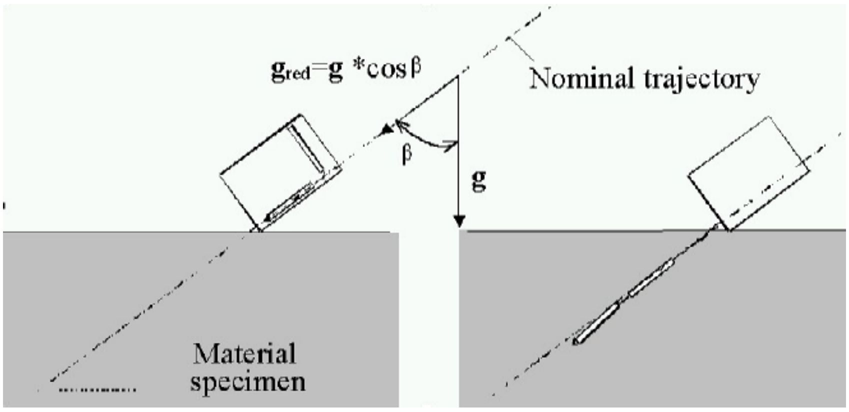


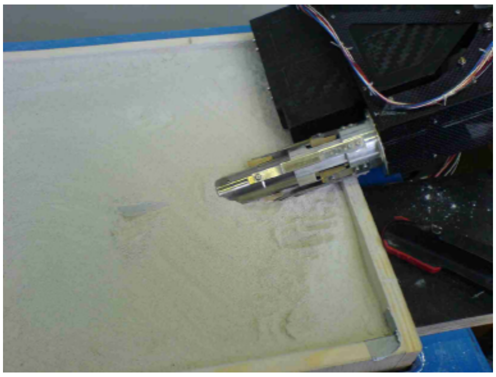
Figure 5-6 Mechanical test set-up for simulated reduced gravity test (β=70°)

The test has been carried out through 4 sessions; the deployment counter recording is the following:

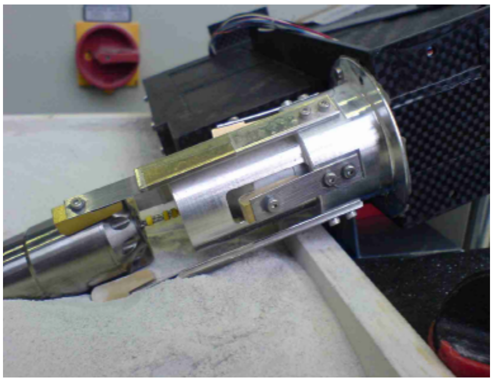
- Session 1: 25 counts.
- Session 2: 8.5 counts.
- Session 3: 23 counts.

During session 4 the deployment counter was not active. Figure 5-7 shows some pictures taken during the test sessions.

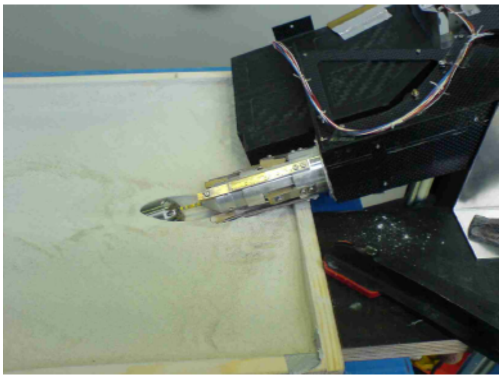
The total deployment of session 1 plus session 2 plus session 3 determined *by means of the sensor* (and including also the 30 mm where no measurement was done) shows a total of 1160 ± 20 mm.
The *actual* deployment of session 1 plus session 2 plus session 3 measured directly on the flat cable was 1165 mm.
The total time for sessions 1, 2, 3 amounts to 12480 seconds, leading to an average speed better than 5.6 mm/minute.



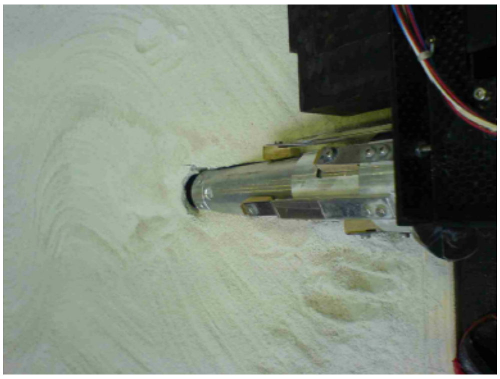
Tractor mole has started entering the soil



Tractor mole is leaving the guiding tube springs



Tractor mole has left the guiding tube springs and trailed mole is within guiding tube



Trailed mole is entering the soil

Trailed mole has left the guiding tube

Trailed mole entered the soil for its full length

Figure 5-7 Pictures taken during simulated reduced gravity test (con't)

Figure 5-8 shows the advancement of the mole as a function of time, on the left for session 1 plus session 2, on the right for session 3.

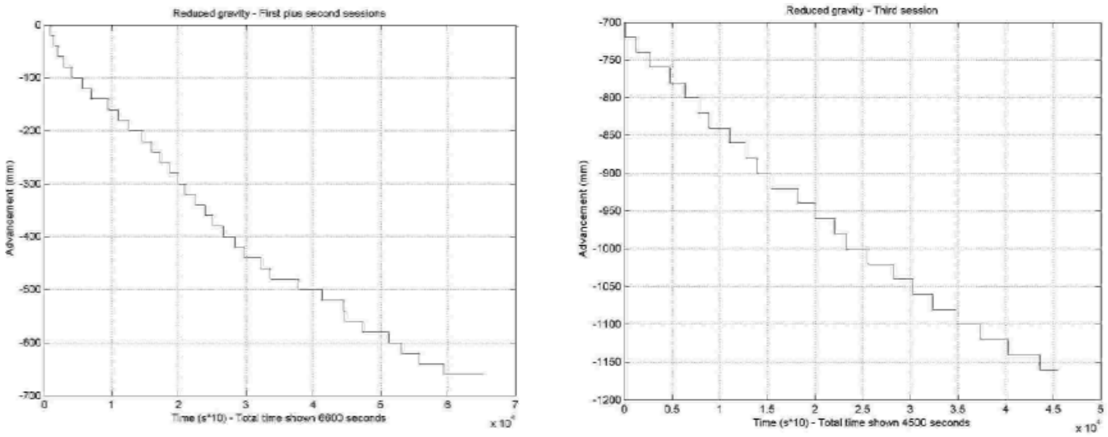
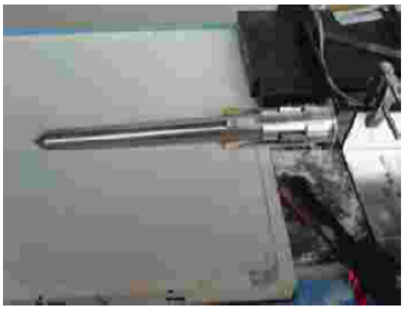


Figure 5-8 Deployment of the mole in sessions 1+2 (left) and in session 3 (right)

Session 4 started from the end of session 3 till the mole physically hammering against the wood box and provided a *further 215 mm*. Summing up session 1 to session 4 *the total true deployment was 1380 mm.*

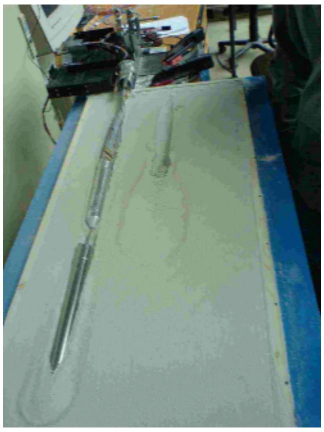
Surface Test

This test was conducted in horizontal condition simply on the surface to check the ability of the IMS to propel itself when simply laid on the surface. The motion was taking place and a total advancement of 690 mm was achieved.
Figure 5-9 show three pictures taken during the test. Picture in the centre shows the trend from the tractor mole to enter the surface. When the tractor mole was fully covered by soil, the test was interrupted and the two moles repositioned on the surface to continue the test as shown on the left.



Tractor mole almost out of springs

Tractor mole partially submerged in the soil, trailed mole out of springs



End of test

Figure 5-9 Pictures taken during surface test

5.4 THERMAL VACUUM TESTS

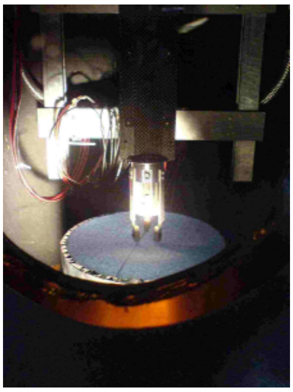
Preliminary Verification In Thermal Vacuum Condition

The scope of this test was to check the functionality of the tractor mole hammering device. The test set-up had the tractor mole hammering against a “bumper; no tether extraction and no soil penetration Tractor mole mechanism was turned on at approximately –150°C (tractor mole housing temperature, with actuator heater activated). Hammering was nominal Test was conducted with approximately 2100 mole shocks delivered, then test was intentionally stopped.

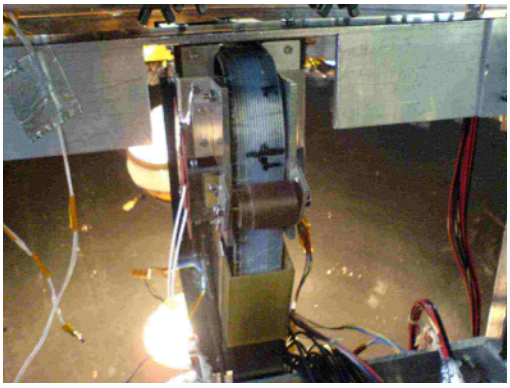
Thermal Vacuum Test

The test set up included a sample container equipped with a breakable membrane to contain the soil simulant. The mole system was suspended above the container with the soil with the trailed mole locked as for launch condition. Figure 5-10 shows some pictures relevant to the set up.

Soil container with membrane



IMS positioned above container



IMS installed within the thermal vacuum chamber

Figure 5-10 Pictures of IMS during installation in the thermal vacuum chamber

In vacuum condition unlocking of the moles, at ambient temperature, resulted in forward movement by some cm (as expected) partly perforating the membrane above the soil container as shown in Figure 5-11.

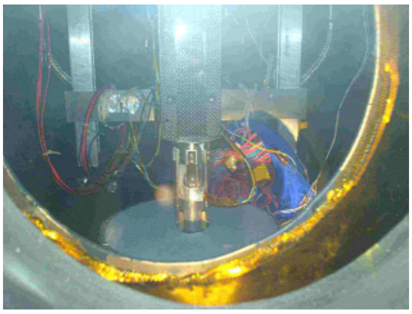


Figure 5-11 The action of the moles brakes the membrane during the test

Tractor mole mechanism was turned on at –128.2°C (mole housing temp., mole actuator heater activated), $P<10^{-3}$ mBar, Tsoil= -146°C and hammering was nominal (frequency and current). Moles motion was observed to be uneven, with phases of elastic bouncing in the structure, interrupted by period of moles net forward motion. Test was conducted with approximately 1400 shocks delivered before being intentionally ended, with estimated total moles forward motion of a few cm into soil

During warm-up, tractor mole operation was repeated at approximately –90°C, -60°C, -30°C with the same behaviour as before. 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 some possible causes of the problem:
- force resistance for dummy flat cable extraction increase up to 60% from ambient temperature to –40°C;
- soil strength increases: force needed for penetration increases from 11 to 17 N at ambient to 17 to 23 N at –40°C
- detachment of teflon tape applied to some parts of the CF structure to reduce friction.

Investigation In Low Temperature Nitrogen Chamber

A further investigation has been performed by utilising a thermal chamber (working at ambient pressure) capable to low the temperature till liquid nitrogen temperature by utilising gaseous nitrogen flow. This facility is at Galileo Avionica in Milano.

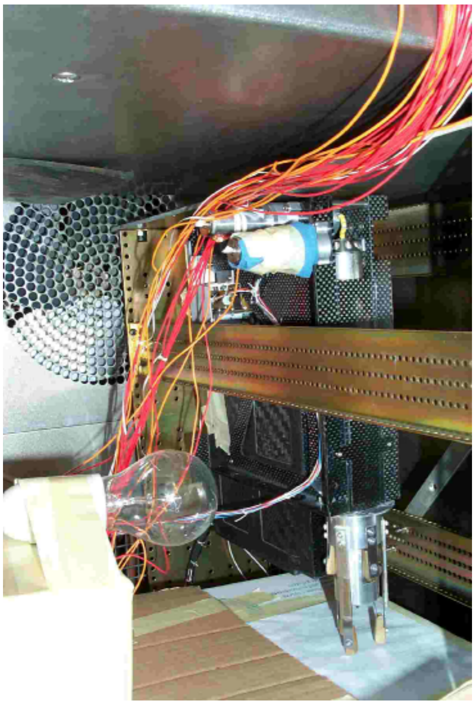
The mechanical layout is shown in Figure 5-12. Initially the flat cable was totally installed within its storage container.

At mole unlock, performed at approximately –40°C, the moles fell on to the surface of the material, as expected. After having reached a test temperature of –145°, the hammering was activated but no mole advancement was possible to achieve.

The temperature was then increased to ambient and the chamber was then re-opened. A marking was done to the mole body to record the position. The hammering was switched on to verify the functionalities and an advancement of ca. 15 mm was done. A second marking was made on the body mole.

The flat cable has been extracted from its storage compartment by some decimetre s as shown in Figure 5-12 d), the chamber cooled again at –145°C and the hammering restarted. The mole advancing was regular and with a mole hammering period of 6 seconds, a total penetration of 90 mm was achieved in 35 minutes, equivalent to 2.6 mm/minute, till reaching the bottom of the sample container. At the end of test the chamber was reopened (after having warmed the whole system to ambient temperature) and a third marking made on the mole. Figure 5-12 e) shows the mole (after being extracted) with the markings on its body made for depth assessment.

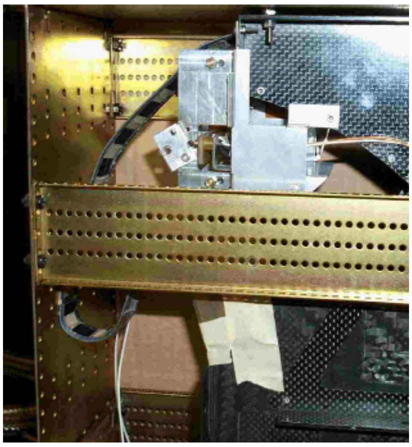
The increase in strength of the dummy flat cable utilised is high and is the cause of the problem happened during thermal vacuum test.



a) Mechanical layout for low temp. test

b) Test instrumentation

c) Beginning of test



d) Dummy cable unfolded

e) Mole recovered after the test

Figure 5-12 Pictures taken during test at low temperature in climatic chamber

5.5 VIBRATION TESTS

The vibration testing allowed the verification of mechanical resistance of the IMS structure and mechanisms. The test was carried on at Galileo Avionica – Milano G.B. Grassi premises. Before the test all the screws were checked and some epoxy glue put on the screw heads to lock them. The flat cable was stored inside the container in the right configuration and its screws were locked and glued. The moles were locked with pins actuated at 0.6 A. The IMS was installed inside the vibration test support.

The conducted tests were:

Sine vibration test	***Frequency range (Hz)***	***Input level***	***Sweep rate***
	5-20	20 mm peak-to-peak	2 oct./min
	20-100	20 g	2 oct./min

•

Random vibration test	***Frequency range (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.

Considering that the long springs do not exert any blocking role on the tractor mole for the vibration tests they were dismounted from the IMS, also because of the not available space inside the vibration test support.

Figure 5-13 shows the definition of the axes for the IMS installed on the vibration test support (left) and the real IMS breadboard installed on the vibration test table (right) in a position suitable for vibration along Z axis.

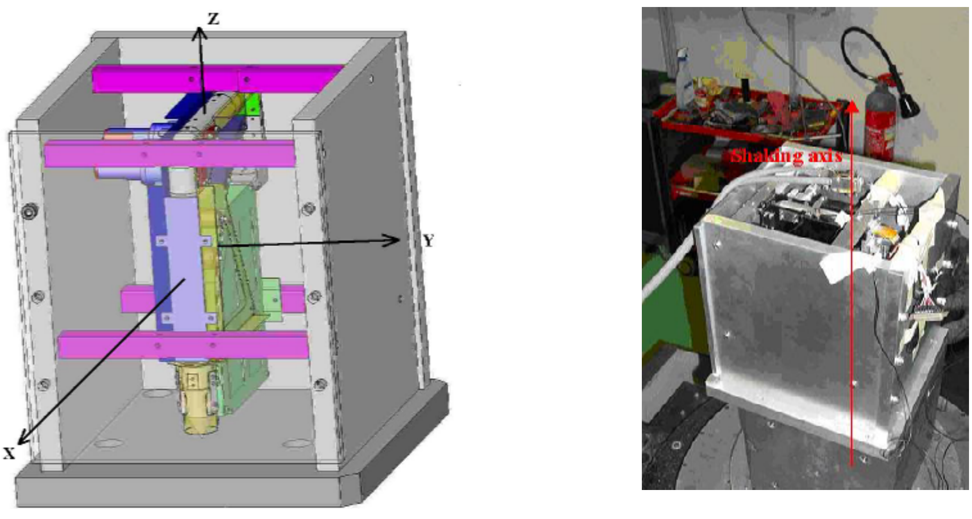


Figure 5-13 Definition of the axes relative to IMS (left) and IMS breadboard installed on the vibration table for Z axis vibration (right)

The sequence of the tests was the following for each of three axes: Resonant Survey, Sinusoidal test, Resonant Survey, Electrical test, Random test, Resonant Survey, Electrical test, Shock test, Resonant Survey, Electrical test. The electrical test was performed after every test to monitor the status of the devices inside the IMS. The resistance values noted at the beginning of the tests did not vary along the tests.
The resonant survey after every test was performed to compare the mechanical behaviour of the structure during the tests with the one found during the first resonant survey. This check was necessary to monitor the mechanical behaviour of the system. For each axis this procedure was repeated.

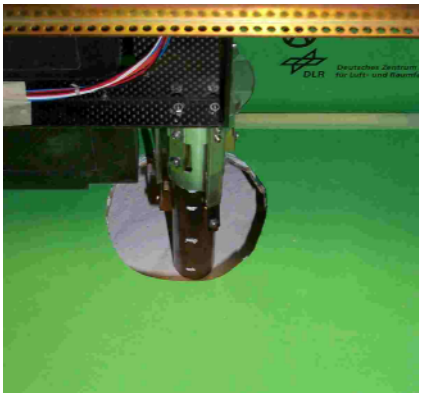
Four accelerometers were mounted on the structure: one for each axis plus one representing the control/feedback signal and their outputs were recorded during the tests. The control/feedback accelerometer was oriented along the shaking axis.

The axes were tested with the following sequence Z-axis, X-axis, Y-axis. During all test no problems appeared and the resonance search before starting the test and after al the tests were comparable.

5.6 FUNCTIONAL TESTS AFTER VIBRATION TESTS

This test was intended to functionally prove that the IMS was correctly working (i.e. tractor mole internal mechanism unlocking, moles unlocking, hammering and penetration into the soil). The IMS was mounted on the structure already used for the test into climatic chamber. The strike-mass inside the tractor mole was unlocked and then the trailed mole and the tractor mole unlocked in sequence. After that the hammering action was activated and the tractor mole got in contact with the soil.

The test was continued for about 13 minutes hammering time till the nose of the tractor mole was almost touching the bottom of the soil simulant container. The depth reached was 17 centimetres. Figure 5-14 shows two pictures taken at the end of the test, with the mole inserted into the soil and after having removed the soil simulant container. The markers impressed on the tractor mole body during advancement are clearly visible.



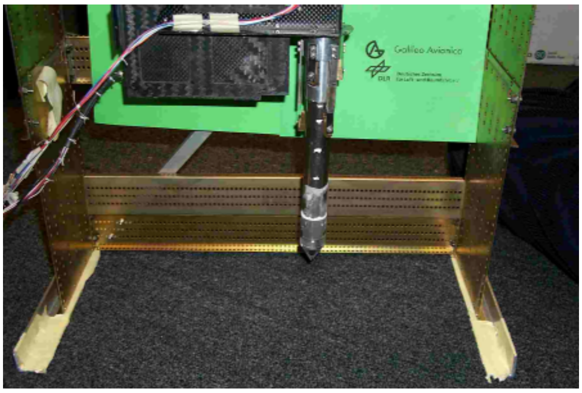


Figure 5-14 The tractor mole in the soil at the end of the test (left) and extracted from the soil (right)

At the end of this functional test the whole system worked correctly.

6. CONCLUSIONS

The project has allowed to develop and validate an innovative concept of mole system for investigations into planetary soil regolith. The system is composed of a tractor mole and a trailed mole connected by a link. The trailed mole can be configured to install scientific instrumentation and navigation sensors necessary to support the mission.

During the development several technological issues have been tackled and solved and the IMS prototype has been extensively tested and the test campaign performed included both functional and environmental tests. The IMS prototype has passed all tests without major inconveniences.

The assembly tractor plus trailed mole is capable to penetrate the soil with appropriate advancing speed and the concept of stowage and deployment have been proved.

The aspects which deserve some further attention for possible future applications are related to: the flat cable characteristics, the short connection link between the two moles, the local electronics embedded into the brushless motor of the tractor mole.

Considering the flat cable, the dummy used in the prototype was much heavier and stiffer to pull than the one foreseen for FM. All deployment test at ambient temperature were successful evidencing that there is a good margin on this IMS functional capability at ambient condition. On the other hand at low temperature (-150°C), due to its size and composition, the dummy flat cable became much stiffer obstacling its deployment from its storage compartment. Therefore it is important, for future system development, to utilise a flat cable as much as representative to the real one and that the development of the final cable itself be done as early as possible.

The short connection between the two moles proved to be effective from the dynamic point if view and with bending flexibility appropriate to install the two moles in stowage conditions in the limited room available. One critical issue appeared to be the lifetime and to cope with this aspect some technological improvements may be needed in future, for example increase the strength of the outer steel sleeve or utilise other approaches like short rigid or semi-rigid links.

Concerning the motor of the tractor mole, the utilisation of DC brushless technology could be preferable to the use of brushed technology (which anyway has been employed throughout the whole test campaign). In case the DC brushless were implemented together with their local electronics commutation then this electronics need be carefully ruggedised in order to avoid possible damages due to local high shock environment. In alternative to this ruggedisation process the commutation electronics itself could be placed remote to the tractor mole (with some increase complexity of the flex cable) or to drive the motor in “direct mode” with no commutation (with some decrease in motor efficiency).

To summarise, the trailing concept appears to be effective and indeed can constitute a valid approach for mole systems operating in regolith in case stowage size limitation does not allow to install a single longer mole.