9th ESA Workshop on Advanced Space Technologies for Robotics and Automation
ASTRA 2006

28 – 30 November 2006 at ESTEC,
Noordwijk, the Netherlands

MERCURY NANOKHOD ROVER - HARDWARE REALISATION AND TESTING

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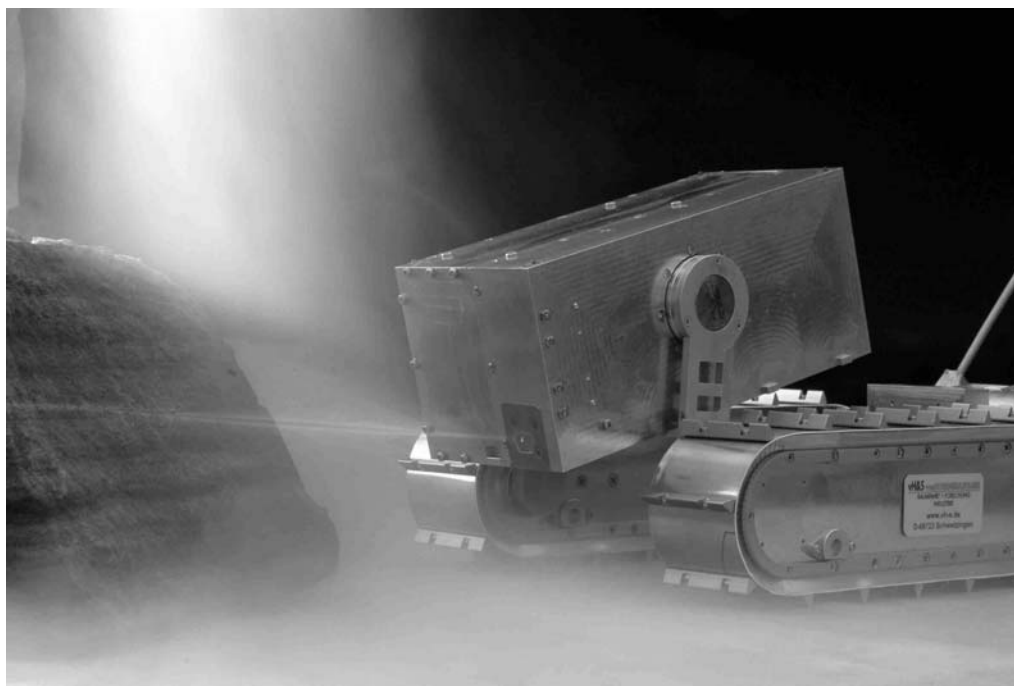[4]*ESTEC, Noordwijk, The Netherlands*

1.   INTRODUCTION

Figure 1 Completed MRP Nanokhod Rover

The Nanokhod Rover type has a development history starting in 1990's during which von Hoerner & Sulger GmbH has taken the leading role. The original Russian concept has been developed to accommodate instruments and prototype versions have been tested on soil stimulants. However it is only now that a contract to make a practical design to withstand the tough requirements of a flight model has been entered into. Having realised a design meeting the requirements, a hardware model has been manufactured to an engineering level which is suitable for environmental testing of vibration, shock and thermal vacuum to the extreme requirements of a mission to Mercury. This paper describes the design and the manufactured model.

2.   MERCURY MISSION PROFILE

The basis of this project was to produce a well matured Rover model in preparation for the Bepi-Colombo Mission [1]. At this time a Lander was being seriously considered and the Nanokhod type rover has been selected to provide local mobility around the landing site. Unfortunately the Rover along with the Lander were cancelled from the Bepi-Colombo mission but it was decided to proceed with the development to better understand and solve detailed technical problems of a real implementation in preparation of future missions. Due to the challenging nature of the Mercury environment the developed technology is considered to be applicable with moderate modifications on variety of other planetary bodies.

2.1.   Mercury Mission Profile

The design of the MRP Nanokhod rover has been driven by the requirements of the Mercury Mission profile whose important points are summarised as follows [2].

After a journey of up to 4 years from the earth the Mercury Lander system will land on the planet surface. Deceleration of the lander is performed using chemical propulsion due to the lack of atmosphere. The landing site for this mission is on the night side of the planet where the extreme thermal environment is simplified by the removal of the sun's radiation. Despite this the environment remains extreme coupling a high vacuum with surface temperatures estimated to be in the region of -180°C. Because of this, all energy must be supplied chemically assuming that a nuclear solution is politically unacceptable.

 Once deployed, the MRP Nanokhod rover will operate for a period of between 7 (baseline) to 14 (extended) earth days during which time the landsite would remain on the nightside due to the 88 day length of the sidereal Hermean day. The rover will communicate and be powered by the lander via tether of at least 50m allowing the rover to explore an area of at least 10m radius from the lander.

The MRP Nanokhod shall be able to move across the fine regolith surface with a speed of 5 metres/hour and negotiate steps 10cm high and trenched 10cm wide. It shall make at least 1 scientific observation per 24 hours with its three instruments: Microscopic camera (MIROCAM), APXS and Mössbauer Spectrometers.

Due to communication constraints between the lander and Earth the rover shall operate near-autonomously with a single communication period once a day.

2.2.   Design Drivers

The main design driver in the design is the mass of the whole system. Ultimately this is derived from the fact that the launch fuel cost for each kilogram landed on the planet surface is very high due to the following:

- Inter-planetary journey between earth and the Mercury itself requires a significant amount of fuel to decelerate and position a spacecraft into orbit.
- Descent and landing system must be performed using chemical propulsion which is mass intensive.

It is obvious that these items scale directly with payload mass and thus the mass of the complete lander system must be minimised in order to make the mission feasible. The low mass of the lander system dictates that its structure shall be limited in it size which results in a strict volume requirement for the Rover.

Opposing these mass and volume requirements is the need to make a practical system which will not only has the strength to undergo the vibration and shock environments dictate by the above but will also allow a practical rover design which can accommodate the required instrumentation and functionality of the rover but will allow for some reasonable facilities to ease the AIV of a future flight model.

The next significant design driver is the energy consumption of the Rover system. This is also related to the mass issue as all energy requirements of the Lander and thus the rover itself must be carried by the Lander itself in the form of

batteries. For a given mission duration, the less energy consumed by the system the less battery capacity is required and thus battery mass is reduced.

By looking at the mission profile it can seen that for a baseline mission the rover will only spend on average 12 hours in the 7 days performing locomotion. This assumes that PLC movements for instrument deployment are relatively insignificant in duration. In comparison, the times required to perform reasonable measurements with the spectrometers can expected to be approximately 2 and 3 hours minimum per measurement for APXS and MIMOS respectively – or in total greater than 35 hours during the 7 days. It should also be noted that whereas the locomotion duration has a hard limit defined by the length of tether the rover carries, measurement quality is improved with longer measurement durations and this may be requested by the scientist during operations. This is illustrated with mission scenario results from the system design studies in Table 1.

Table 1 Comparison of different activities during a 7 day mission

Activity	Description	Duration		Energy Consumed	
		Hours	% Total	Wh	% Total
Checkout	System test on lander	8	5%	13	6%
Deployment	Exit Lander perform first measurement cycle	9	5%	17	9%
Movement	Move between two measurement sites	14	8%	76	38%
Measurement cycle	1 measurement with each instrument	57	34%	95	47%
Idle	No activity	111	66%	0	0%

With this in mind the system design should attempt to meet the following principles:

- Energy consumption during measurement phase needs to be minimised
- Energy consumption to do "nothing" must be eliminated wherever possible -. i.e. passive thermal control and mechanism which do not require power to maintain their state

Passive thermal control in this instance means that the rover does not attempt to maintain its temperature to a set level but the rover is allowed to heat up and cool as defined by the mechanical design and selected materials and finishes. As there may be extended periods when the rover is powered off all components should be able to function from the surface temperature upwards.

3. DESIGN OVERVIEW

A brief overview of design is given in the following paragraphs. For a more detailed description of the Rover design including its instruments please refer to [3].

The main components which are generic to all Nanokhod rovers are:
- Two locomotion units (LU) enclosed by walls and the driven caterpillar tracks which provide the method of locomotion
- The tether unit (TU) which rigidly attaches both locomotion units and holds the spools from which the tether wire is deployed
- The payload cabin (PLC) containing the instruments
- Arms connecting the PLC to the LU giving the PLC two degrees of freedom allowing the instruments to place next to sample sites and for the PLC to act as an extra limb for negotiating obstacles.
- Four internal drive units used to drive the caterpillar tracks and position the arms relative to the LU and the PLC.

These components are identified on the current design in Figure 2.

Externally the new design does not display significant differences from previous models. The main items to note are that the TU has been designed to give greater ground clearance to prevent a "bulldozing effect" of regolith that occurred in previous models. Similarly the tether guides are angled upwards to prevent both regolith entering the tether guides or the rover running over the tether when reversing. The modifications have meant that the current design loses its

top/bottom symmetry allowing full operation in both orientations. In reality, any operational scenario would avoid any instances where the rover is at risk of rolling over and even if it did, the rover still has the ability to right itself by lifting the tracks over the PLC.
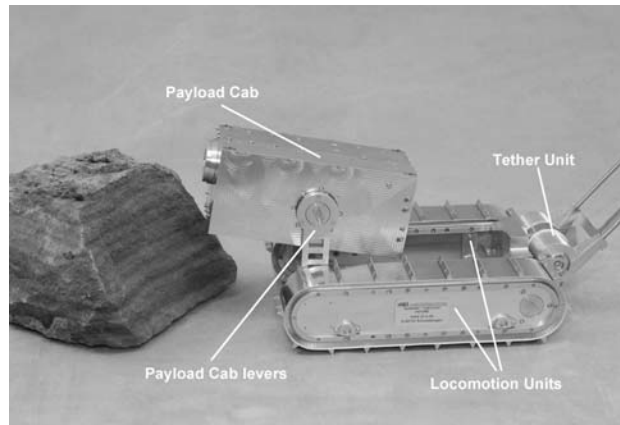

Figure 2 Generic Nanokhod rover components

The other noticeable addition is facilities for accommodation of the rover in flight which had not been fully considered previously. The sealing system between the LU walls and the track are delicate and would experience damaged from the landing shock. The new stowage concept uses four cups on each LU which are clamped by the conceptual hold-down device. The PLC is held separately to prevent damage to the arm mechanisms with teeth located on the base of the PLC (Figure 3). The tether guides also feature a spring loaded deployment device so they can be held against PLC during flight and landing.

Internally the new design differs significantly from previous models both electronically and mechanically. Mechanically the overall structure has been upgraded to withstand the rigours of vibration and shock with the inclusion of four rigid yokes in the LU's. Analysis has been performed on all components to ensure that they are compatible to the mechanical and thermal environment.
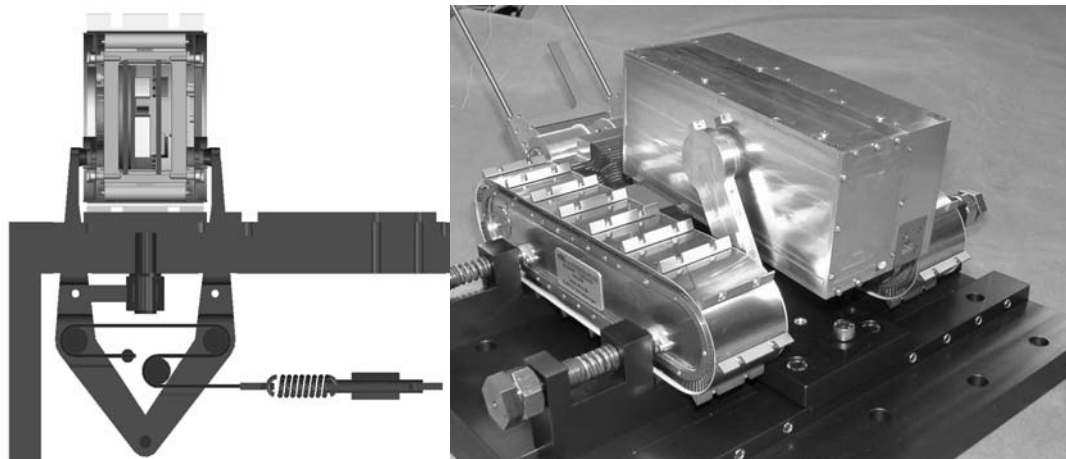

Figure 3 Left; LU conceptual holddown mechanism; Right: mock up for vibration testing (PLC released & raised)

A completely new drive system has been implemented based on a similar concept for all four drives within the rover. Due to the high vacuum environment it is not possible to use standard DC motors for extended durations and so the Faulhaber AM1020 stepper motor was selected as the motor for the drives. This motor had been previously tested and selected during the RTPE project and although stepper motors have significant disadvantages it was the only available device at the time which met both the volume and the torque requirement needed for operation on both Mercury and Earth. The motor itself is attached to 64:1 planetary gear in front of a crown and pinion gear stage. The output stage is a miniature harmonic drive whose input is coupled directly to the crown gear. The output is taken either from the flexspine or the circular spine depending if it is a track or arm drive. Dicronite dry lubricant was used on both the

Harmonic Drive and crown gear the application of which had been tested at Harmonic Drive AG. The other components were supplied pre-lubricated with MOS2 by the manufacturer.

Electronically the system is has been partitioned into a number of nodes each of which perform a distinct function. The nodes are connected using a 9 way bus containing both power and a I2C communication link which is selected that allows for reliable and simple communication over the temperature range. Power for the drive system nodes is supplied by a 28V line which is also controlled by the tether interface node (TDU). When the power is removed from this line all drive units are powered off minimising the power consumption during instrument operations. Central to each node is a piece of digital logic which controls each node and provides is data interface. For a flight model this would be implemented in a common ASIC which contains all the functionality required for each node. In the current model this has been simulated using a SOC microcontroller whose code is common to all nodes.

4.   THERMAL DESIGN AND SIMULATION

The thermal control system of the rover is completely passive. The design was carried out in order to retain as much heat within the rover as possible. At the same time the design shall avoid local hot spots, which can occur on active elements in a vacuum environment. The approach that was made in the Nanokhod layout can be summarised with:

- Heat conduction from the tracks to the regolith is minimised by using PTFE seals in-between the track foil and the track body;
- Heat radiation to the environment is minimised with the low emissive surface finish, Alodine 1200 (e = 0.12);
- The PCB's are all mounted with Aluminium standoffs onto the main structure of the rover, this allows a good conduction of the heat away from the boards.
- There are Thermistors on the motor drivers and other critical components to monitor the heat distribution inside the rover

Although basic thermal modelling was performed during the design phase of the current rover design, the extreme environment makes it necessary to develop a more sophisticated model using ESARAD/ESATAN which has been undertaken by the Institut für Raumfahrtsysteme at the University of Stuttgart

In order to allow easier changes in the model for future calculations, the model is developed with a Design compiler "43" provided by the institute of Statik und Dynamik (ISD) of the University of Stuttgart, which translates the geometry of the Rover in to the ESARAD and ESATAN language. Although this simplifies the future modifications in either the rover or the environment, it is not essential for future work on the model as the output is standard ESARAD-model.
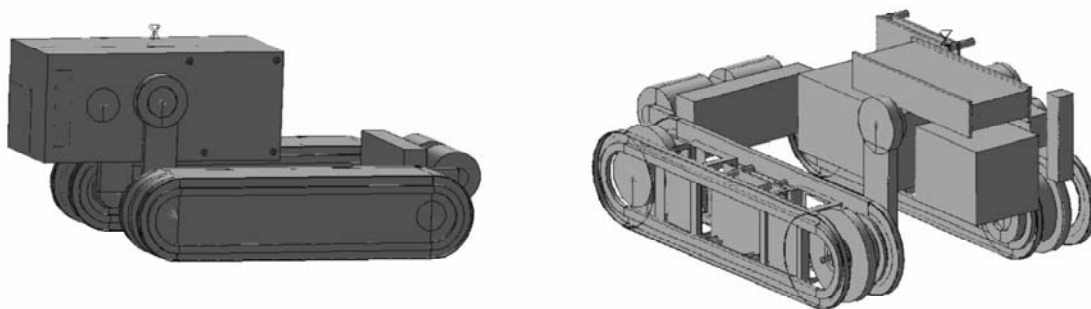

Figure 4 Thermal model components (inside and out) of the Nanokhod

The basic thermal model, which was developed in the MRP project, takes the assumption that the Rover is on the night side of the Mercury surface. As the results of the thermal behaviour can not be compared directly to future results from thermal vacuum tests, the ESARAD-model has been developed with the environmental conditions of the test chamber that will be used for the proposed MRP thermal vacuum testing.

This allows good comparison of the test results and the ones of the thermal modelling. The comparison can then be used for iterative steps to improve the thermal Rover model and thus for an optimum prediction of the thermal behaviour of

the rover. By adjusting the environmental conditions, it is also possible to have an analysis of the thermal distribution inside the rover under Mercury environment conditions.

The rover thermal model can be seen in Figure 4. Although some simplification in the geometry of the rover were done, the model realistically reflects the hardware components of the design.

5. MANUFACTURED ROVER

Figure 5 shows various aspects of the manufactured rover. Despite efforts to simplify the integration process, successfully assembling the rover is a slow and careful process. The small geometrical size of the rover meant that all components had to be miniaturized especially the fasteners which required very careful handling in order that they are located correctly into position without risking damage to the thread. All other operations such as component positioning, cleaning, gluing and lacing of harness became extremely complex to perform due to the lack of space in the half assembled rover. The size also made it impossible for more than one person to perform work on it simultaneously.
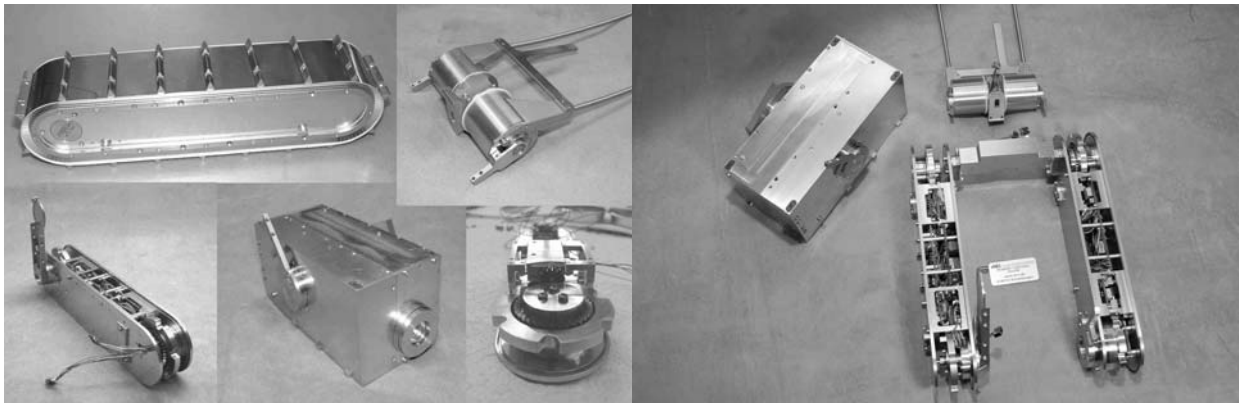

Figure 5 Manufactured MRP components

Another factor that caused problems during the integration of the rover, is the difficulty to perform any inspection once a unit (LU, PLC or the TU) had been fully assembled. Although it initially intended to be able to assemble and test a complete LU on a single wall before its final closure, this was not possible due to harness constraints. The use of more miniature connectors in the electrical system would solve this problem, however the number was minimised in the design largely due to the high cost of the miniature connectors.

Table 2 Requirements versus manufactured values

Parameter	Unit	Requirement	Manufactured	Notes
Stowed Length	mm	240	232.0	
Stowed Width	mm	165	162.2	
Stowed Height	mm	65	67.4	Extra height due to protruding LED's which are raised for better visibility
Rover mass	g	1800	1820	Manufactured mass includes central subsystem PCB which is not include in requirement
Instrument mass + central subsystem	g	900	550	From GIPF project and measured value does not include central subsystem mass

Table 2 compares the design values with the actual values of the rover system. The whole rover system is within the required mass constraint when taken in conjunction with the GIPF instruments. The mass not displayed in the table are items which are accommodated on the lander. The requirements budgets 500g for the mass of these items. Manufacture of the hold down device was not with in the scope of the project and the EGSE interface electronics is not totally representative of a flight system as it contains additional components and an external case. For comparative purposes EGSE interface has a mass of 414g including case but for a flight version the card would be incorporated within the

lander subsystem. For the hold down device a rough estimate of mass from conceptual design is in the region of 900g – the significant increase of weight is required to successfully support the rover during shock conditions: A reduction of this mass may be achieved with more information about the landing scenario and also by incorporating the mechanics within the lander structure itself.

6.   INITIAL FUNCTIONAL TESTS

After integration, a sequence of functional tests was performed to ascertain whether the rover met the operational requirements laid down at the start of the project. Table 3 summarises the results.

Table 3 Summary of Functional Test Results

Requirement	Description	Status	Notes
Mobility – reverse	Reverse by at least its own length	Fulfilled	
Mobility – spot turning	The rover shall perform a spot turn >90°.	Fulfilled	
Mobility - obstacle	Climb a step of 0.1m or traverse a ditch 0.1m deep	Fulfilled	
Mobility - speed	Maximum traverse speed of 5m per hour	3.06m.h^{-1}	Limited by planetary gear
Payload Cab movement	Orientation of PLC apertures to a surfaces at inclinations from horizontal to vertical	Fulfilled	
Payload Cab contact	The Rover shall push the payload cab against a hard surface with a force > 1N	Fulfilled	
Rover – peak power	The rover shall consume no more than 6W peak power from a 28V source	Fulfilled	See text

The rover fulfils all requirements except the speed requirement which is limited by the maximum rpm allowed by the planetary gear. However the reduction of maximum speed still allows the design to meet the input requirements of the mission scenario as presented in Table 1 which uses the slower design speed in its calculations.

During tests the current consumption during forward locomotion was measured to be at peak 190mA (5.3W) measured on the lander side. This value is a maximum value and includes approximately 40mA used by two controllable heaters which provides local component heating of the driver circuits which may be required for starting at the most extreme temperatures. During instrument operations the rover subsystem will only consume approximately 17mA (<0.5W). These values are less than those predict from the rover design which were used in the energy usage calculations in Table 1 and results in a predicted total energy consumption for the baseline mission of 202Wh. This compares to a requirement that the total energy consumption for the baseline mission shall be less than 265Wh.

7.   OPEN ISSUES

Two problems have been accounted during the functional testing of the MRP rover which has delayed the proposed environmental testing of the Rover.

The first issue was a track jam that occurred after performing the functional tests where the grouser/track tooth unit assembled in positioned on the track became twisted such that it did not locate correctly with the sprocket. As the twisted grouser caused plastic deformation of the track the blockage would not clear by reversing the track and repeating the movement.

Causes for the problem, which had not been seem on previous models of the rover were caused by three different factors: for the MRP rover a different steel track foil material had been selected which was thinner and more flexible under extreme low temperatures compared to those tested in a previous project RTPE. The disadvantage of this was that the torsion forces needed to twist and deform the track were significantly smaller than had previous been in previous breadboard models. Secondly the climbing had been performed on a hard surface with a significantly heaver rover mass than previous Nanokhod models meant that application of forces required for deformation was possible when most of the rover mass was supported on only one or two grousers – this would be unlikely in a regolith environment. Finally the addition of a chamfer on the lower side of the track tooth to increase internal volume for the PCB's meant that the

angle required for a blockage was significantly less – how ever this angle was still much greater than would be operationally acceptable as the twist angle of the grouser causes significant failure of the track sealing. Solutions preventing excessive twisting of the grouser/tooth assembly are currently being considered.

Second problem relates to the drive system. Tests on the drives system has clearly demonstrated that it is capable of producing torque sufficient to perform all operations both on Mercury and earth. However during testing the drive occasionally would block whilst running. The blocking was independent of load and could not be correlated to any particular position or configuration of the drive components. Although investigation is on-going, the current understanding is that a number of factors are causing the torque margin possessed by the stepper motor to be significantly reduced so that a slight variation in torque required for the drive will cause the motor to miss a step. As the motor is unable to run at the operation speed without a controlled acceleration, the missed step invariably leads to the motor stopping.

Possible factors leading to the reduction of margin includes the control of tolerances over the whole drive system which incorporates a significant number of interfaces (9 in the harmonic drive alone) and also the effect of the drive lubricant which may increase the stiction forces of the faces of the gear teeth. The effect of these are exasperated by the small scale of the components relative to the torque levels being used.

8.   CONCLUSION AND THE FUTURE

Although a mission to the Mercury surface is currently unlikely, the Moon has now become very popular in consideration for proposed visions. The night side environmental conditions of the Moon is similar to Mercury and would allows easy adaptation of the current concept. For a dayside landing the new Nanokhod model is still very applicable although new attention would need to be given to the thermal design.

The MRP Nanokhod rover is huge advance towards a practical flight model despite limited resources that were available. Solutions are available to the current open issues and its hoped that these will be implemented in the immediate future allowing the Rover to be subjected to environmental testing . It is planned to perform both vibration and shock tests before an extended thermal vacuum test down to temperatures approaching –180°C.

9.   ACKNOWLEDGEMENT

10.   REFERENCES

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