ACCESSING, DRILLING AND OPERATING AT THE LUNAR SOUTH POLE: STATUS OF EUROPEAN PLANS AND ACTIVITIES

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ABSTRACT

Exploration of the Moon is considered a high priority in the overall strategy of the European Space Agency (ESA), together with activities in Low Earth Orbit and missions to Mars. The Lunar South Polar region presents key opportunities for scientific discovery and advancement of exploration capabilities, but is also a uniquely challenging operational environment for robotic missions and for human explorers. ESA has placed accessing this environment, and the surface and subsurface material found there, as a high priority. In this context ESA is discussing with international partners, in particular with ROSCOSMOS, how these ambitions might be realised in cooperation. To support this work ESA is engaged in a range of mission level activities with ROSCOSMOS on the Luna-27/Luna-Resurs Lander mission as well as Lunar Polar Sample Return (LPSR). In addition to this ESA is undertaking, with European institutes and industries, a set of specific development activities which seek to address the challenges of operating in the environment of the Lunar South Pole.

This paper will specifically discuss the ongoing work on sampling and handling icy materials, both for in-situ analysis (as planned for the Luna-27 mission) and for sample return (as a cooperation with the Luna-28 mission), considering aspects such as regolith penetration, sample extraction and preservation. The next steps shall also be presented, including the approach to requirements verification via early testing activities, component level breadboarding and full scale development model tests in laboratory environments and in the field.

1. INRODUCTION

The Moon, and in particular the Lunar South Polar region, is seen by ESA as a stepping stone for human exploration farther into the solar system and as an important destination in its own right. This view is shared among many of ESA's partner agencies within the International Space Exploration Coordination Group (ISECG) and is reflected though the Global Exploration Roadmap (GER, http://www.globalspaceexploration.org/). Recognising the importance of this destination ESA has placed a high priority on accessing surface sites in the polar region and on realizing near-term flight opportunities for European 'products' which deliver both industrial experience and valuable scientific & operational data.

2. WHY THE LUNAR SOUTH POLE?

Past Lunar missions of the Apollo and Luna era opened up the lunar surface as a destination for study and exploration, however those missions were also limited in the sites and types of Lunar terrain they could access, i.e. near-side and predominantly low-latitude. More recent orbital missions have, with the aid of 21st century instrumentation, provided us with a much more comprehensive picture of the Moon including its polar regions. Many of these results have posed new questions regarding the Lunar environment and the properties of the regolith, and have highlighted the polar regions as locations which are in many senses unique in the solar system.

The polar regions, and in particular the Lunar South Pole, offer extremes of environments in terms of extended illumination on topographic highs, through to some of the lowest temperatures in the solar system found in permanently shaded craters. These low temperatures in particular have been connected with orbital results indicating the possibility of volatile materials, including hydrogen potentially in the form of water ice. This was confirmed at one location via direct measurements made during the L-CROSS impact into the Cabeus crater (Figure 1), which also exposed a range of other volatile materials [1]. Such volatiles may also be found in partially shaded locations at depth beneath the lunar surface where low temperatures may be maintained.

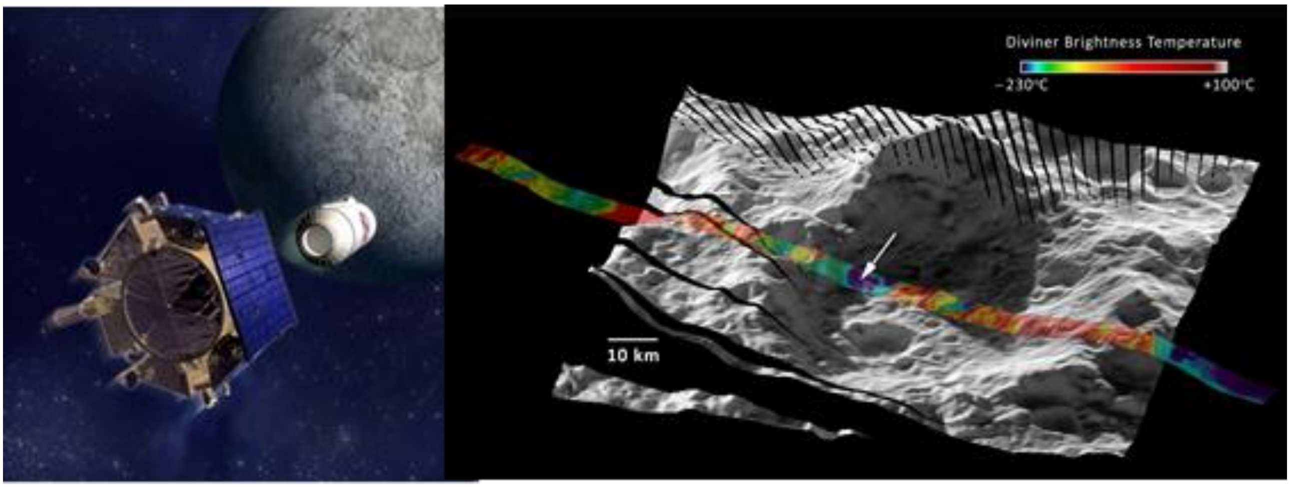

Figure 1: Artists impression of L-CROSS mission (left, NASA); Depiction of L-CROSS impact site in Cabeus crater with temperature overlay from Diviner instrument onboard LRO (right, UCLA/NASA/JPL/Goddard).

Volatile materials in the polar regions can provide an insight into the history of water and its delivery to the inner solar system, an understanding of key aspects of the lunar environment including the possibility of a 'lunar water cycle', and can offer the prospect of sustainable lunar exploration through the use of volatiles in-situ as resources. Alongside volatile materials, the proximity of the South Pole region to important lunar features such as the South Pole Aitken (SPA) basin make it a very important location for future robotic and human exploration. In this context ESA, and other agencies around the world have recognized the importance of the Lunar polar regions, and the role they can play as stepping stones to prepare the next steps of human exploration out into the solar system.

3. MISSION PLANS & RUSSIAN COOPERATION

A major aspect of ESA's plans for accessing the Lunar South Polar region involve cooperation with ROSCOSMOS on a sequence of lander, orbiter and sample return missions. This is part of the broader European-Russian cooperation already in place via the International Space Station and the ExoMars missions. The missions which make up this cooperative roadmap are shown in Figure 2, and consist of the following: the Luna-25 (Luna-Glob) lander mission which shall demonstrate the core capabilities of landing and operating on the lunar surface; the Luna-26 (Luna-Resurs-O) orbiter mission which shall embark instrumentation and provide communications relay support for subsequent missions; the Luna-27 (Luna-Resurs-L) lander mission which shall advance precise & safe landing technology as well as performing analysis of subsurface samples; and the Luna-28 (Lunar Polar Sample Return, LPSR) mission which shall return regolith from the polar regions, targeting in particular the return of icy volatiles.

Each of these missions provides both Europe and Russia with opportunities to advance technological, operational and scientific experience, in preparation for the subsequent mission. ESA's focus in this cooperation is on specific products which not only play a key role in the cooperative missions, but also provide direct benefits to European industry and other stakeholders, including applicability to the missions of other international partners.

The PROSPECT package is a major contribution to the Luna-27 (Luna-Resurs-L) lander mission in that it shall provide access to the subsurface and an important part of the sample analysis capability. The PROSEPCT package must operate in the polar regions where low temperatures and potential ice can lead to extremely challenging regolith characteristics. This paper will describe in more detail the current definition of the PROSPECT package and the challenges it will face, as well as the development activities ongoing in Europe to address those challenges.

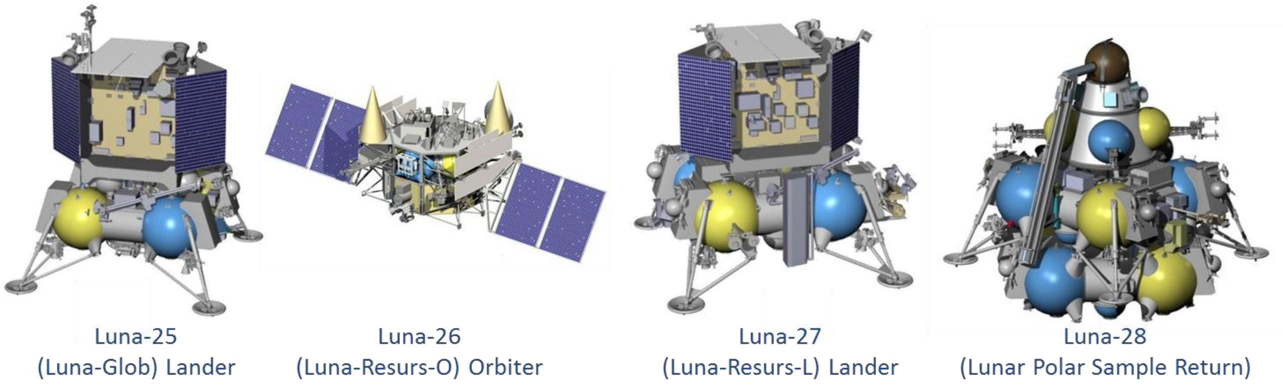

Figure 2: European-Russian Lunar exploration cooperation - roadmap of missions

4. PROSPECT PACKAGE

PROSPECT is a Platform for Resource Observation and in-Situ Prospecting in support of Exploration, Commercial exploitation and Transportation. For this purpose a package of elements as been defined which includes: 1) a drill for accessing subsurface material, 2) a sample processing stage which can both demonstrate the extraction of useful components from the sample and prepare material to be transferred to the analysis stage, and 3) a set of analytical instrumentation which will focus on measuring the volatile composition of the sample. In the context of the Luna-27 (Luna-Resurs-L) lander mission, PROSPECT shall also pass samples directly from the drill to a Russian sample processing and analysis package.

The current requirements on PROSPECT are driven by the expected operational environment at the Lunar poles, and by the objectives associated with analysis of icy volatile materials which may be found there. Key requirements are summarized below:

- Acquire sub-surface samples from depths up to 2m: while icy materials are believed to be stable at the surface on the floors of dark craters, conditions may also permit ice to be stable (on sufficiently long timescales) under the surface of partially shaded regions [2]; understanding the depth distribution of volatile materials is a key objective of PROSPECT;
- Acquire samples from regolith at low temperature (~120K) and with potentially high ice content: experiments on Earth have shown that regolith at such cold temperatures and with ice content near saturation can have very high strength properties [3; 4] and may therefore be very challenging to drill;
- Preserve volatile materials throughout the drilling process: volatile materials are extremely sensitive to temperature increase, especially when in vacuum [5], and so an important part of the PROSPECT package is the preservation of these volatiles and avoiding their sublimation and loss prior to analysis;
- Minimize cross-contamination between samples: given that the abundance of volatiles, including the variation with depth and spatial distribution, is unknown then the importance of minimizing contamination between samples is critical.
- Determine the chemical and isotopic composition of volatiles within the sample, and the abundance of those volatiles: understanding the types of volatiles present as well as the isotopic composition of key volatiles can help to understand the potential original and history of those materials; determining the abundances of volatiles, and their distribution with depth, can help to understand the potential of those materials for utilization in future exploration missions.
- Demonstrate the extraction of volatiles in their various forms (ices, surface layers on grains, mineral-bound) from regolith: while the PROSPECT sample processing equipment will be on a much smaller scale than that required for actual implementation of ISRU, demonstration of the principles of ISRU with real lunar materials in-situ will represent a major step towards its use in an operational mission context.

The operational environment and mission context of the Luna-27 (Luna-Resurs-L) lander mission provide a number of challenges for the PROSPECT package which include the restrictions of the stationary surface platform and the requirement for solar illumination in order to operate (resulting in potential thermal issues for sample preservation).

5. TECHNOLOGY DEVELOPMENT

Realising the PROSPECT package, with the focus on the first application on-board the Luna-27 (Lunar-Resurs-L) lander, will require the development of hardware elements which can meet the challenging requirements (drill, sample processing, instrumentation) but will also require a more comprehensive understanding of the nature and behaviour of regolith under the specific conditions of low temperature and significant icy volatile content. ESA has initiated a set of activities with industries and institutes across Europe in order to achieve this. These activities build on the very relevant experience already in place in Europe, particularly through the Rosetta mission and the developments for ExoMars.

5.1. Lunar Drill Development

At the start of the chain in terms of PROSPECT functionality is the need to acquire subsurface samples from up to 2m, and to do this while preserving the volatile content of those samples (where volatiles may be in various forms, including water ice). Selex-ES (Italy) is leading a consortium of industries and institutes to develop such a drill concept in the frame of the Lunar Drill Development (LDD) activity. Selex-ES already has significant experience in the domain of planetary/non-terrestrial drilling applications in particular through the SD2 drill system [6]) on board Rosetta's Philae lander. Selex-ES are also leading the development of the drill system for the ExoMars rover mission planned for launch to Mars in 2018 [7].

The drill concept being developed includes both rotational and hammering drill functions (Figure 3) , with the goal to achieve an even more efficient penetration than with rotary action alone. In this way the drill should be able to penetrate high strength material, while still minimising the energy which makes its way into the regolith, so helping to ensure volatile content is preserved. The LDD activity has already initiated early breadboarding activities to start investigating the likely range of material strength properties and the specific challenges of drilling such icy material (Figure 4). A fully functional breadboard shall be assembled, including both rotation and hammer actions, in the summer of 2015, for subsequent testing under low temperature conditions.

5.2. Lunar Generic Regolith Acquisition/Sampling Paw (L-GRASP)

The L-GRASP activity, led by Selex-ES, focuses on the investigation of concepts for the tool which shall practically realize the physical separation of the sample from the bulk regolith and contain the sample until delivery to the sample processing stage, i.e. the sampling tool which shall be present at the very tip of the drill. First options have been investigated, including solutions merging some of the features in the Rosetta-SD2 and ExoMars drill applications (Figure 5), with involvement of OHB AG.

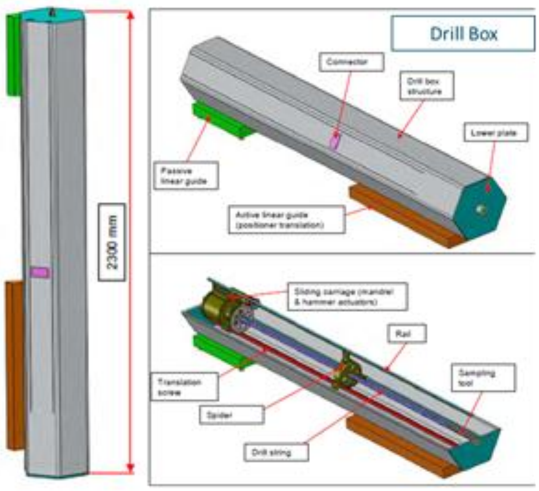

Figure 3: Roto-hammer drill concept established in Lunar Drill Development activity

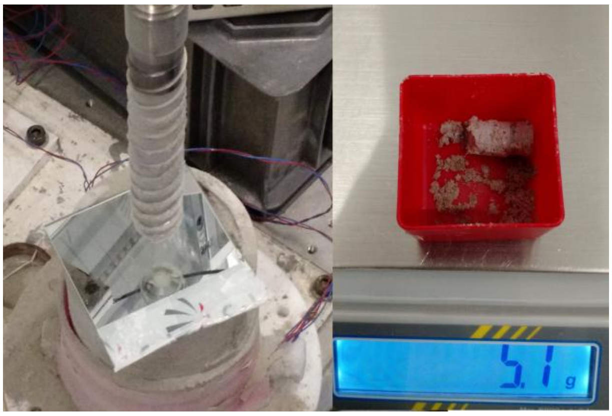

Figure 4: Early drilling tests into icy lunar regolith simulant

Another important aspect of the L-GRASP work is the definition of icy regolith simulant materials which can be used to perform breadboard tests of the sample acquisition tool concepts, and which may ultimately be applied to full drill breadboard tests. Following a workshop on lunar simulant materials held at ESA-ESTEC it was decided to baseline the use of NU-LHT-2M as the main regolith simulant, which may then be augmented with other simulants (e.g. JSC-1AC) in order to include a more representative range of particle sizes.

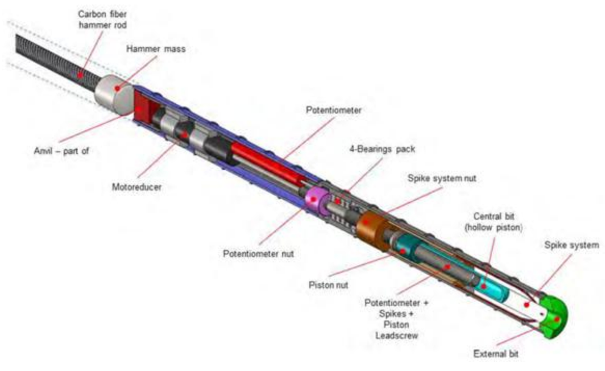

Figure 5: Sampling tool concept established in L-GRASP

5.3. Handling Planetary Ices

The Handling Planetary Ices (HPI) activity, also led by Selex-ES, addresses the demands on the overall sampling chain arising from the requirements associated with investigating icy volatile samples. This work considers both the in-situ case which is directly related to the application of PROSPECT onboard the Luna-27 (Luna-Resurs-L) lander, and the Lunar Polar Sample Return case. With the support of the Open University (UK) and ADS Ltd (UK), this activity has defined a set of reference sample properties which aim to cover the range of possible cases which may be encountered at the lunar poles. Starting from these reference cases, the HPI activity then takes an holistic approach to the consideration of the sampling chain and its interaction with the sample, from the point of sample acquisition up to the point of measurement by the analytical instrumentation.

The goal of the HPI activity is to establish sample handling concepts for both the in-situ and sample return mission cases which take into account the sensitivities associated with icy samples, and in particular the demands associated with the measurement requirements relating to the volatile content of those samples. The results of HPI shall be used to coordinate the hardware development activities on the drill, sample processing and instrumentation elements of PROSPECT, particularly with respect to volatile preservation and cross-contamination issues. HPI shall inform parallel experimental work aimed at verifying assumptions on the behaviour of volatile-containing samples.

5.4. Volatile Processing & Analysis Instrumentation

The ultimate purpose of the PROSPECT package is to demonstrate the extraction of volatiles (such as oxygen) from the lunar regolith and to perform measurements, particularly of the volatile content of the regolith, as part of our investigation of the abundance, distribution, nature and potential origins of these polar volatiles. To achieve this, the final part of the PROSPECT chain is a suite of sample processing and analysis instrumentation.

Work has already been performed by the Open University on an instrument package concept, Lunar Volatiles Resource Analysis Package (L-VRAP), which builds on Rosetta-Ptolemy and Beagle-II GAP heritage. The L-VRAP concept was developed in the context of a different lunar mission application [8] however this already contains many of the key elements required for investigating polar volatiles.

As part of the PROSPECT development, ESA has initiated work on the sample processing and analysis instrumentation element, so-called ProsPA. This shall include all of the hardware required to accept the sample from the drill system, process it (e.g. via heating, pyrolysis) in order to demonstrate volatile extraction and to convert volatiles into a form compatible with the measurement instrumentation, and the instruments themselves. Recommended instrument types include an ion-trap mass spectrometer and magnetic sector mass spectrometer. A preliminary concept for the ProsPA element is shown in Figure 6, which includes the carousel of ovens, and the separate analysis instrument block.

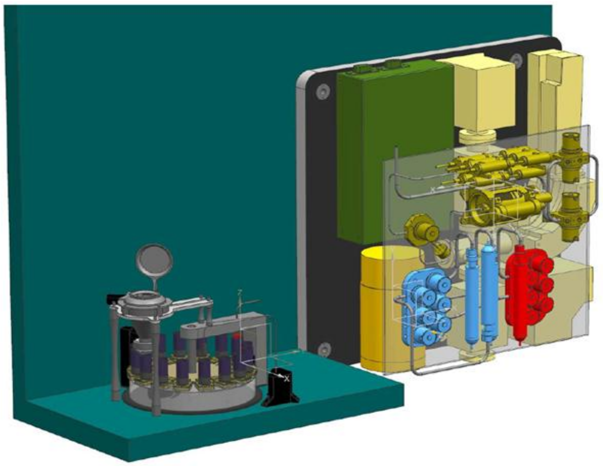

Figure 6: Prospect Processing and Analysis (ProsPA) package concept established by the Open University.

6. NEXT STEPS

At the ESA Council Meeting at Ministerial Level in December 2014, ESA received a mandate to advance its overall exploration activities including work on the Lunar exploration contributions proposed for cooperation with ROSCOSMOS. At the time of writing the detailed scope of work is being elaborated, and for PROSPECT this shall consist of a coordinated development of the full package, including drilling system and sample analysis instrumentation, up to Preliminary Design Review (PDR). In addition to this advancement of the design, a comprehensive set of HW breadboarding and Development Model (DM) testing activities shall be performed.

6.1. Breadboarding

The next steps of PROSPECT development shall exploit as far as possible the experience and HW already in place as a result of the pre-development activities. This testing shall tackle a range of questions including:

- Confirmation of the material strength properties which can be expected in regolith at different levels of ice saturation;
- Demonstration of sample acquisition, transportation and delivery for a range of sample types;
- Execution of specific functional tests of the drilling and sample analysis system under more representative (low-temperature & low-pressure) conditions;
- Investigation of volatile sublimation processes and the behaviour of icy materials when exposed to different conditions;
- Investigation of the sensitivity of key components to low-temperature and dusty conditions.

6.2. Development Model Testing

A set of Development Models are foreseen which shall provide the PROSPECT team with the opportunity to investigate end-to-end functionality and performance under different conditions. These models shall precede the full Engineering Model (EM) and so may be used to inform design updates in advance of the PDR, which is critical for designing such a unique system for application in such a challenging and uncertain environment.

The first type of Development Model foreseen is a Bench-top model of the so-called ProsPA sample analysis ‘laboratory’. This shall not be representative of the sample handling stage, and may use COTS equipment for some of the measurement hardware, but shall concentrate on representing the functionality of the gas processing which goes on inside PROSPECT. This testing will give designers and instrument operators a chance to understand how the complex gas processing HW and operations chain works, and how to best make use of the system under a range of conditions.

The second type of Development Model foreseen is a Laboratory model of the functional sampling chain of PROSPECT. The Lab-DM shall include a fully functional drilling system (including roto-hammering, sampling and sample delivery functions), and a representative sample inlet, sealing system and oven. This setup will be operated within a dedicated Lunar polar simulator (a chamber capable of low temperature and low pressure, and which is compatible with hosting large volumes of icy regolith simulant), similar to facilities which have been established in the US [9]. Within this chamber the end-to-end sample chain can be operated with different material compositions and ice contents, and can be investigated in terms of its volatile preservation performance. This setup will also allow investigation of the specific behaviour of the drill and of the material during different drilling operations under more representative conditions.

The third type of Development Model foreseen is one for carrying out Field Testing, where the field test environments will be those presenting a combination of low temperatures, variations of material composition and some degree of subsurface ice content. Similar drilling field test campaigns [10; 11] have highlighted important operational issues that are very difficult to investigate in the controlled conditions of laboratory tests. Such testing shall therefore provide important inputs to the design activities, and shall also help advance the engagement with the operator and user communities.

7. CONCLUSIONS

ESA is coordinating a set of design and test activities which support the development of the PROSPECT package. The next step is to integrate these activities into the full scale manufacturing and test of PROSPECT ready for integration and first operation on-board the Luna-27 (Luna-Resurs-L) lander mission planned for launch in 2019.

Alongside the developments for the PROSPECT application on Luna-27, ESA shall also investigate opportunities for implementing the package, or elements of the package, in other mission scenarios such as Lunar Polar Sample Return and potentially on mobile platforms.

Altogether these activities shall provide Europe with access to an important opportunity to access an as yet unexplored region of the Moon to make measurements of key scientific importance and vital for the preparation of future exploration. With an important focus on HW development and testing, the next stage of developments shall advance the level of experience and expertise acquired while at the same time helping to minimise the risks associated with operating in the extreme environment of the Lunar South Pole. Finally, elements like PROSPECT provide a solid foundation for future cooperation on yet more advanced missions with international partners, such as Lunar Sample Return and lunar surface exploration with mobility.

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