

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION-

BRITISH NATIONAL SPACE CENTRE

JOINT WORKING GROUP REPORT ON LUNAR COOPERATION



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# TABLE OF CONTENTS

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## JOINT WORKING GROUP REPORT ON LUNAR COOPERATION

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1. Executive Summary.....	3
2. Objectives of the study .....	6
3. Potential concepts for lunar collaboration .....	7
3.1 The approach to developing cost effective missions.....	8
4. The MoonLITE mission concept.....	11
4.1 Mission Science Goals .....	12
4.2 Areas identified for collaboration on the MoonLITE mission.....	13
5. Knowledge exchange activities .....	14
6. UK PPP for NASA Commercial Development.....	15
7. Other areas of potential collaboration .....	16
7.1 In-situ Sample Analysis and Age Dating – lunar sortie proposal .....	16
7.2 Search for Terrestrial Material on the Moon.....	19
7.3 Atmospheric Site Testing Package .....	21
7.4 Rover Design and Associated Autonomous Systems.....	22
7.5 MagEX Examining the Earth’s Magnetosphere from the Moon – Lunar Sortie proposal .....	23
7.6 Lunar Drilling .....	24
8. Conclusions/recommendations .....	26

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## APPENDICES

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Appendix I.....	29
Appendix II.....	36
Appendix III.....	40
Appendix IV .....	41
Appendix V .....	44
Appendix VI .....	45

## 1. Executive Summary

Pursuant to a Joint Statement of Intent for Cooperation in the Field of Space Exploration signed by National Aeronautics and Space Administration (NASA) Administrator Michael Griffin and Sir Keith O’Nions, United Kingdom (U.K.) Director General for Science and Innovation, on April 19, 2007, representatives from NASA and the British National Space Centre (BNSC) have engaged in Joint Working Group (JWG) discussions toward identifying areas of lunar science and exploration cooperation. The NASA-BNSC JWG held face-to-face meetings and participated in numerous video- and teleconferences to complete a final report. As a result, the NASA-BNSC JWG agreed upon a programme for possible implementation from 2008 onwards. The programme meets the following objectives:



Sir Keith O’Nions and Dr. Michael Griffin following the signing of the Joint Statement of Intent on April 19, 2007, in Washington, DC.

- In a United States (U.S.) context, it would explicitly advance the human and robotic goals of the Vision for Space Exploration and relevant scientific decadal surveys.
- From a U.K. perspective, it would build on national scientific and technological strengths and be a key element in the new BNSC Space Strategy 2007–2010.
- Bilaterally, it would further strengthen the bonds and common motivations in science, technological innovation, and economic expansion shared by the U.S. and the U.K. in space exploration.
- Internationally, it would be a first implementation of the new age of global space exploration foreseen in the “Global Exploration Strategy (GES): The Framework for Collaboration,” which was released by 14 space agencies in May 2007.

The NASA-BNSC JWG has identified potential elements of collaboration:

- first, the implementation of a U.K.-led robotic lunar mission, such as the Moon Lightweight Interior and Telecoms Experiment (MoonLITE) mission; and
- second, the development of enabling science and technology needed for midterm robotic and human exploration activities.

The MoonLITE mission would meet some of the scientific goals identified by the U.S. National Research Council and by the Science and Technologies Facilities Council (STFC) in the U.K.; demonstrate telecommunications and some risk-reduction capabilities needed for a lunar architecture; and provide a cost-effective lunar milestone beyond NASA’s Lunar Reconnaissance Orbiter (LRO), which is scheduled for launch in the October 2008 timeframe.

MoonLITE could also address several items or themes in the “open architecture” introduced by NASA in December 2006, which are basic communications and navigation, the characterization of In Situ Resource Utilization (ISRU), the use of small satellites, and the development of instrumentation. There are opportunities for knowledge exchange in the MoonLITE mission. Finally, MoonLITE represents an early opportunity for rapidly achieving the goals of the GES framework.

Other existing exploration activities, such as the U.K.’s leadership of the ExoMars rover, could also feed into the programme. Export control issues would have to be addressed through bilateral arrangements to be negotiated at a government-to-government level.

Underpinning these activities will be a joint U.S.-U.K. project team (JPT) to ensure the successful implementation of MoonLITE and continue the examination of overall science and technology needs.

### **What is MoonLITE?**

MoonLITE is a U.K.-led small robotic mission (of less than 1 tonne at launch) to the Moon. It comprises a polar orbiter and multiple instrumented penetrator vehicles. The penetrators would emplace a global network of three to four 13-kilogram science stations equipped with seismometers, heat sensors, and spectrometers and powered by primary batteries. Both orbiter and surface stations have a nominal 1-year life.

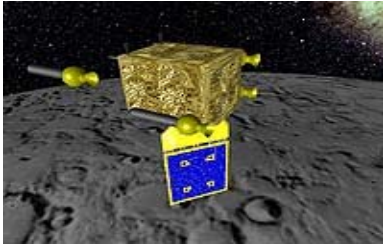
### **Why develop the MoonLITE mission?**

Given the successful launches of lunar missions such as the Small Mission for Advanced Research in Technology-1 (SMART-1), SELenological and ENgineering Explorer (SELENE), and Chang’e missions and the upcoming launches of Chandrayaan-1 and the LRO, MoonLITE offers a unique and timely opportunity to make important new and complementary robotic discoveries on the Moon in preparation for future human missions.

The U.S. and U.K. have enjoyed a long history of successful space cooperation. MoonLITE would build on this history and allow both partners the opportunity to take advantage of their relative strengths to build capacity and maximize national capabilities in a precursor mission to human activities on the lunar surface. In particular, the U.K. has expertise in the development and implementation of cost-effective small spacecraft missions, while the U.S. brings expertise in descent and landing systems, and these complementary capabilities provide an obvious central point for collaboration.

Beyond the immediate scientific return, MoonLITE would further advance the U.K.’s world-class ability in small satellites; assist both partners in the development of capabilities needed for the exploration of the Moon, Mars, and beyond; and create a fertile environment for attracting and training skilled scientists and professionals.

While the U.K. is not yet in a position to commit to longer term human aspects of lunar exploration, the two elements of the initial programme are nonetheless fully compatible with such a strategic involvement.



Artist's concept of the MoonLITE mission.

### **What benefits will MoonLITE deliver?**

The science goals include investigating the following:

1. size and physical state of lunar core,
2. deep structure of the lunar mantle,
3. thickness of the farside lunar crust, and
4. sources of natural moonquakes.

Exploration benefits arising from the science are to

1. determine the natural seismicity of proposed lunar base locations, which will feed into engineering constraints on outpost designs, and
2. follow-up on results from LRO and other orbiters by determining “in situ” the nature and composition of volatiles if present (with implications for both improved scientific knowledge and possible ISRU).

The direct contributions to the lunar architecture would be to

1. test polar orbital telecoms (and possibly navigation) capabilities and
2. validate the concept of a low-cost, recurring lunar telecom satellite design subsequently needed for the human lunar architecture.

Wider technological impacts would be to

1. provide a platform for testing at the Moon certain technologies needed for exploration missions (especially descent and landing, as well as power and communications capabilities with ground assets) and
2. demonstrate the use of highly instrumented penetrators for subsequent application to the scientific exploration of Mars, Europa, and other airless bodies in the solar system.

### **What activities are foreseen in the science and technology programme?**

MoonLITE will allow the first flight demonstration to validate key technologies needed for future human lunar exploration. By carrying out a joint programme and pooling collective knowledge and innovative thinking, MoonLITE would provide a key first step towards a visible and incremental build up of capabilities needed to bring the U.S. Vision for Space Exploration into reality.

The JPT will be a key body in coordinating and planning these activities by identifying areas of low technology readiness and developing appropriate technology roadmaps to ensure successful implementation of MoonLITE. Additionally, the JPT would further refine the science goals of the mission and oversee the process of instrument selection and tradeoffs to ensure successful implementation. Finally, the JPT would be tasked with supporting the U.S. and U.K. scientific communities through a series of workshops in coordination with existing meetings such as those held by the Lunar Exploration Analysis Group.

For the MoonLITE mission concept, the JWG has identified the following areas as high priority for initial development:

- Development of Terrain Relative Navigation systems employed by the orbiter.
- Development of high-bandwidth communications relay capabilities between the orbiter Earth assets.
- Emerging developments in the area of radiation tolerant electronics.
- Highly instrumented penetrators employing a range of miniaturized scientific instruments including seismometers, water/volatile packages, dust characterization, subsurface sampling, and radiation detectors.

The JPT would continue to examine other areas for potential longer term NASA-BNSC lunar cooperation, which could include (but are not limited to), the following:

- In situ sample analysis and age dating.
- The search for terrestrial material on the Moon.
- Atmospheric site-testing packages.
- Rover design and autonomous systems.
- MagEX—Examining Earth’s magnetosphere from the Moon.
- Lunar drilling based on synergies with the oil and gas industry.

The JWG has identified technologies where capabilities are low and which therefore represent significant development risk. The JWG would foster knowledge exchange between the U.S. and the U.K. in these areas to accelerate the technical readiness of these items faster than if pursued unilaterally.

A final area of potential collaboration arises from the U.K.’s expertise in Public Private Partnership (PPP). NASA’s Exploration Systems Mission Directorate is seeking to implement its recently ratified Commercial Development Strategy, which aims to reduce the cost of mission procurement and aid the growth of the private-sector space industry. The U.K.’s experience in PPP could contribute to NASA’s programme management and the implementation of any future large-scale transportation projects.

## **2. Objectives of the Study**

Pursuant to the Joint Statement of Intent, NASA and BNSC agreed upon terms of reference for a Joint Study Group on Cooperation in the Field of Lunar Science and Exploration. The major component of the joint study terms of reference was the formation of the JWG, which undertook the following tasks in order to advance understanding of potential cooperative efforts:

- Identify potential mission concepts, along with initial roles and responsibilities.
- Foster interaction among the working group participants and other technical experts (before, during, and after the two working group meetings) as necessary in preparation for discussions on specific initiatives.

- Prepare, upon conclusion of the second meeting, a final NASA-BNSC JWG report, the format and content of which would be agreed upon by both delegations. This report would highlight the results of the discussions and identify common areas of interest, proposed mission concepts, initial roles and responsibilities, and possible timeframes for NASA-BNSC cooperation in lunar science and exploration. Each initiative should reflect timelines for potential implementation and points of contact for future deliberations.

NASA and BNSC jointly appointed study managers to coordinate the activities of the JWG. This was subsequently handled through a series of face-to-face meetings in Washington and London, two videoconferences between STFC and NASA Headquarters, and a series of regular teleconferences and written updates.

### **3. Potential Concepts for Lunar Collaboration**

A cost-effective approach to lunar robotic exploration through the development of missions with a short development cycle is seen as a key part of a strategy to achieve early, high-profile lunar science goals within the framework of the BNSC-NASA JWG and could also potentially be an important precursor mission for the GES. NASA and BNSC could leverage the development of technology and commercial capabilities and capacity in a sector with high economic impact and inspire a new generation of scientists and engineers who would contribute to the knowledge economy of both partners. Thus, the intention is to develop, through mutual cooperation, a sustainable rolling programme of missions that are flexible and build on an established common vision of U.K. and U.S. technological strengths through an incremental approach in technology development.

The advantages to NASA and BNSC of pursuing a bilateral activity within a small satellite concept include the following:

- Exciting and high-profile science in an area where the U.K. and U.S. are very strong, one that has been identified by both partners as high-priority science.
- The building of technological capability in a sector that has major potential for knowledge exchange and economic impact. In the U.K., this would serve as a major driver for the implementation of the Harwell Science & Innovation Campus.
- An important step towards advancing robotic lunar exploration consistent with the U.S. Vision for Space Exploration, which would serve as trailblazers to reduce the risks and costs of future human operations at the moon.
- An important element of the British national space programme that could leverage the advantages of the proposed European Space Agency (ESA) centre which the UK hopes to secure at the Harwell Science & Innovation Campus.
- Exciting knowledge exchange programmes in low-cost satellites, which are recognized as a rapidly developing worldwide commercial market. Through Surrey Satellite Technology Limited, the U.K. has pioneered this area through the rapid development and incorporation of new technologies in order to reduce costs and increase capabilities.

- A basis for the first implementation of the new age of global space exploration foreseen in the NASA-led “Global Exploration Strategy (GES): the Framework for Collaboration.”
- An inspirational programme that, for example in the U.K., would demonstrate leadership, encourage the pursuit of science and engineering subjects, and, with its rapid mission turnaround, provide a challenging and dynamic environment in which engineers and scientists can experience the full development life cycle of a space project on a tractable timescale, providing much-needed opportunities for training the next generation of space specialists.
- A programme that is seen by the U.K. as laying the ground for possible involvement in the lunar outpost programme.
- A programme that provides the U.S. with an opportunity for early validation of key technologies such as precision landing and communications that would enable future human lunar exploration missions.

### 3.1 The Approach to Developing Cost-Effective Missions

Capability in the development and operation of small satellite missions in the U.K. has been principally developed through SSTL in collaboration with other industrial and academic partners. To date, SSTL has designed, built, and put into operation 27 satellites and has well over 200 in-orbit years of satellite operations experience. Through this capability, the U.K. is now recognized as a leader in developing innovative technology and providing cost-effective satellites.

The short development periods and frequent launches of small satellite missions have led to the rapid accumulation of experience in spacecraft and component performance. Of fundamental importance is the company’s development of commercial off-the-shelf (COTS) technology. A mission like MoonLITE would benefit from this experience and on the extensive flight heritage accumulated by both partners in incremental steps, minimizing risk and offering a cost-effective mission platform and technology.

Through SSTL, the U.K. would bring a unique approach to the engineering and management process that differs significantly from classical space industry practices and builds on a proven heritage, from early pre-feasibility studies, spacecraft design and manufacture and ground segment manufacture to in-orbit operations.

In brief, this approach would:

- rapidly build highly capable satellites, with high levels of redundancy using advanced commercial off-the-shelf technologies;
- manage risk by proving key technologies and techniques required for future missions; and
- design space systems that would result in well-informed and flexible trade-offs between system-, subsystem-, and equipment-level design decisions.

By harnessing U.K. strengths in small satellites, responsive missions of high quality and cost-effectiveness can be developed by reducing levels of qualification, formal documentation, and quantitative reliability analysis and replacing them with system-level validation, strong internal communications, and demonstrated in-orbit heritage.

NASA's main interests are to demonstrate key technologies for future human exploration missions and to characterize the lunar surface environment. The goals set out in NASA's *Lunar Robotic Architecture Study (LRAS)* that are necessary or desired prior to human missions include the following:<sup>1</sup>

### **Mapping**

- A high-resolution visual map, including information on the near-permanently lit regions of both poles. The Polar Regions and other sites of interest would be measured at approximately 1 m/pixel, the rest of the Moon at approximately 50 to 100 m/pixel.
- A high-resolution topographical map of the Moon. Absolute altitude would be gained at approximately 25 m error limit, with relative error less than approximately 0.5 m.
- A map of hydrogen deposits > 100 ppm on the Moon < 10 km/pixel.
- A measure of the space radiation environment near the Moon.

### **Landing and Assessment of In Situ Resources**

- Demonstrate precision landing (< 100 m error eclipse)
- Characterize the lunar dust
  - Measure percent of dust < 5 um
  - Relative reactivity
  - Passivation characteristics
- Characterize regolith thickness, composition
- Provide ground truth lighting and thermal environment of landing site

### **In-Situ Resource Utilization (ISRU)**

- Checking for water ice in at least 20 sites in a shadowed crater. It was noted that hydrogen deposited by the solar wind is ubiquitous, but only in a concentration of 50–100 ppm; consequently, mining H<sub>2</sub> is not practical. Having a large number of sites would allow scientists to determine, with confidence, that if there is water available in the crater selected for searching, it has not been missed.
- Measure the radiation shielding effects of regolith (this experiment could be moved up to as early as the fixed Lander mission if necessary).
- Through biological experiments using small model organisms, measure the combined lunar environmental effects on life (this experiment could be moved up to as early as the fixed Lander mission if necessary).
- Prove that mechanical systems can survive and operate for approximately 1 year in this lunar environment.

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<sup>1</sup> *Lunar Robotic Architecture Study*, NASA, May 2006, pp. 60–63.

### **Larger Scale ISRU/Roving**

- ISRU production of oxygen or oxygen and hydrogen of up to 1,000 kg
- Characterize fluid and two-phase systems in 1/6 gravity (this experiment could be moved up to as early as the fixed Lander mission if necessary)
- Up to 30 km of roving as a precursor to human rovers for the outpost

The following technologies and experiments are potential NASA contributions to the MoonLITE concept:

- Demonstration of a Terrain Relative Navigation (TRN) system that uses cameras on board the orbiter to image features on the lunar surface during its closest approach to the Moon. The TRN system matches these features to a crater database to determine the orbiter's position and attitude. This technology would enable autonomous precision landing and hazard-avoidance systems. The Johns Hopkins Applied Physics Laboratory and the Jet Propulsion Laboratory (JPL) are working on TRN technology.
- Demonstration of communications technologies to validate high-bandwidth connections directly from the MoonLITE Comm-Nav payload to Earth ground stations. This may include the development and demonstration of Mini-RF technologies at S- and/or Ka-band frequencies and advanced optical communications terminals.
- Demonstration of high energy-density lithium ion batteries that are capable of operating at low temperatures (-60°C). These batteries would provide power for the penetrators for at least 1 year. Low-temperature batteries are needed for rovers, spacesuits, and extravehicular activity (EVA) tools. The Jet Propulsion Laboratory has developed low-temperature batteries for the Mars Exploration Rovers.
- Demonstration of radiation-tolerant, ultra-low-power electronics that are capable of operating at extremely low temperatures (-180°C). These electronics would allow rovers and instruments to function in the permanently shadowed polar craters. Georgia Tech is developing Silicon-Germanium electronics for extreme environments.
- Demonstration of a subsurface sampling system that is incorporated into the penetrators to acquire small samples of the regolith approximately 2 m below the surface. These samples would be analyzed by instruments on the penetrator. A miniature drill and a sample acquisition system were developed by the Jet Propulsion Laboratory for the DS-2 mission.
- Instruments on the penetrators to detect the presence of water ice and other volatiles that may be present in the regolith in the lunar Polar Regions. The detection of volatiles is essential for demonstrating the feasibility of in situ resource utilization systems that would produce oxygen, water, and rocket propellants. A tunable diode laser to detect water was developed by the Jet Propulsion Laboratory for the DS-2 mission.
- Characterization of the mechanical properties of the lunar dust to understand how it would affect the operation of equipment, seals, bearings, and mechanisms. This knowledge would be used to design lunar surface systems and to develop methods that prevent dust from accumulating on equipment and spacesuits. Properties of

regolith could be measured by impact accelerometers, subsurface sampling drill, or microscopic imager. Electric field measurements could improve understanding of the dusty plasma that may be levitated by static charges generated by terminator passage. Glenn Research Center (GRC) is leading NASA's dust mitigation technology project. In addition to the work at GRC, NASA has sent funding to Mihail Horanyi at the University of Colorado to look at dusty plasmas in the context of lunar exploration.

- Measurement of the lunar surface radiation environment and the shielding effectiveness of lunar regolith using radiation detectors on the penetrators. This knowledge would help to reduce the radiation exposure risk for future human explorers. The Southwest Research Institute has developed the Radiation Assessment Detector (RAD) for the Mars Science Laboratory mission.

NASA would develop these technology experiments and instruments and deliver them to BNSC for integration into the penetrator and orbiter systems.

#### **4. The MoonLITE Mission Concept**

The JWG identified a technology demonstration spacecraft as a preliminary mission concept. Called MoonLITE, the concept consists of a lunar orbiter and a number of surface penetrators (minimum three), which are deployed in a network around the lunar surface. The orbiter shall relay the science data back to Earth for the entire penetrator lifetime of nominally 1 year. The penetrators allow key scientific investigations of airless solar system bodies via such affordable precursor missions. The demonstration of non-aerodynamic penetrators would also provide a technology relevant to the exploration of other high-priority planetary bodies in the solar system such as Europa. The penetrators themselves would be highly instrumented projectiles that would impact the lunar surface at high speed and bury themselves below the surface. In the concept identified by the JWG, a typical penetrator has a mass of 13 kg and is designed to have an impact speed of up to 300 m/s and penetrate 2 to 5 m below the surface, presenting a high-g environment (up to 10,000 g) for instruments to survive.

The MoonLITE mission can provide significant opportunities to develop and demonstrate advanced space technologies needed for lunar exploration. In the area of communication and navigation technology, a critical component for the MoonLITE satellite would be the space-to-Earth communication system. New technology derived from the Lunar Reconnaissance Orbiter (LRO) Mini-Radio Frequency (RF)-Synthetic Aperture Radio system would provide a low-power, low-mass solution for the S-band communication link with Earth. This system could be included as either the main communication system for the space-to-Earth link or as a technology demonstration. In addition, the Mini-RF system could be expanded to include a high-rate Ka-band capability that could be either used to transport MoonLITE data back to Earth or implemented in a technology demonstration mode. Another space communication and navigation technology demonstration might be an optical communication system capable of Gbps-level data transfer as well as achieving cm-level satellite tracking capability. The precise tracking of MoonLITE would both support operational tracking of the satellite and include

opportunities for further lunar gravity field research. When the MoonLITE mission nears its end, additional technology development opportunities would exist for the demonstration and validation of new Disruptive Tolerant Network (DTN) communication protocols. With regard to the penetrators, although survival at these speeds has been demonstrated by ground tests of NASA DS2, Mars 96, and the Japanese Lunar-A probes, and extensively in military applications, the development of the penetrators remains a highly challenging area. From an initial assessment of the level of technology readiness, it is clear that the penetrator development lies on the critical path for the mission; however, there are many clear opportunities to harness innovative technologies and approaches from both partners to accelerate their development for MoonLITE.

A system overview of the MoonLITE concept is given in Appendix II. Appendix III provides a top-level product tree for the penetrators used by the JWG to assess the potential technology development programmes for the scientific payloads and the descent systems. A more detailed technical description of the penetrator instrumentation and associated technologies is given in Appendix IV.

#### **4.1 Mission Science Goals**

A detailed science case for the penetrometer based MoonLITE mission is given in Appendix I. In summary, the principal scientific objectives of the MoonLITE penetrator mission are as follows:

- Constraining the origin, differentiation, internal structure, and early geological evolution of the Moon.
- Gaining a better understanding of the origin and history of the volatile flux in the Earth-Moon system.
- Collecting of “ground truth” geochemical data for the calibration of orbiting remote-sensing instruments.
- Collecting in situ surface data that would help in the planning of future lunar exploration activities.

This mission concept would involve emplacing the following scientific instruments in widely separated locations by means of a minimum of three penetrators deployed from orbit. By deploying a range of instruments (e.g., seismometers, heat-flow probes, x-ray spectrometers, and volatile detectors) to diverse locations on the Moon from which geochemical and geophysical measurements have not yet been obtained (including the poles and the far side), the MoonLITE penetrators have the potential to make major contributions to lunar science. At the same time, they would provide knowledge (e.g., of lunar seismicity and polar volatile concentrations) that would be of central importance in the planning of future human missions to the Moon, and they would also demonstrate a technology that would have wide applications for the exploration of other airless bodies throughout the solar system. Achieving these science objectives would require the design and development of a robust proximity communications system between the penetrators and orbiting communications payload, thus requiring close coordination between the science/instrument and communications teams.

## 4.2 Areas Identified for Collaboration on the MoonLITE Mission

The JWG has identified preliminary roles and responsibilities for key elements of the mission. The first table illustrates areas of the development relating to the orbiter and delivery system for the penetrators. The second table is a breakdown of the scientific instruments for the penetrator, along with an assessment of the associated technology readiness levels available in both the U.K. and the U.S. It is worth noting that a detailed scientific assessment of the penetrator instrument suite has not been carried out, and so the instrument technologies represent a straw-man concept. A detailed trade-off would be carried out by the science definition team as part of a Phase A study; however, instrument priorities are likely to be the seismometer, water/volatile detector, descent camera, and dust analyser packages.

**Table 1. Areas identified as priorities for the U.K. and U.S. (✓✓), necessary to achieve a short-duration, cost-effective mission. ✓ Indicates a strong capability in this area exists.**

Areas of Development	U.K.	U.S.
<b>Orbiter</b>		
System Prime	✓✓	
Trajectory Analysis	✓	✓
Platform Operations	✓✓	✓
Primary Structure	✓	✓
Propulsion System	✓✓	
Platform Avionics	✓✓	✓
Solar Array	✓✓	
Navigation and Communications Payload		✓✓
Payload Operations	✓✓	✓
Launch Vehicle	✓✓	
<b>Penetrator Delivery System</b>		
System Prime Role	✓✓	
Solid Rocket Motor & Carbon Fiber Reinforced Plastic Structure	✓	✓
Avionics	✓✓	✓✓
Structure	✓	✓
Terrain Relative Navigation System		✓✓

**Table 2. Technology priorities for the scientific instruments on the penetrators. ✓✓ Indicates a national priority, and ✓ indicates a strong capability in this area. The corresponding Technology Readiness Level (TRL) assessment is also shown in brackets.**

Penetrator System	Technology Priorities and Technology Readiness Levels (TRL)		
	U.K.	U.S.	Comments
Accelerometer/tilt	✓✓ (6)	✓ (4)	COTS system (Endevco), flown on DS-2. U.S. developing Silicon Carbide systems for impactors
Seismometer	✓✓ (4)		Microelectromechanical systems based—needs ruggedized development. Very low-mass solution.
Water/volatile	✓✓ (4)	✓✓ (4)	Multifaceted. Ideally includes mass spectrometer. U.S.-developed laser diode tuned for water detection (DS-2 heritage).
Sample acquisition		✓✓ (8)	Based on DS-2 sample acquisition system.
Geochemistry	✓✓ (4)	✓ (5)	Essentially solid-state X-Ray Spectrometer and therefore robust with Beagle 2 heritage. U.S. system tested for Mars.
Heat flow	✓ (36)	✓ (4)	Issues associated with antenna, body material, and insulation. Open University collaboration with Japan Aerospace Exploration Agency [JAXA]).
Mineralogy	✓ (2)		On-board microscopy (low-priority instrument).
Magnetometer	✓ (4)	✓ (4)	Essentially solid-state, but inclusion in penetrator would require development.
Descent camera	✓ (7)	✓✓ (7)	Part of the Terrain Relative Navigation system.
Lithium-ion battery		✓✓ (6)	Low-temperature electrolytes developed for Mars mission. Minimum operating temperature -60°C.
Low-temperature and radiation-tolerant electronics		✓✓ (4)	Silicon Germanium electronics under development by Georgia Tech are capable of operating at -180°C.
Radiation detector		✓✓ (6)	RAD instrument developed for Mars Science Laboratory mission.
Lunar dust characterization		✓✓ (3)	Measurement of dust mechanical properties and electric field to understand dusty plasma environment.

## 5. Knowledge Exchange Activities

To exploit national technology programmes to their best effect, each partner should develop instruments or subsystems that are complementary. However, the JWG has also identified other areas that are rich for collaboration where the required Technology Readiness Level (TRL) is too low, and so there exists significant development risk. Through the exchange of knowledge in these areas, the technology can be rapidly developed to a sufficient level of flight maturity. Other important reasons why knowledge exchange should occur include the following:

- There are political and economic benefits in exchanging knowledge on the development of new technologies.
- NASA has shown a great deal of openness and willingness to adopt U.K. technologies within U.S. missions, and this should be reciprocated in a U.K.-led mission.

- Exchanging knowledge strengthens partner understanding and potential utilization of technology capabilities that in turn benefit space exploration.

Areas for possible exchange of engineers and scientists could involve access to training in the form of theoretical or hands-on and practical activities related to the lunar mission. For example, SSTL provides training for the design and manufacture of cost-effective small satellite space missions using the design of lunar missions as a learning tool as well as a deliverable asset. Typically, these programmes are 2 to 3 years in duration and immerse the trainee fully in the design exercise. Often, they are combined with spacecraft engineering short courses held at the University of Surrey. Training typically includes all elements of the project, from concept development, mission and system design, subsystem training and design, and participation in mission reviews all the way to operations training.

## **6. U.K. PPP for NASA Commercial Development**

Both the U.S. and the U.K. can benefit from applying the U.K.'s PPP (Public Private Partnership) experience to NASA's commercial development activities.

NASA's Exploration Systems Mission Directorate (ESMD) is seeking to implement its Commercial Development Policy, which would encourage the development of commercial market capability and solutions in order to accomplish NASA exploration mission goals at lower cost and risk to NASA. Its approach is to apply a set of policy elements and evaluation criteria to all ESMD programmes and projects in a way that addresses the requirements of new business ventures for market demand, supply, and investment.

ESMD has identified partnership opportunities in the near, mid-, and far terms that show the most likely areas of commercial investment interest.

The U.K.'s experience in PPP includes about 700 contracts now under operation that altogether have raised £65 billion of private investment. Space PPPs include the U.K. military satellite communications programme Skynet, which have led to the successful launch of Skynet 5A and 5B using this model.

The lessons learned can be applied to NASA's relations with the U.S. space industry, for both established companies and new entrants, including space operators, launcher primes, spacecraft primes, component suppliers, research and development (R&D) specialists, lawyers, and financiers. The implications extend to international collaboration for space exploration programmes.

One method of working is for the U.K. to participate in NASA management seminars and workshops in which NASA's commercial development plans are promoted together with the lessons learned from the PPP experience. Content could include market development, product/service development, risk management, investment financing, contractual structures, governance, and the procurement process.

Another method is for the UK to support reviews of NASA's projects to maximize their commercial potential in line with the policy and to select projects of special commercial

interest and procurement treatment. Reviews could include business modelling, supplier strategy, procurement planning, and the approvals process.

In addition to ESMD, other NASA departments with a PPP interest would be the Innovative Partnerships Program, the Space Operations Mission Directorate, the Science Mission Directorate, the Office of Chief Financial Officer, the Office of Legislative and Intergovernmental Affairs, the Office of the General Counsel, and the Advisory Committee Management Division.

Benefits include more clarity on the roles of the two governments, prospects for U.S.-U.K. commercial collaboration and interoperability, and the application of PPP within the context of GES.

## **7. Other Areas of Potential Collaboration**

This section summarizes a number of other areas identified by the JWG as having potential for collaboration. In defining these areas, collaborations with high scientific value that also leveraged the particular strengths of both partners were selected. These include the following:

- In situ sample analysis and age dating
- Searching for terrestrial material on the Moon
- Atmospheric site-testing packages
- Rover design and autonomous systems
- MagEX—Examining Earth’s magnetosphere from the Moon

Some of these areas (MagEX and in situ sample analysis) are already the subject of collaboration between the U.S. and the U.K. through the NASA lunar sortie programme.

### **7.1 In Situ Sample Analysis and Age Dating—Lunar Sortie Proposal**

Lunar in Situ Sample Analysis would allow the geomorphology, geochemistry, and mineralogy of any site to be understood and hence would address a wide range of lunar science. A package of instruments can be developed around existing instrumentation and from those under development for future missions. In situ analysis has been proposed for lunar sortie missions where such a package could be used to investigate volatiles at polar sites (proposals of Gibson and Glavin). An offshoot of such a package is the ability to date samples in situ.

#### **In Situ Age Dating**

One of the highest-ranked science goals presented in the National Research Council’s report *The Scientific Context for Exploration of the Moon* is to establish a precise, absolute chronology for the lunar impact history. Since the bombardment history of the early inner solar system is uniquely revealed on the Moon, a well-calibrated lunar chronology would provide important and valuable constraints on models of the first few hundred million years of solar system history. A challenge in implementing this science goal for a diverse set of several key benchmark craters, young lava flows, and old impact basins during the early robotic precursor phase of lunar exploration (and to supplement

sites sampled by human missions) is to develop the technology to make these measurements in situ and to integrate that technology for use in robotic spacecraft.

The whole of planetary surface aging, with the exception of returned samples, relies on the lunar cratering rate and corrections to it depending on the location of the target within the solar system. This rate has been calibrated only over a narrow range of dates via the Apollo samples. To fully calibrate the rate, samples are required from young lavas on the Moon such as those in Procellarum. In situ dating would be a valuable tool for assessing the age of surfaces and interpreting the geomorphology of any site as a tool for initial dating of surfaces, e.g., on a robotic lander or in the screening of samples prior to returning with them. The Committee on Lunar and Planetary Exploration (COMPLEX) stated in 2006 that “COMPLEX recommends that studies of the feasibility of in-situ determination of rock ages should be pursued” (“Workshop on Surface Ages and Histories: Issues in Planetary Chronology,” JPL, May 21–23, 2006). In situ dating would not, however, supplant dating of samples in the laboratory in the short term, as any in situ techniques would be relatively crude compared to laboratory-based techniques such as U-Pb.

Various methods of in situ dating are possible, namely:

1. K-Ar, which would provide dates to billions of years with a likely accuracy at best of 15–20 percent (Talboys et al., 2007 paper in preparation).
2. Exposure age via measurements of isotopes such as neon ( $^{21}\text{Ne}$ ) useful for ages  $< 10^7$  years.
3. Ar-Ar dating. This technique requires neutron activation of the sample. This may be possible if either RTG or nuclear power sources are available on the mission.

The K-Ar dating instrument, which is perhaps the simplest option and certainly the one most developed, consists of separate instruments to measure K and  $^{40}\text{Ar}$ . There are several options for these instruments.  $^{40}\text{Ar}$  can be measured by various mass spectrometers, of which several have been developed around Europe for space applications. Beagle 2 aimed to exploit this technique on Mars using the x-ray spectrometer to measure the potassium content of rock samples and the Gas Analysis Package (GAP) to measure the argon content. To achieve the best accuracy then the K measurement should be integrated into the mass spectrometer system, which should include weighing the sample. Preliminary work in this area has been completed by Swindle et al. (2003) in the development of their AGE (Argon Geochronology Experiment) instrument, although this work has been focused on in situ dating on Mars. AGE is an argon geochronology experiment capable of analysing 12 samples with a mass of 5.7 kg power of 10-100W and a volume of 29 cm by 30 cm by 16 cm. This is almost identical to the accommodation requirements of the Beagle 2 GAP. Capabilities to build a dating experiment therefore exist on both the U.K. and U.S. sides, and having obtained a package with a mass spectrometer, exposure age dating is now also possible.

## In Situ Sample Analysis

It is essential to include instrumentation in the payload at any site to provide context for the samples that are dated. A high-quality imaging system is required. This could consist of panoramic cameras (with some multispectral imaging capability) and a close-up imager or microscope. The payload should also include instrumentation for mineralogical and geochemical analyses, e.g., an X-ray Diffraction Experiment and Mossbauer. A rock preparation and sampling tool is clearly essential to support the dating instruments. An age-dating package with or without the mineralogical experiments would also be able to identify minerals of interest to In Situ Resource Utilization (ISRU), such as ilmenite, which could be a source of oxygen.

Such a package can be used to investigate other science on the Moon such as volatiles; for example, the NASA SORTIE study by Everett Gibson of Johnson Space Center (JSC), an experiment that intends to use Beagle 2 instrumentation at the South Pole, would be capable of age-dating the regolith as well as studying any trapped volatiles. In situ analysis is required to avoid inadvertent contamination of samples with methane, hydrogen, and water that would be associated with engine exhaust, crew EVA suits, crew habitation, and the transfer of samples back to Earth for analysis. Therefore, the problem of collecting low-temperature volatiles needs to be addressed.

A package at the South Pole could address the following science and exploration questions:

- Solar wind species have been found on the Moon. What are other sources? Lunar or cometary? Where is the H, H<sub>2</sub>O, C, and N found?
- To support the U.S. Vision for Space Exploration, we need to “live off the land”. Are there amounts of lunar volatiles and water that would support human exploration and habitability?
- Is Moon geologically active?
- If volatiles exist, what are the absolute (K/Ar) and exposure (Ne isotopes) ages of lunar samples and sites?
- What is the geochemistry, mineralogy, and geomorphology of the area with the volatiles?
- Where are the volatiles? Look in permanently shadowed and subsurface sites.
- Is the Moon conducive to human life? How do the environment, atmosphere, and ionosphere vary?
- What is the evolutionary history of the Moon (including the atmosphere)?

A summary of the instrument package is given in the table below.

Sample acquisition is a key requirement for such a package; samples can be delivered robotically using a 5 Dof Arm or can be acquired via astronauts. Samples could be extracted via a simple corer, via an ultrasonic drill, or even subsurface via a Mole.

A package could be deployed in a variety of formats, e.g., on a fixed Lander, on a robotic rover, as a station deployed via EVA, or even inside a lunar laboratory. The following

table illustrates the development status based on the NASA definition of TRL and the use as is of Beagle 2 technology. Note that this would require modification for the lunar environment and so, for any lunar scenario, would need to drop at least 2 TRL levels.

Technology	TRL	Comments
Gas Analysis Package*	9	Based on Beagle 2 heritage.
X-ray spectrometer*	9	Separate unit needs to be integrated into sample processing system of GAP for accurate results.
X-ray diffraction	5	Under development for ExoMars. NASA Chemin experiment on MSL.
Mossbauer	9	Provided by Germany on Beagle 2. Could be provided by U.K.
Imaging systems	9	Panoramic, close-up imager and microscope may be needed depending on configuration.
Seismometer	5	Under development for ExoMars.
Heat flow using instrumented mole	5	Based on Beagle 2 heritage.
Water detection	2/3	Developments under way for Watsen sensor for ExoMars.

\* Minimum instrument complement required for in situ age dating.

## 7.2 Search for Terrestrial Material on the Moon

In an important paper, Armstrong et al. (2002) have suggested that the Moon may have collected meteorites blasted off the other terrestrial planets in the first billion years of solar system history. Such samples may preserve evidence of the early surface environments of those planets, which may not be preserved anywhere else. The recovery of such material would provide a hugely important window into the early history of the solar system, including possible information on the nature and prevalence of early life, which is unlikely to be obtained in any other way. It is fair to say that although Mars is currently the focus of attention with regard to the search for early signs of life outside Earth; the Moon may be the better place to search for the remains of both early Martian and early terrestrial life.

In order to assess the potential value of the lunar record in this respect, it is necessary to estimate the quantity of terrestrial (and other terrestrial planet) material expected to have landed on the Moon, demonstrate that some fraction of it would have survived the impact, and consider how we might identify such exotic materials on or below the lunar surface. Armstrong et al. estimate that the continual gardening of the regolith by meteorite impacts would ensure that some fraction of it is exposed at the lunar surface at any given time. For a well-mixed regolith, Armstrong et al. estimate that 200 kg/km<sup>2</sup> of

terrestrial material, mostly dating from 3.8–3.9 Gyr, should be exposed at the surface at the present time. As the Moon has no atmosphere to decelerate impacting meteorites, it is necessary to consider how much, if any, of this material would survive impact with the lunar surface in any recognizable form. Recent work in the U.K. (Crawford et al., 2007, *Astrobiology*, submitted) indicates that such survival is in fact quite likely, especially for low-velocity and/or oblique impacts.

### Locating Techniques

Locating terrestrial samples on the lunar surface would be challenging, but they are likely to have unique spectral properties that would cause them to stand out from the surrounding lunar materials. For example, hydrated silicates exhibit a strong absorption band at approximately 3  $\mu\text{m}$  and weaker bands at 1.4 and 1.9  $\mu\text{m}$ . Similarly, carbonates exhibit a characteristic series of sharp, narrow absorption features in the spectral region between 2 and 3  $\mu\text{m}$ . Lunar rocks are wholly devoid of water and carbonates, so any rocks found on the Moon with these spectral signatures would be good candidates for terrestrial meteorites. In this respect, we may draw a parallel with the now-routine collection of meteorites in Antarctica—just as there are places in Antarctica where any rock found on the surface is likely to be a meteorite, we can imagine scanning the lunar surface with infrared eyes sensitive to hydrated silicates such that every spot detected stands a good chance of being a terrestrial (or Martian) meteorite and thus deserving of more detailed analysis. It is certainly possible, in principle, to design a suitable infrared imaging system that could survey hundreds of square kilometres quite quickly and thus efficiently identify candidate terrestrial meteorites, or their breakdown products in the regolith, despite their expected rarity. However, it is true that in order to have survived intact to the present, macroscopic terrestrial meteorites would have to be buried to a sufficient depth to protect them from later impact erosion, possibly precluding their detection by remote sensing techniques. An alternative approach would be to sift through returned regolith samples in terrestrial laboratories, searching for finely comminuted (micron-scale) terrestrial fragments through their unique geochemical signatures. Clearly, this approach would require lunar sample return capabilities, ideally from regoliths of a wide range of ages.

Both partners have a strong academic and industrial base to develop the necessary remote sensing technologies, as well as experience in lunar sample analysis, which would permit laboratory-scale searches for terrestrial materials once additional lunar samples become available. With regard to the remote sensing approach, the key enabling technologies are summarized in the table below. Particular competencies in ruggedness, miniaturization, instrument engineering, and component technologies are seen as essential areas for further development. The area of infrared (IR) detectors and the associated multiplexing readout electronics is an area of strong U.S. leadership and capability (e.g., JPL). Optical design in the near to mid-IR bands is an area of U.K. capability with heritage in space instruments such as MIRI. Sophisticated data processing systems and techniques have significant heritage in both the U.S. and U.K.

Technology	TRL	Comments
IR detectors and front-end readout electronics	8–9	Mature technologies with flight qualification or heritage
IR optics and coatings	9	Mature technologies with flight qualification or heritage
Data processing	9	Mature technologies with flight qualification or heritage

### 7.3 Atmospheric Site Testing Package

Characterization of the lunar dust environment would be a necessary step in establishing experiment facilities on the Moon. There is strong evidence for the existence of dust above the lunar surface, probably extending to heights of many kilometres. Evidence first came from the unmanned Surveyor spacecraft, images from which seemed to show glows above the lunar horizon. This was confirmed by visual and photographic observations by astronauts on many of the Apollo missions. Current thinking is that electrostatic charging is responsible for the levitation of the dust (both from solar radiation on the day side and solar wind on the day and night sides). The dust has potential implications for almost any telescopic observations from the Moon’s surface and also for manned and unmanned operations on the lunar surface. This environment, as well as the meteoritic dust input to the Moon and the subsequent ejecta generated in the lunar surface, needs to be characterized. This can be done by remote sensing–type instruments (i.e., light scattered from an emitted beam of light or observation of a stellar source) or direct in situ measurements (or a combination of the two types). It would be essential to characterize this aspect in particular of the lunar environment (equivalent to terrestrial “site testing”) before any significant efforts are put into astronomical observations from the Moon. A further aspect of site testing is the characterization of the seismic environment. This can be achieved by the seismometer package as described previously.

Technology	TRL	Comments
Telescope	9	Instrument could be very “simple”—small aperture and image only. Many such instruments flown in space.
Nephelometer	9	Space heritage since Pioneer Venus probes (4 off).
Lidar	9	Space heritage through, e.g., ESA’s ADM-Aeolus and NASA’s MOLA.
Dust impact detector (piezoelectric, impact plasma and/or PVDF film)	9	Long space heritage, including HEOS-2, Helios, Pioneer 10, Pioneer 11, <u>Giotto</u> , and Galileo space missions, on the Earth-orbiting LDEF, <u>Eureca</u> , and Gorid satellites.
Quartz microbalance (for dust deposition measurement)	9	Deployed on several Space Shuttle flights for local environment characterization.

## 7.4 Rover Design and Associated Autonomous Systems

This section provides a brief review of U.K. capabilities in rovers and associated autonomous systems for space exploration missions along with a table that indicates U.K. areas of strength and capability and where potential joint development programmes could be established. This U.K. perspective has been derived from Astrium's experience in developing in-house expertise and procuring U.K. expertise for the ExoMars Rover Vehicle and its associated navigation system.

The U.K. has developed a large knowledge and experience base of in the areas of locomotion, including algorithms for traction control and novel chassis design; navigation; autonomous mobile science; and planetary protection. This latter field encompasses the most demanding standards of sterility and organic cleanliness through ESA's Planetary Protection Working Group. Another area of particular interest is the ground and atmospheric environment, as it is clearly a key component in exploration missions, particularly relating to how a rover operates and survives in the full range of conditions it would encounter. The U.K. has extensive knowledge of the characteristics of the Mars environment, which is essential to the development of a faithful model with which to generate scenery and other aspects of the Mars terrain. Areas of expertise encompass visual texture, features, rock distribution models, atmospheric optical effects, surface materials and properties, weather (including dust and electrostatic conditions) and solar irradiance.

Through STFC Collaborative Research in Exploration Systems and Technology (CREST) funding activities, breadboard systems that demonstrate new developments in robotic rover technology, particularly related to navigation algorithms, autonomous sample acquisition, autonomous science programming, and non-contact velocimetry using compact lasers. The 'Bridget' Rover development programme continues, being used in the CREST activities as well as being a test-bed for early developments of on-board control and on-board data processing technologies in support of the ExoMars programme. Astrium is experienced in the logistical, programmatic, and technical aspects of conducting field trials overseas in simulated Mars conditions and has developed goodwill with support organizations and agencies able to provide the required facilities.

The table below identifies U.K. strengths and possible joint development programmes. The current position on collaborating with NASA on rovers is understood to be that NASA would not wish to collaborate internationally on rovers (e.g., MSL). Should this change, then the strongest advantages that the U.K. has are a) planetary protection for astrobiological robotic missions and b) vision-based navigation.

Technology	TRL	Comments
Locomotion including wheel-soil interactions, traction control, chassis design	4–5	ExoMars heritage; Reading already working with JPL on novel chassis design
Navigation and autonomous operations	4–5	ExoMars
Planetary protection measures	N/A	Beagle 2 and ExoMars
Environmental simulation	N/A	
Ground simulation	N/A	Indoor Mars Yard surface simulation built at UWA
Small robotic manipulator arm	6	Heritage from Beagle 2, ExoMars
Rover design, manufacture, integration, and testing	N/A	ExoMars
Microrobot vehicles	2–3	Proof of concept development
Stereo camera systems	8	Beagle 2, ExoMars (PanCam)

### 7.5 MagEX—Examining Earth’s Magnetosphere from the Moon—Lunar Sortie Proposal

Microchannel plate optics as used on the Bepi-Columbo MIXS experiment can be used to construct an innovative telescope that could one day be deployed on the surface of the Moon. The proposed telescope design is called MagEX, which stands for “MagEX” and is the subject of an international collaboration between scientists from the United States, the Czech Republic, and the U.K. This is another of the *Lunar Sortie* proposals; it is led by Collier of Goddard Space Flight Center (GSFC) and includes a U.K. contribution from the University of Leicester (Dr. S. Sembay).

MagEX would study the magnetosheath, the magnetic shield that protects Earth from the solar wind—the high-energy particles that continuously flow out from the Sun. Without this shield, life on Earth as we know it could not exist. The MagEX telescope is quite compact, being less than one metre tall. It is designed to be placed on the lunar surface, facing back towards Earth. The Moon is the ideal location for measuring the x-ray emission of the magnetosheath.

Looking from the Moon, Earth's magnetosheath covers an area about 30 degrees across on the sky. The magnetosheath glows as solar wind particles strike gas trapped within the region; however, the glow is not in visible light but in x rays. MagEX would be unique in that it would be able to view our Earth's entire magnetosheath for the first time. The magnetosheath is not static, but contracts and expands quite dramatically as the solar wind pressure changes during solar storms. It would provide a global monitoring

capability for Earth's magnetosphere that would supplement information collected from spacecraft such as Cluster.

The primary science goal of MagEX would be to study soft x-ray emission from the Solar Wind Charge Exchange (SWCX) process that occurs between the solar wind and geocoronal neutrals that are concentrated in Earth's magnetosheath. This would provide a unique three-dimensional view of the dynamic interaction of the solar wind and Earth's magnetic field. In addition, the telescope would simultaneously observe the interaction of the solar wind with the tenuous lunar atmosphere.

The MagEX concept combines a compact wide field-of-view microchannel plate optic with a CCD detector system to provide imaging capability with good spectral resolution. The total mass of the instrument would be less than 40 kg and would require 20 to 30 W of power, depending on whether the instrument requires an independent power source or is combined with that of another project. The telescope is envisaged as a low-cost, low-mass addition to some larger lunar science package. The project web site is <http://www.src.le.ac.uk/projects/magex/>.

Technology	TRL	Comments
Micro-channel plate optics	4-5	Developments from BepiColombo, imaging XRF, and WFXT
Charge Coupled Detectors	9	Require repackaging for Mission
Data Processing Electronics	9	Extensive capability in both U.K. and U.S.

## 7.6 Lunar Drilling

Deep robotic drilling provides the opportunity for low cost, sub-surface exploration at depths from tens of metres to, ultimately, kilometres. It requires technical developments in telerobotics i.e., near real-time control, together with developments in operational procedures suitable for the lunar environment.

Scientists are interested in the variation of lunar crust composition with depth, the extension to and validation of remote measurements, better temperature gradients, etc. For example, the uppermost regolith contains a record of events from 3 to 4.5 billion years ago, such as solar wind, early terrestrial capture, nearby supernova explosions, and other galactic events. Of special interest is a potential ancient palaeoregolith preserved between protective basalt layers.

By learning what the mineral composition is during the 2010 decade, both within and below the regolith, exploitation for energy and other uses can be predictably planned, and manned missions during the 2020 decade can be designed to include specific mineral extraction aims and techniques that would not be justified without that prior knowledge. This could lead to an economic case for drilling based on operating the eventual permanent base at a lower cost.

Formulating detailed mission requirements and plans requires a systems development approach in the following technical areas: autonomy regime; instrumentation; sample handling; analysis and storage; bore structure; bit design; casing; mechanics of surface operations; residue disposal; guidance; power source and control; environmental variation and survivability; telemetry transmission; contamination; materials; number of holes; and sensors and radiation. The MoonLITE and other missions could provide data to assist drilling site selection and operational profiles.

Additional terrestrial benefits derive from the synergies with the Oil and Gas industry which is interested in low cost telerobotic drilling in inhospitable locations such as hard cold and ice terrains; soft marshy terrains; forests and jungle; and underwater.

## **8 Conclusions and Final Recommendations**

The NASA-BNSC JWG has identified the MoonLITE as the primary mission for potential cooperation. The U.K.-led MoonLITE is an ambitious mission that would allow the first flight demonstration and validation of key technologies, such as navigation and communications capabilities, needed for future human lunar exploration. The MoonLITE also would carry out high profile lunar science to complement current and future missions such as NASA's LRO. By carrying out this programme, the MoonLITE is able to harness the collective knowledge and innovative thinking of both partners, resulting in a trail blazing programme that would lead to a visible and incremental increase of the capabilities required to develop a long term exploration strategy. Beyond the immediate scientific return, the MoonLITE also would advance the U.K.'s lead in small satellites and develop capabilities needed for the exploration of the Moon, Mars, and beyond, as well as lead to possible involvement in the lunar outpost programme.

In addition to cooperation on the MoonLITE in the near term, the JWG outlines a long-term plan for joint U.S. and U.K. continued examination of overall science and technology needs for mid-term robotic and human lunar exploration activities.

The MoonLITE would be an inspirational programme that would demonstrate scientific and technical leadership. And with the programme's rapid mission turnaround, the MoonLITE would provide a dynamic environment in which engineers and scientists can experience the full development lifecycle of a space project on a tractable timescale, thus providing much needed training opportunities for the next generation of space specialists.

### **Recommendations**

The working group recommends a range of supporting actions to build a strategic partnership. These actions include the following:

- Establishing a formal joint U.S./U.K. MoonLITE JPT. This team would further refine the science goals of the mission and oversee the process of instrument selection with the goal of ensuring the successful MoonLITE implementation. The JPT also would be tasked with building the U.S. and U.K. scientific communities through a series of workshops in coordination with meetings, such as those of the Lunar Exploration Analysis Group and the International Space Exploration

Coordination Group (ISECG)<sup>2</sup>. This team would further advance the mission concepts, initially as part of a Phase A mission study. The team also would oversee the technology roadmap activities and coordinate and harmonize the development plans for the areas identified in the report as having a low level of technology readiness. This would ensure the adoption of the most cost effective route to flight and mitigate any development risks. Team members would be drawn from the BNSC, the NASA Science, Exploration Systems, and Space Operations Mission Directorates, and the scientific communities of both partners.

- A nine month Phase A activity should be initiated in early 2008 to further refine the mission architecture and develop a robust cost to completion. The output of the Phase would be a detailed description of the mission, including roles and responsibilities and an assessment of the programmatic risk. The Phase A activity would be concluded with an independent review by NASA and BNSC experts to assess the mission programmatic. This is seen as a necessary step to any formal implementation of the mission by both partners. The Phase A activity would also identify any technology developments on the critical path and recommend early NASA and BNSC activities required to bring these to sufficient maturity.
- A joint workshop should be held during the spring or summer of 2008 to build the scientific communities of both partners. The workshop activities would be coordinated by the JPT. The workshop should produce a joint report on the lunar science of the MoonLITE and further possibilities for lunar exploration using small satellites.
- The JPT would continue to examine the other areas for potential longer term NASA-BNSC lunar cooperation in areas such as in-situ sample; analysis and age dating; searching for terrestrial material on the moon; atmospheric site testing packages; rover design and autonomous systems; MagEX; and lunar drilling based on synergies with the Oil and Gas industry.
- Other existing exploration activities, such as the U.K.'s leadership of the ExoMars rover could also feed into the joint programme. Export control issues would have to be addressed, but these issues may be assisted by bilateral arrangements currently being pursued at a Government to Government level and through the adoption of clean interfaces in the MoonLITE mission.
- The U.K. should provide support to a NASA management seminar, which combines an exposition of the strategy with the lessons learned from the PPP experience and subsequent assistance to NASA in the selection of future large scale transportation projects to maximize their commercial potential in line with the strategy is also envisaged.

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<sup>2</sup> International Space Exploration Coordination Group is a voluntary, non-binding international coordination mechanism for the exchange of information and plans in the field of space exploration. It was formally established in November 2007 as one element of the Global Exploration Strategy.

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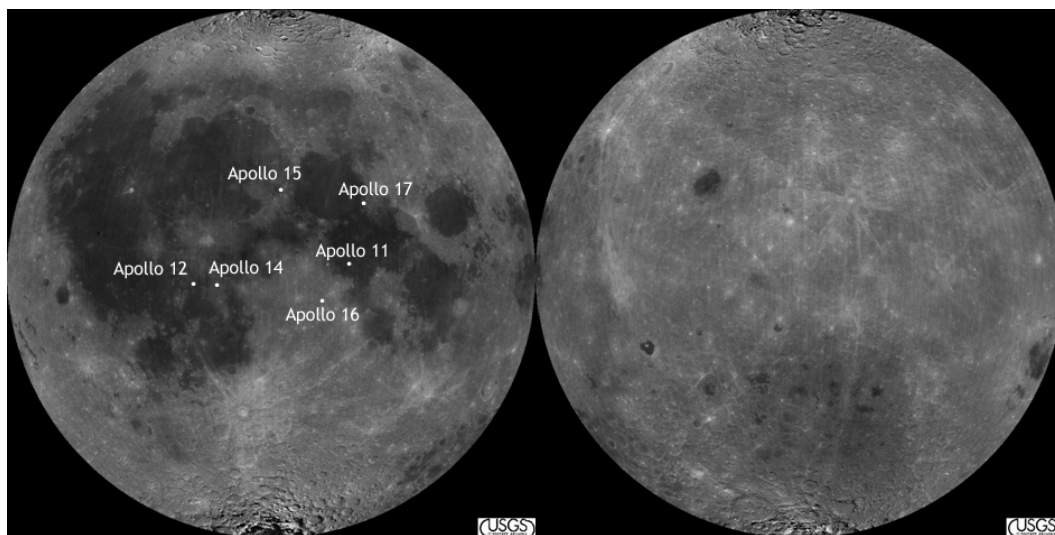
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## APPENDIX I

### MoonLITE Science Case

The principal scientific importance of the Moon is as a recorder of geological processes active in the early history of terrestrial planets (e.g., planetary differentiation, magma ocean formation and evolution, etc.) and of the near-Earth cosmic environment (e.g., bombardment history, solar wind flux and composition, etc.) throughout solar system history (e.g., Spudis 1996, Crawford 2004, NRC 2007). Some of these objectives are astrobiological in nature, in that they would enhance our understanding of the cosmic conditions under which life first arose on Earth (Crawford 2006). However, although the Clementine and Lunar Prospector missions have in recent years greatly added to our knowledge of the geochemical and mineralogical makeup of the lunar surface, our knowledge of the interior still largely relies on geophysical measurements made during the Apollo programme. As can be seen from figure 1, these landing sites are all located at low to mid-latitudes close to the centre of the lunar nearside, and were thus unable to provide anything approaching global coverage. To build on the Apollo data and advance our knowledge of lunar science, the MoonLITE mission would fly about 4 penetrators to the Moon for the purpose of conducting a range of in situ geophysical and geochemical measurements at widely separated localities. The top level science objectives here mirror very nicely top lunar science goals called out in the National Research Council's report "The Scientific Context for Exploration of the Moon".



*Figure 1. Locations of the Apollo landing sites on the nearside of the Moon (left); the farside is at right. The Apollo seismic network occupied an approximate equilateral triangle, roughly 1200 km on a side, defined by the Apollo 15 site at the northern apex, Apollos 12 and 14 (close together at the SW apex), and Apollo 16 at the SE apex. The two Apollo heat-flow measurements were made at the Apollo 15 and 17 sites. No long-term*

*geophysical measurements were made at the Apollo 11 site. Note the geographically restricted nature of these measurements.*

The top-level science objectives for the MoonLITE fall into the following four categories: seismology, heat-flow, geochemical analysis, and polar volatile detection. We now address these three objectives in more detail.

### **Lunar seismology**

Seismology is the most powerful geophysical tool available to us for determining the interior structure of a planetary body. However, to-date the only object, other than Earth, where it has been successfully applied is the Moon, where the Apollo missions deployed a network of four highly sensitive seismometers close to the centre of the nearside. The Apollo seismometers remained active for up to eight years and provided important information on the Moon's natural seismic activity and the structure of the lunar crust and upper mantle (see Goins et al. 1981 and Lognonné 2005 for reviews). However, the deep interior of the Moon was only very loosely constrained by the Apollo seismology—even the existence, disregarding the physical state and composition, of a lunar core remains uncertain.

The main problem was that the Apollo seismometers were deployed in a geographically limited triangular network (between Apollos 12/14, 15, and 16; see figure 1) on the nearside. As a consequence, the information obtained on crustal thickness and upper mantle structure only refers to the central nearside and may not be globally representative. Moreover, seismic waves capable of probing the deep interior had to originate close to the centre of the farside, and were therefore limited to rare, relatively strong, events. Indeed, the tentative seismic evidence for a lunar core arises from the analysis of just one farside meteorite impact that was sufficiently strong to be detected by more than one nearside Apollo seismic station in eight years of operation. This is clearly an unsatisfactory state of affairs, and there is a pressing need for a much more widely-spaced network of lunar seismic stations, including stations at high latitudes and on the farside. Penetrators delivered from orbit are ideally suited as a means of emplacing a global seismometer network, which would address the following scientific questions:

### **Size and physical state of lunar core**

Because the Apollo seismic data were unable to constrain the size or physical state of the lunar core, the knowledge we have has been obtained from studies of the Moon's moment of inertia, physical librations (as determined by laser reflector measurements), and electromagnetic induction studies (see Wiczorek et al. 2006 for a review). These studies favour a small ( $R < 400$  km) partially liquid core, with suggested compositions ranging from iron-nickel, Fe-FeS alloy, or molten silicates. Whether this liquid core possesses a solid inner core is currently unknown. Information on the size, composition, and physical state of a lunar core would have profound impacts on our understanding of the Moon's origin, mantle evolution, and magnetic history. The latter point, when combined with studies of remnant magnetization of surface rocks, would have important

implications for our understanding of the origin and evolution of planetary magnetic fields. For these reasons, constraining the nature (and even the existence) of a lunar core is the top scientific priority of the penetrator-deployed seismic network.

### **Deep structure of the lunar mantle**

One of the general main contributions that lunar science can make to planetary science is an enhanced understanding of the internal differentiation processes that occur immediately after the accretion of a terrestrial planet. Magma oceans are likely to have been a common phase in the early evolution of all rocky planets, and, in contrast to the more evolved mantles of the larger terrestrial planets, the structure of the lunar mantle may preserve a record of these early times. Seismology may help elucidate these processes in several ways.

Most fundamentally, seismology may determine the initial depth of the magma ocean, thus determining the fraction of the Moon's volume that was initially molten. The Apollo data appear to indicate a seismic discontinuity at a depth of about 550 km, which is sometimes interpreted as the base of the magma ocean (see review by Wieczorek et al. 2006). However, because of the placement of the Apollo seismometers, it is not currently known whether this discontinuity is global in extent or exists only under the nearside. A competing explanation is that it represents the depth to which later partial melting has occurred which led to the formation of the nearside mare basalts. As noted by Wieczorek et al. (2006), determining between these two possibilities is of key importance in understanding lunar mantle evolution.

In addition, measurements of seismic wave speed as a function of depth help constrain the mineralogy of the mantle (e.g. Lognonné et al., 2003). This may be used to constrain both the bulk composition of the Moon (and its origin), and the crystallization history of the lunar mantle and its implications for magma ocean evolution. Again, new, more widely spaced seismic data are now required to make new advances beyond what has been learned from the Apollo data.

### **Thickness of the farside lunar crust**

Reinterpretations of the Apollo seismic data have now constrained the thickness of the nearside anorthositic crust to about 30–40 km (Khan et al. 2002, Lognonné et al. 2003, Wieczorek et al. 2006). However, the thickness of the farside crust has not been constrained seismically. Estimates based on gravity data are typically in the range from 70 km to 90 km (Wieczorek et al. 2006), but these are non-unique and depend on whether the lunar highland crust should be considered as a single anorthositic layer or as two layers with the lower layer having a more mafic (Fe-rich) composition. Farside measurements are required to determine the average lunar crustal thickness, which, because of its very aluminium-rich nature, has significant implications for understanding the bulk composition (and thus origin) of the Moon.

In addition, there is considerable interest in the thickness of the crust (if any) remaining under the giant South Pole-Aitken (SPA) impact basin on the farside—the largest impact structure currently known in the solar system. Together with the nearside Procellarum [potassium](#), [rare earth elements](#), and [phosphorous](#) (KREEP) Terrain on the nearside (well studied by Apollo) and the farside highlands, the floor of the SPA forms one of the three main lunar terrains identified by Jolliff et al. (2000). The SPA may have exposed lower crustal or upper mantle materials. Seismometers located within the SPA would, for the first time, make a definitive measurement of the crustal thickness remaining under this important structure.

### **Studies of natural moonquakes**

The Apollo seismometers detected four types of natural moonquake: 1) deep (700–1200 km), relatively weak, moonquakes which occur in “nests” and appear to have a tidal origin; 2) shallow (5–200 km), relatively strong, moonquakes of unknown origin; 3) thermal moonquakes due to thermal stresses in the near surface; and 4) meteorite impacts (summarized by Vaniman et al. 1991). Of these, numbers 1, 2, and 4 may be used as sources of seismic energy to probe the lunar interior. A better understanding of the causes and clustering of moonquake number 1 would provide additional knowledge of the physical properties of the deep lunar interior.

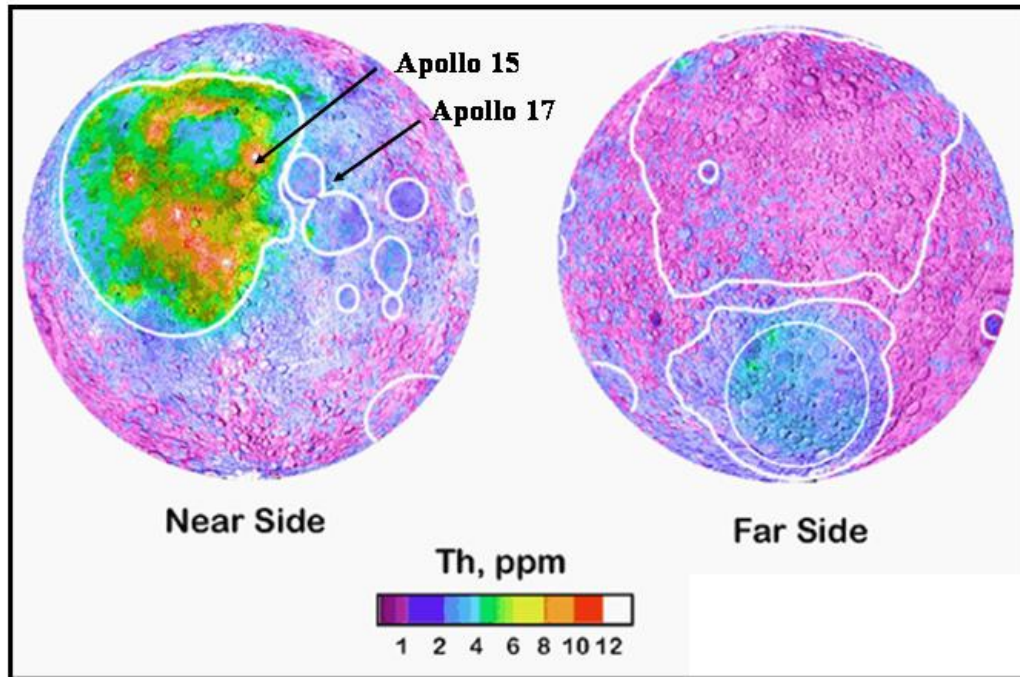
The shallow moonquakes (number 2) are probably the most interesting scientifically. These were the strongest (up to magnitude 5) and most rare (only 28 recorded in 8 years), and currently their cause is unknown. Concerning these unknown tectonic processes, our knowledge of present-day lunar geological activity would remain incomplete until their cause and locations can be identified (e.g., Nakamura 1979). Due to the spatially restricted locations of the Apollo seismic stations, the Apollo data lacks the resolution to pinpoint the precise epicentres or depths of these events, and a global distribution of seismometers would be required.

Understanding these events is also important in the context of future lunar exploration. For example, a magnitude 4–5 moonquake is sufficiently strong, and it would be prudent not to construct a lunar base at localities where they are likely to occur (Neal 2005). Some scenarios for future lunar exploration also envisage placing optical astronomical instruments on the lunar surface, and knowledge of lunar seismicity could be useful in deciding where to site such instruments. Thus, in addition to providing fundamental information about lunar geophysics, a better understanding of the origins and locations of shallow moonquakes would make a significant contribution to future lunar exploration.

### **Lunar heat-flow**

Measurements of surface heat-flow provide valuable constraints on the composition and thermal evolution of planetary interiors. To date, the only planetary body other than Earth for which surface heat-flow has been measured in situ is the Moon, during the Apollo 15 and 17 missions (Langseth et al. 1976). However, both these measurements were relatively close together on the nearside (figure 1) and may thus not be representative of

the lunar heat-flow as a whole. Moreover, both these Apollo measurements have been subject to a great number of re-interpretations due to uncertainties in determining the thermal conductivity of the regolith, the extent to which the temperature sensors were in contact with the regolith, and the uncertain effects of local topography (both measurements were very close to highland/mare boundaries).



*Figure 2. Concentrations of Th in the lunar surface, measured by the Lunar Prospector spacecraft. The PKT is the region of high Th concentrations around and to the south of the Imbrium basin on the nearside.*

One important measurement would be to determine the heat-flow as a function of distance from the Procellarum KREEP Terrain on the north-western part of the lunar nearside. Remote sensing measurements have determined that the heat-generating elements (U, Th, K) are concentrated at the surface in this area of the Moon (figure 2); but a question remains over whether this is a surficial effect (owing to excavation of a global underlying layer of incompatible element-rich material by the Imbrium impact), or whether these elements are concentrated in the mantle below the Procellarum KREEP Terrain. The latter scenario would predict a much higher heat-flow in the Procellarum KREEP Terrain than elsewhere, and it would have major implications for our understanding of the early differentiation and crystallization of the Moon (e.g., Wieczorek and Phillips 2000). While the Apollo 15 and 17 data appear to indicate a decrease in heat-flow away from the Procellarum KREEP Terrain ( $21 \pm 3$  and  $16 \pm 2$   $\text{mW/m}^2$ , respectively; Langseth et al. 1976), the experimental uncertainties are such that

it is far from clear that this trend is statistically significant. In addition, Hagermann and Tanaka (2006) have drawn attention to fact that the Apollo results may simply reflect the different thicknesses of (U, Th, K-rich) Imbrium ejecta at the two Apollo sites, and not the underlying mantle heat-flow.

For all these reasons, there is a pressing need to extend these measurements to new localities far from the Apollo landing sites (e.g., the Polar Regions and the farside highlands). Such measurements would greatly aid in constraining models of lunar thermal evolution. Finally, we note that in situ measurements of both the temperature and thermal conductivity of the regolith in permanently shadowed polar regions (inherent in any heat-flow measurement) would be valuable in constraining the possibilities for frozen volatiles, which are another of our key scientific objectives (see below). Penetrator deployment of a global heat-flow network would be an attractive means of achieving these objectives.

### **In situ geochemistry**

The only places on the Moon from which samples have been collected in situ are the six Apollo landing sites (figure 1) and the three Russian Luna sample return missions from near the Crisium basin on the eastern limb of the nearside. No samples have been returned from the Polar Regions or the farside, greatly limiting our knowledge of lunar geological processes. Although, statistically, many of the 50-odd lunar meteorites must be derived from these unsampled regions, the provenance, and thus geological context, of any given meteorite is unknown, which limits their value in interpreting lunar geology.

Although sample return missions to currently unsampled regions would be the preferred means of furthering our knowledge of lunar geological diversity, this may not be practical in the short term. An alternative would be to make in situ geochemical measurements of at least the abundances of the major rock-forming elements (e.g., Mg; Al; Si; Ca; Fe and Ti). In principle this could be achieved by X-ray fluorescence spectroscopy, using instruments like the X-ray Spectrometer (XRS) designed for Beagle2 (Sims et al. 1999). Penetrator-deployed XRS devices therefore have the potential to determine the composition of lunar materials in regions remote from areas sampled to-date. In addition to teaching us much about the geology of the particular sites visited, such measurements would provide additional “ground truth” for the calibration of remote-sensing instruments on forthcoming lunar orbital missions (e.g., Chandrayaan-1, SELENE, and LRO).

### **Polar volatiles**

As is well known, the Lunar Prospector neutron spectrometer found evidence for enhanced concentrations of hydrogen at the lunar poles, which has been widely interpreted as indicating the presence of water ice in the floors of permanently shadowed polar craters (Feldman et al. 1998). This potentially very important result is still awaiting confirmation; but if water ice is present, it is most likely derived from the impacts of comets with the lunar surface (although solar wind implantation and endogenic sources

might also contribute). The confirmation of water ice (and other volatiles) would be important for at least the following three reasons:

1) Even though the original cometary volatiles would have been considerably reworked by impact vaporization, migration to the poles, and subsequent condensation, it remains possible that some information concerning the composition of the original sources would remain. Among other things, this may yield astrobiologically important knowledge on the role of comets in “seeding” the terrestrial planets with volatiles and pre-biotic organic materials (eg., Chyba & Sagan 1992, Pierazzo & Chyba 1999).

2) As pointed out by Lucey (2000), lunar polar ice deposits may be of considerable astrobiological interest even if they do not preserve any vestigial information concerning their cometary sources. This is because any such ices would have been continuously subject to irradiation by galactic cosmic rays and may be expected to undergo “Urey-Miller-like” organic synthesis reactions. Analogous reactions may be important for producing organic molecules in the icy mantles of interstellar dust grains, and on the surfaces of outer solar system satellites and comets, but the lunar poles are more accessible than any of these other locations.

3) The presence of water ice at the lunar poles would be a valuable resource in the context of future human exploration of the Moon (as a potential source of oxygen, rocket fuel, and drinking water). Confirmation of its presence would make a significant contribution to the developing Global Exploration Strategy, a strategy that has renewed human exploration of the Moon as a key element.

We consider that volatile detectors, deployed on penetrators and landed within permanently shadowed craters, would be a powerful and economical means of determining whether scientifically and operationally valuable deposits of volatiles exist at the lunar poles.

## **Conclusion**

By deploying a range of instruments (e.g., seismometers, heat-flow probes, X-ray spectrometers, and volatile detectors) to diverse locations on the Moon from which geochemical and geophysical measurements have not yet been obtained (including the poles and the farside), the MoonLITE penetrators have the potential to make major contributions to lunar science. At the same time, they would provide knowledge (e.g., of lunar seismicity and polar volatile concentrations) that would be of central importance in the planning of future human missions to the Moon, and would also demonstrate a technology that would have wide applications for the exploration of other airless bodies throughout the solar system.

## APPENDIX II

### Mission Overview

The basic straw-man mission profile assumes direct injection of the spacecraft into Geostationary Transfer Orbit (GTO) by the PSLV-XL launch vehicle. The spacecraft propulsion system then performs the Trans-Lunar Injection (TLI) manoeuvre to enter a lunar transfer orbit through a series of phasing orbits. On arrival at the Moon, several additional manoeuvres are performed to capture into lunar orbit and circularize the orbit at 100 km ready for penetrator deployment. It is currently assumed that the orbiter shall raise its orbit to a stable 250 km after the deployment for data relay and navigation/communications payload demonstration. Figure 1 is an early concept showing the accommodation of four penetrators on the spacecraft.

Several options are possible for the mission level architecture; however an attractive option from the point of view of cost and simplicity is to reuse the U.K.-developed Mars Express propulsion module (figure 2). This module is a highly efficient bi-propellant system with a proven flight heritage that has been optimized for high performance and low cost, but with minimal mass—an important factor in a very aggressive margin philosophy.

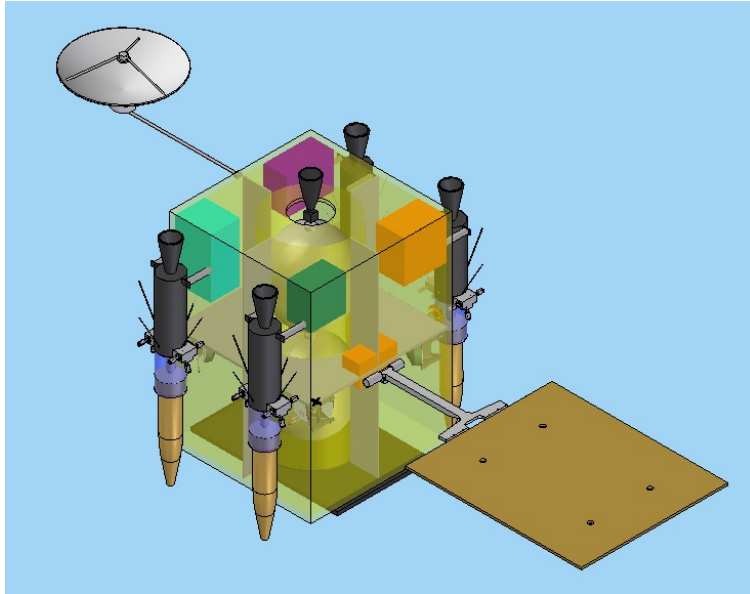
In the straw man profile, the spacecraft dry mass derived from this approach is 434 kg (structure, propulsion, and avionics) with further reductions in mass resulting from the development of SSTL avionics and other spacecraft systems. The payload mass delivered to lunar orbit would include the following:

- 3 x Penetrators (with mass of 52 kg each)
- 40-55 kg range for the Navigation/Communication payload

As a result, the total spacecraft launch mass is 1155 kg. This is compatible with the PSLV-XL which can deliver approximately 1200 kg directly into GTO.

Some additional areas to investigate to further increase the payload mass are as follows:

- Modify the transfer to deliver the spacecraft to a sub-GTO type orbit, as this can be slightly more efficient than starting in a standard GTO orbit. This may require variations in the on-board propulsion system described above.
- Reduce penetrator mass.
- Reduce spacecraft redundancy (currently all units are dual redundant).
- Review of other staging options e.g., Dnepr launch with a Lisa Pathfinder propulsion module or solid rocket boosters but at increased cost.



*Figure 1. Early concept rendering of a lunar orbiter illustrating accommodation of four penetrators*



**Figure 2. MeX propulsion system and mechanical structure**

### **MoonLITE orbiter concept**

The primary function of the orbiter platform is to deliver the surface penetrators into suitable lunar deployment orbits and support the payload which provides the surface assets with communications and navigation capabilities. The platform would consist of a large, high thrust propulsion system and associated support structure. Since no commercially developed systems currently exists that exactly match the mission

requirements, although there is a heritage in the U.K. for interplanetary propulsion systems (described above), internal development and/or collaboration is required in this area and would be a key element of any joint programme. The avionics architecture of the spacecraft is based on units with extensive flight heritage. Power for the spacecraft is supplied via a single solar array.

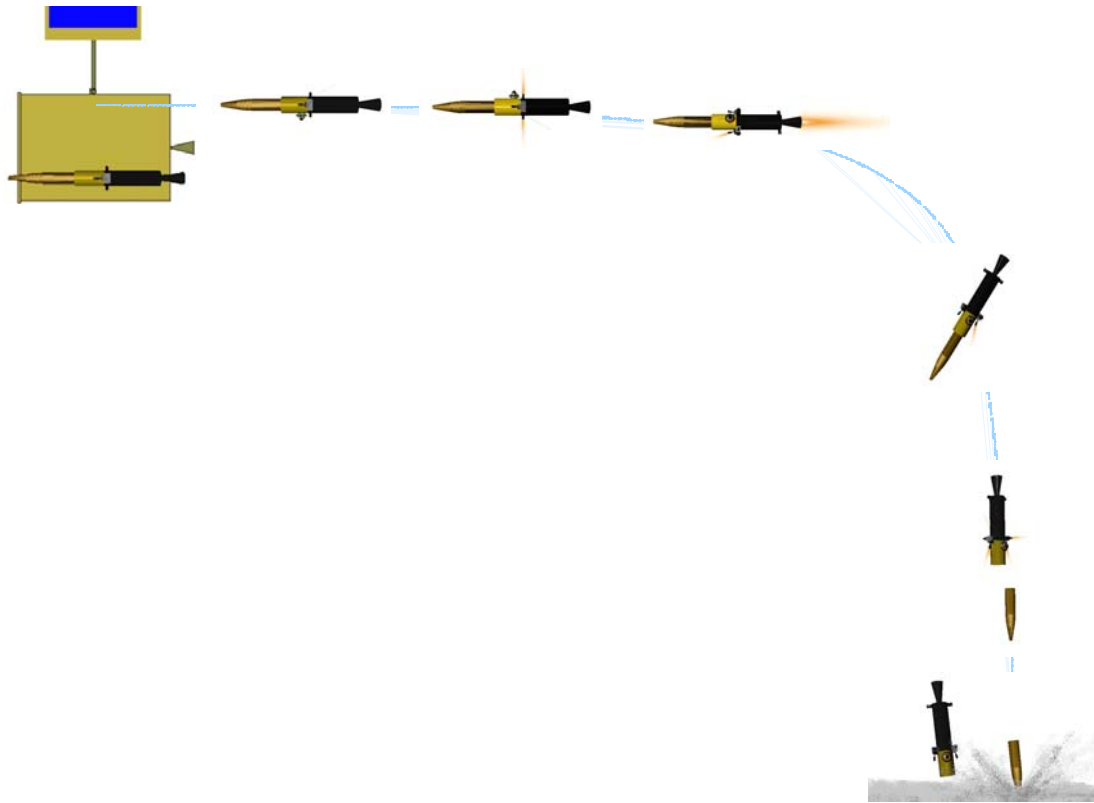
The payload is a key technology required to establish a navigation and communications network around the moon. This payload must be developed for this mission either within the U.K. or U.S. where the required expertise exists.

### **Communications (area identified as significant U.S. interest based on MiniSAR)**

The payload would handle the communications relay from the Moons' surface, store the data on board the payload, and transmit back to an Earth ground station. The Tracking, telemetry, and telecommand aspects of the communications were studied, along with the ranging requirement. The equipment baselined for the orbiter communications system with the ground station is a 4 kg (European technology) S-Band ranging transponder with a radio frequency output of 5W. This S-band system is designed to provide telemetry, telecommand, and ranging functions compatible with NASA/ESA ground stations and most commercial ground stations. The transponder has proven heritage from previous missions. It would be operated at nominal data rates used for telecommand and telemetry. The transponder design supports the following functions; demodulate uplink-ranging modulation and demodulate signals on the downlink. An S-band patch antenna facilitates uplink and downlink communications with hemispherical coverage. The downlink can be modulated from 200 bps to 3 kbps in a standard format (BPSK/QPSK) to a 9 m ground station. The uplink rate would be from 500 bps to 2 kbps. The data rates provided are typical to obtain the reasonable link margin to command the spacecraft during the mission. When the spacecraft is out of sight, the requirement is to store data and then download it whilst in sight of a ground station.

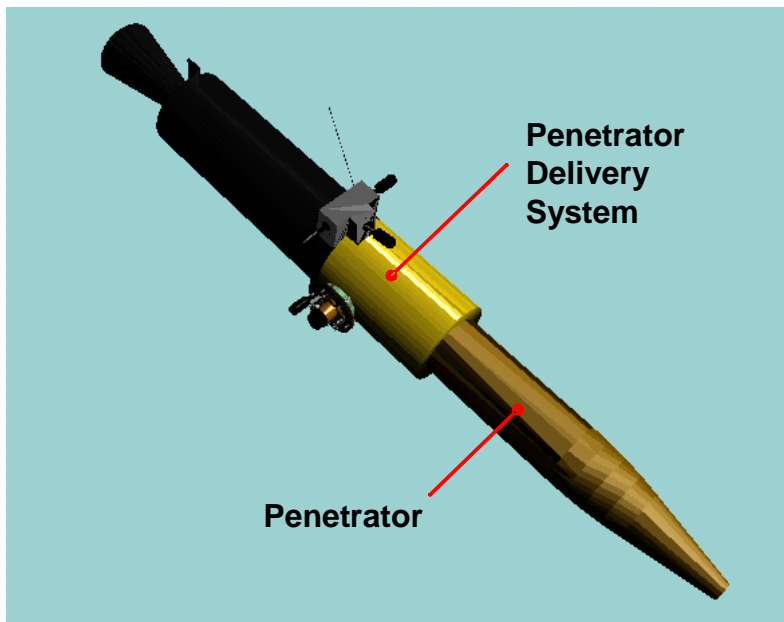
### **Penetrator Delivery System**

Penetrators are missile shaped impactors that embed themselves into the lunar regolith. The Penetrator Delivery System (PDS) delivers the impactors to the lunar surface at the correct velocity and impact angle. The deployment of surface elements requires a low orbit to reduce the PDS propulsion system propellant requirements, reduce the de-orbit delta-V, and minimize the landing site positional errors. Initially, the orbiter would have to enter a 100 km altitude circular orbit, lowering the periapsis to just 40km for deployment of the PDS. After deployment of all the penetrators, the orbiter may have to manoeuvre to a higher orbit to improve surface visibility and increase long term orbit stability. The PDS would be released from the orbiter into the 100x40km altitude orbit. After separation, the PDS would spin up before firing its solid rocket motor to cancel its orbital velocity. The burn equates to  $\Delta V$  of approximately 1700m/s.



***Figure 3. Penetrator deployment sequence***

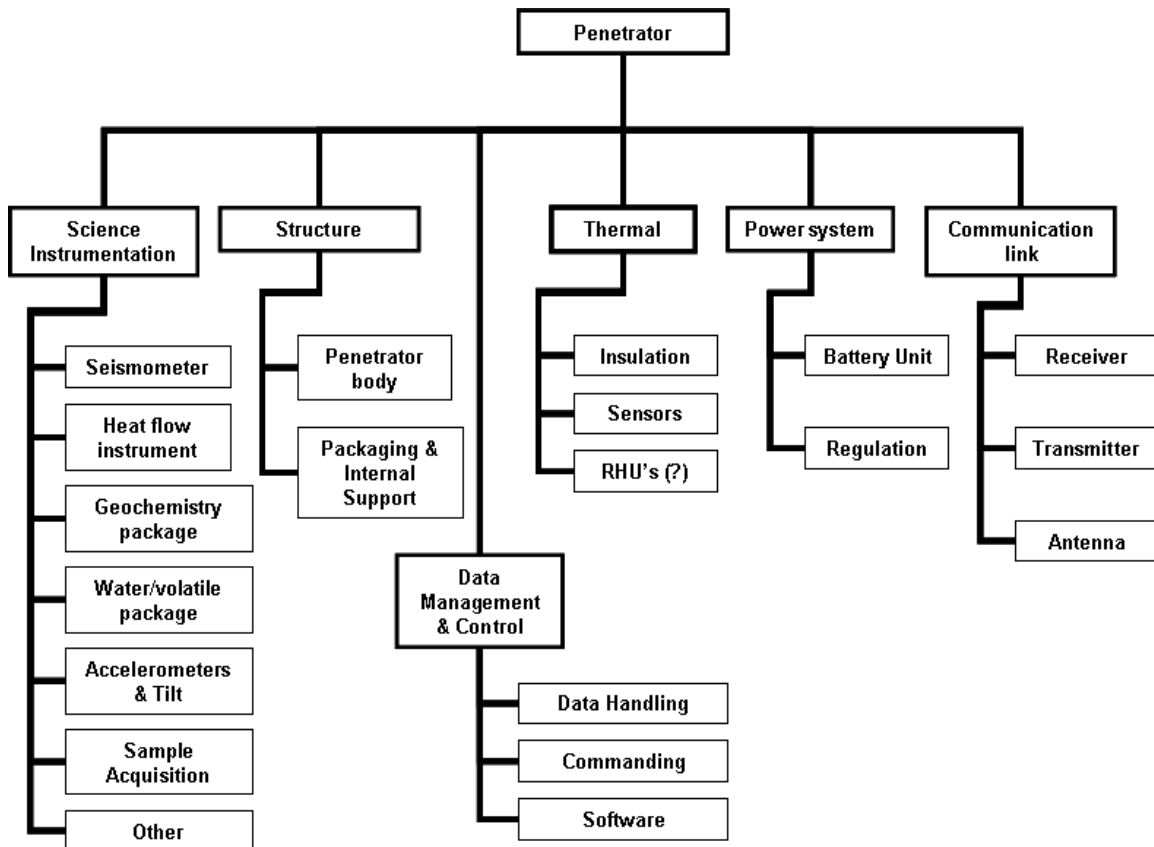
After completing the deceleration manoeuvre, the PDS begins a free fall lasting approximately 3.5 minutes. During this time, the PDS realigns its body axis to the velocity vector to ensure a near vertical impact of the penetrator into the lunar surface. Moments before surface impact, the PDS shall separate from the penetrator to avoid interfering with it during impact. The final impact velocity of the penetrator would be about 350 m/s. Figure 4 shows the orbital components for the PDS deployment.



*Figure 4. Preliminary Penetrator Delivery System (PDS) concept*

### **APPENDIX III**

#### **Penetrator Product Tree**



## APPENDIX IV

### Penetrator instrumentation

Below is a summary of the instrumentation identified to address the scientific areas of the MoonLITE mission. Each penetrator consists of a highly integrated scientific payload and support systems (e.g., power, data management, etc.). During the descent phase, a camera is used to provide impact site location and context information. The exact payload composition would be subject to a detailed Phase A study; and should the mission be implemented, the Joint Science team would carry out instrument selection.

### Accelerometer/tilt assembly

The accelerometry has a high level of TRL 8 due to its commercial availability as a COTS part available from companies including Endevco (e.g., model 7570A flown on DS-2). Tilt meters are seen as TRL 6–8 depending on choice of sensor. Examples to evaluate for this application include the following:

- Incline sensors from the Taiko Device Group (Japan), which originate from automotive applications but were space qualified for use in the *Lunar-A* penetrators. For each axis a cylindrical cell is part-filled with a dielectric liquid and its level detected capacitatively by electrodes on the circular faces.

- Spectron L-series, as used by The Open University group on *Huygens* and the *Mars 96* penetrators.
- Analog Devices ADXL320.
- Two-axis electrolytic inclinometer (e.g., from Fredericks Company).

The analogue front-end electronics does not require new technology but is judged at a level TRL 6 for integrated system with high-g (potted) survivability (*Lunar-A* electronics: TRL 8). Fast analog-to-digital converters (ADCs) and solid-state data recorders are available from military applications and achieve a TRL of 6.

### **Seismometer**

The baseline microseismometer consists of Micro Electro Mechanical Systems (MEMS)-based technology. The microseismometer was originally developed for Netlander, a network geophysics mission for Mars, and is currently accepted and funded as part of the Geophysical and Environmental Package of ExoMars. This system employs a micromachined silicon suspension and acts as a spring/proof-mass converting an external vibration to a displacement of the proof-mass. Currently the microseismometer is at TRL 4 and would require further ruggedization.

### **Water/Volatile instrument**

The pressure sensors are devices in use on the Ptolemy instrument on Philae the Rosetta Lander, and a little ruggedization would be required so the TRL is assessed as 4. The heritage for the optical detection system is based on the laser detection system, which flew on the NASA Deep Space 2 instrument at TRL 6/7.

The impedance spectrometer is based on proven mutual impedance probes, which have been demonstrated on instruments flown on Philae the Rosetta and Huygens spacecraft. The subsurface element is based on a mutual impedance probe being considered for mole deployment. TRL 4 and can be expected to increase as part of the HP3 instrument on ExoMars development.

The mass spectrometer is a compact version of the ion trap mass spectrometer system currently flying on the Ptolemy instrument on Philae the Rosetta Lander at TRL 4.

### **Sample acquisition**

Heritage for the sample collection and thermal control system is based on the drill and the pyrotechnic sample volume sealing device which flew on the NASA Deep Space 2 instrument at TRL 6/7.

### **Geochemistry**

Heritage for penetrometer-borne XRS is provided by the ANGSTREM instrument in the aftbody of the Mars 96 penetrators. The LunarEX penetrator benefits from Beagle 2

heritage. Some modification would be required for higher velocity impact; hence we assign a TRL of 4.

### **Heat flow**

COTS space qualified NTC thermistors are available e.g., from Betatherm (<http://www.betatherm.com>).

Thermal sensors based on LUNAR-A flight heritage: TRL 6.

The heat flow experiment on board the JAXA-ISAS LUNAR-A penetrators had flight readiness level.

Needle probe based on Mars-96: TRL 6.

A needle probe for thermal measurement on board penetrators was developed for the Mars-96 penetrators.

### **Mineralogy**

On-board microscope – TRL 4 internationally. Little U.K. experience with optical system ruggedization (TRL 2).

### **Radiation**

Solid state radiation sensor – TRL 4 but ruggedization would not be difficult.

### **Magnetometer**

Magnetometers have been used in many environments. Inclusion in penetrator body will require development (TRL 4).

### **Descent Camera**

Optical cameras for use in space are relatively common-place (certainly TRL>7). These cameras could be employed here with modest use of resources, though we would aim to space qualify the lower mass and power COTS mobile phone camera modules for which the TRL is currently low at about 3. An international team of German, Swiss, and Austrian collaborators would be assembled to develop the instrument (c.f., the Pan Cam consortium for ExoMars).

**APPENDIX V**


**Joint Statement of Intent for Cooperation in the Field of Space Exploration**

**JOINT STATEMENT OF INTENT  
FOR COOPERATION IN THE FIELD OF SPACE EXPLORATION  
BY THE  
UNITED STATES NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
AND THE  
UNITED KINGDOM BRITISH NATIONAL SPACE CENTRE**


The United States and the United Kingdom have a long history of successful cooperation in space and aeronautics activities. In the spirit of continued collaboration, the United States National Aeronautics and Space Administration (NASA) and the United Kingdom's British National Space Centre (BNSC) desire to continue technical discussions on potential cooperative lunar exploration activities.

The United States and United Kingdom have technical capabilities and expertise in: space-based remote sensing; satellite communication and navigation systems; planetary exploration; rovers; small satellites; and related technologies. Because cooperation involving these unique capabilities may be extremely valuable for future lunar exploration, NASA and representatives of the BNSC recently held several exploratory discussions on potential lunar collaboration. BNSC, which is responsible for coordinating civil space activities in the United Kingdom, has also contributed valuable input to the NASA-led, multi-national Global Exploration Strategy effort.

NASA and BNSC confirm their mutual desire for detailed discussions on specific areas of potential collaboration involving lunar science and exploration. These cooperative efforts may range from the exchange of information related to research and development to actual hardware contributions for particular missions. They will be studied in greater detail by a technical team representing NASA and appropriate British technical organizations designated by BNSC. The composition, schedule, and scope of this technical team will jointly be determined as soon as possible. Any joint activities to be carried out as a result of these technical discussions will be documented by appropriate international agreements.

  
Dr. Michael D. Griffin  
Administrator  
National Aeronautics and  
Space Administration

19 Apr. 2007  
Date

  
Sir Keith O'Nions  
Director General  
Science and Innovation  
Department of Trade and Industry

19.04.07  
Date

## **APPENDIX VI**

### **Terms of Reference for the Joint Study Group on Cooperation in the Field of Lunar Science and Exploration**

**JOINT STUDY GROUP ON COOPERATION IN THE FIELD OF  
LUNAR SCIENCE AND EXPLORATION  
BY THE  
UNITED STATES NATIONAL AERONAUTICS AND SPACE  
ADMINISTRATION  
AND THE  
UNITED KINGDOM BRITISH NATIONAL SPACE CENTRE**

#### **TERMS OF REFERENCE**

**July 19, 2007**

The United States and the United Kingdom have a long history of successful cooperation in space and aeronautics activities. In the spirit of continued collaboration, the United States National Aeronautics and Space Administration (NASA) and the United Kingdom's British National Space Centre (BNSC) agreed on April 19, 2007, to establish a technical team (hereinafter the "Joint Study Group") representing NASA and appropriate British technical organizations designated by BNSC to explore potential cooperation involving lunar science and exploration.

#### **Objectives of the Joint Study Group**

In order to advance technical understanding of potential cooperative efforts ranging from the exchange of information related to research and development to actual hardware contributions for particular missions, the Joint Study Group will undertake the following tasks:

- Identify potential mission concepts, along with initial roles and responsibilities.
- Foster interaction among the working group participants and other technical experts (before, during, and after the two working group meetings) as necessary, in preparation for discussions on specific initiatives.
- Upon conclusion of the second meeting, prepare a final NASA/BNSC Joint Working Group report, the format and content of which will be agreed upon by both delegations. This report will highlight the results of the discussions and identify common areas of interest, proposed mission concepts, initial roles and responsibilities, and possible timeframes of NASA/BNSC cooperation in lunar science and exploration. Each initiative should reflect timelines for potential implementation and points of contact for future deliberations.

The NASA/BNSC Joint Working Group will play an advisory role only. Actual collaboration will be established through the normal programme or project selection mechanisms of NASA or BNSC.

### **Joint Working Group Membership**

The Joint Working Group will be coordinated by NASA and BNSC points of contact. For NASA, the point of contact is Mr. Garvey McIntosh, and the BNSC point of contact is Mr. Chris Castelli. Participation in Joint Working Group meetings will be limited and agreed to by NASA and BNSC. The NASA Joint Working Group participants will be Mr. Tom Cremins, Deputy Associate Administrator for Management and Policy, Exploration Systems Mission Directorate; Dr. Colleen Hartman, Deputy Associate Administrator for Science; and Ms. Lynn Cline, Deputy Associate Administrator for Space Operations. The BNSC participants will be Dr. David Parker, Director of Space Science and Exploration; and Professor John Zarnecki of the Science Strategy Team of the Science and Technology Facilities Council (STFC).

### **Timeline**

Kick Off meeting and presentations	late July 2007
Second meeting	late August 2007
Draft Final report and Recommendations for review	late September 2007
Final report ready for circulation	end of October 2007