Lunar Net

A submission to ESA in response to the 2010 call for medium sized missions opportunity in ESA's Science Programme for a launch in 2022.

[submission number 017]

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Executive Summary

While the surface missions to the Moon of the 1970's achieved a great deal, scientifically a great deal was also left unresolved. The recent plethora of Lunar missions (flown or proposed) reflects a resurgence in interest in the Moon, not only in its own right, but also as a record of the early solar system including the formation of the Earth. Results from recent orbiter missions have shown evidence of ice within shadowed craters at the Lunar poles.

We propose a highly cost effective M-class Lunar mission that will place 4 or more scientifically instrumented penetrators into the Lunar surface.

LunarNet will address key issues related to the origin and evolution of planetary bodies as well as the astrobiologically important possibilities associated with polar ice. LunarNet will provide important information about:

- The size and physical state of the Lunar core
- The deep structure of the Lunar mantle
- The thickness of the farside Lunar crust
- The nature of natural Moonquakes, in particular the origin of shallow Moonquakes
- The composition and thermal evolution of the Moon's interior
- The existence, nature and origin of polar ice – exciting scientifically and key to future manned exploration of the Moon and beyond

The penetrators will be globally dispersed (unlike the Apollo missions) with landing sites on the nearside Procellarum KREEP Terrain, poles and farside, and will operate 2-5m beneath the Lunar surface for 1 year.

Each penetrator will include a suite of scientific instruments including micro-seismometers, a geochemistry package, a water/volatiles detector (for the polar penetrator(s)), a heat flow experiment, and an impact accelerometer.

For an instrument to survive an impact at 300 ms^{-1} is entirely feasible and a vast amount of resources have been devoted to such conditions within a defence context. 'Penetrators' are common-place within that sector and instrumentation is available off-the-shelf which will survive impacts of >50,000g (LunarNet expects <20,000g). This expertise is by no means purely empirical in nature; a very sophisticated predictive modeling capability also exists. The LunarNet project plans to tap this capability for a scientific end. Moreover, Mars 96, DS-2 and Lunar-A penetrator development programmes have overcome many key problems and demonstrated survivability in ground tests.

The penetrator delivery to the Lunar surface will take place in two stages:

- The Penetrators will be transferred to Lunar orbit as the payload of what will become a polar orbit communications relay satellite
- Release, de-orbit and descent. Each penetrator will have an attached de-orbit motor and attitude control systems (both of which are ejected before impact)

The mission is compatible with a single Soyuz-Fregat launch for a nominal 4 penetrator payload with a 30% mass contingency.

LunarNet will fill an important gap within the proposed international Lunar mission portfolio and facilitate the future scientific exploration of the Moon.

1 Introduction

1.1 The Moon

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), and of the near-Earth cosmic environment (e.g. bombardment history, solar wind flux and composition) throughout Solar System history (e.g. Spudis, 1996; Crawford, 2004; NRC, 2007). Some of these objectives are astrobiological in nature, in that they will 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 2-1*, 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. In order to build on the Apollo data, and thus advance our knowledge of Lunar science, the *LunarNet* mission will fly 4+ penetrators to the Moon for the purpose of conducting a range of *in situ* geophysical and geochemical measurements at widely separated localities.

1.2 Penetrators

Penetrators are small, instrumented probes which impact planetary bodies at high speed and bury themselves into the planetary surface. For the Moon we propose deployment of 4 13Kg penetrators that are designed to survive impact at high speed (~ 300 m/s) and penetrate ~2-5m. The impact process generates decelerations of >10,000g, which together with the low mass, restricts the type and capability of payload that can be accommodated. However, a surprisingly large range of instruments have already been constructed and qualified for penetrator use, and an ever widening range of scientific instruments have a robust nature which lend themselves to the necessary ruggedisation.

Figure 1-1: Penetrator after impact at Pendine

Survival at these impact speeds has been demonstrated by ground tests of NASA DS2, Mars 96 and Japanese Lunar-A probes, and extensive military experience of impacts into materials mostly consisting of sand, concrete, steel and ice. In 2008 highly successful full-scale trials of penetrator technology were undertaken in Pendine, see above figure (Smith et al., 2010).

Penetrators were earlier proposed for UK led MoonLITE mission with significant NASA and international support, and later rebadged as LunarEX for an earlier ESA call though were unsuccessful at that time. Subsequently interest has increased with application to Europa on EJSM, which has resulted in completion of an ESA system study (Astrium, 2010), with significant technology advances and definition.

1.3 Current and Future Space Missions

This LunarNet proposal builds upon a growing interest in a penetrator mission to the Moon. The scientific objectives of LunarNet are complementary to the goals of ESA's Lunar Lander project, which is managed by D-HSF and aims to deploy a soft lander at the lunar south pole to characterise the environment for future human exploration. As the Lunar Lander mission would only conduct measurements in one particular locality, the wider geographical spread of measurements obtained from a penetrator-based mission such as LunarNet would lead to a much broader understanding of the wider lunar environment. This enhanced understanding is crucial for both the scientific understanding of the Moon and its environment, and for planning future exploration activities.

LunarNet could also provide technical assistance to future ESA astronauts by determining the effectiveness of lunar regolith for radiation shielding for astronauts; the frequency and location of possibly structurally damaging surface Moonquakes; and further information concerning the concentration and extent of water in the polar regions, in particular in the permanently shaded craters. Such water is important for astronauts as a source for drinking, and manufacturing of air and propellant.

LunarNet should also be seen in the context of a number of international lunar initiatives and the Global Exploration Strategy (GES, 2007). The UK is a signatory to the International Lunar Network which aims to coordinate lunar un-manned landed science packages. LunarNet can be seen as a pre-cursor or early element of a more extensive global network. Moreover, LunarNet builds upon other proposed penetrator missions including DS-2 (Smrekar, 1999), Polar Night (Mosher and Lucay, 2003) and, in particular, Lunar-A (Mizutani, 2003) – a similar, albeit discontinued Japanese mission.

General interest in Penetrators has also grown and with the recent completion of an ESA study into a Penetrator Mission to Europa as part of Laplace/EJSM, and potential application to the exploration of Mars interior structure and astrobiological potential. The report of this ESA study also informs this LunarNet proposal (Astrium, 2010).

2 Scientific objectives and requirements

The principal scientific objectives of the LunarNet penetrator mission are as follows:

- Constraining the origin, differentiation, internal structure and early geological evolution of the Moon.
- Develop a better understanding of the origin and history of the volatile flux in the Earth-Moon system.
- Collect 'ground truth' geochemical data to calibrate orbiting remote-sensing instruments.
- Collect *in situ* surface data that will help in the planning of future lunar exploration.

2.1 Introduction

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; Jolliff et al., 2006). Some of these objectives are astrobiological in nature, in that they will enhance our understanding of the cosmic conditions under which life first arose on Earth (e.g. Crawford 2006). The most detailed summary and prioritization of lunar science activities was that conducted by the US National Research Council's *Report on the Scientific Context for Exploration of the Moon* (NRC 2007).

Although recent space missions (e.g. *Clementine*, *Lunar Prospector, Kaguya, Chandrayaan-1,* and the *Lunar Reconnaissance Orbiter*) have greatly added to our knowledge of the topography and geochemical and mineralogical makeup of the lunar surface, our knowledge of the deep interior still largely relies on geophysical measurements made during the Apollo programme. As can be seen from *Figure 2-1*, 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. Moreover, these recent orbital missions have uncovered evidence for hydrated minerals, polar ice deposits, and 'exotic' lunar lithologies which have not yet been sampled *in situ* by any lunar mission.

In order to follow-up on these earlier results, and thus advance our knowledge of origin, internal structure and evolution of the Moon, the *LunarNet* mission will fly 4-6 penetrators to the Moon for the purpose of conducting a range of *in situ* geophysical and geochemical measurements at widely separated localities. It builds on work performed for an earlier mission study, *LunarNet* (Smith et al., 2009), updated in the light of recent results, especially those relating to polar volatiles.

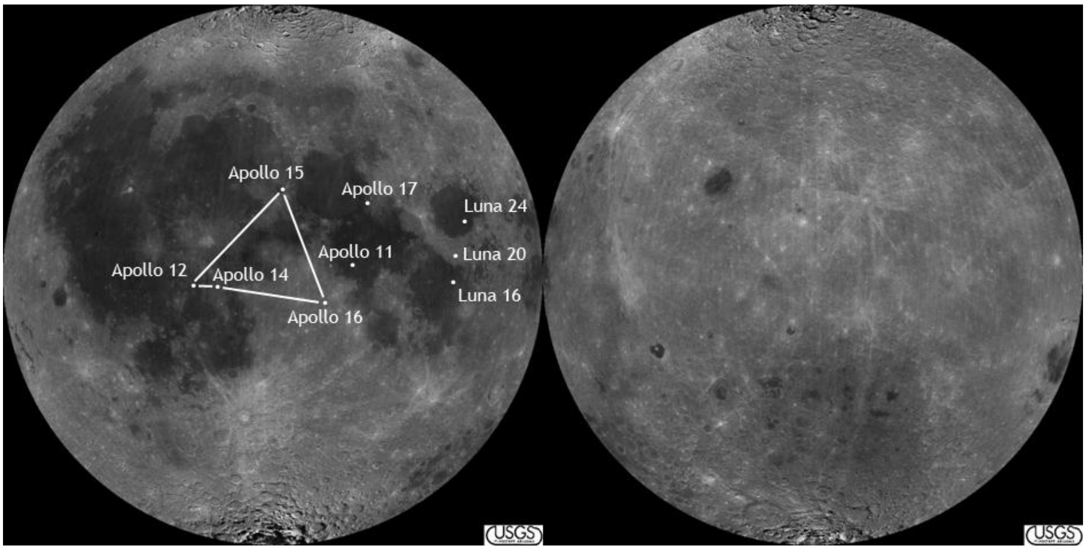


Figure 2-1: Locations of the Apollo and Luna landing sites on the nearside of the Moon (left); the farside is at right. These are the only locations from which lunar samples have been returned to Earth for analysis. The Apollo seismic network occupied an approximate equilateral triangle, roughly 1200 km on a side, as indicated. 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 (Image courtesy Katherine Joy/USGS).

The top-level science objectives for *LunarNet* fall into four categories: seismology, heat-flow, geochemical analysis, and the characterisation of polar volatiles. These objectives address three of the top four key 'lunar science concepts' identified by the US National Research Council's Report on *The Scientific Context for Exploration of the Moon* (NRC, 2007), and this comparison is made directly in *Table 2-1*.

Key lunar science concept (NRC 2007)	**Relevant LunarNet measurements**
1. The bombardment history of the inner solar system is uniquely revealed on the Moon	N/A (requires *in situ* dating or, preferably, sample return from multiple localities)
2. The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body	Seismology and heat-flow measurements at widely-spaced localities
3. Key planetary processes are manifested in the diversity of lunar crustal rocks	Geochemistry measurements of regolith at previously unsampled sites
4. The lunar poles are special environments that may bear witness to the volatile flux over the latter part of solar system history	Polar volatile detection and characterisation measurements in shadowed polar craters

Table 2-1: Comparison of proposed LunarNet measurements with the four highest priority 'lunar science concepts' identified by NRC (2007).

2.2 Lunar seismology

Determining the structure of the lunar interior was the second highest scientific objective for lunar science identified by NRC (2007; see their Table 3.1). Seismology is the most powerful geophysical tool available for determining the interior structure of a planetary body. However, to-date the only object, other than the 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 did provide 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, never mind 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; *Figure 2-1*) on the nearside. As a consequence, the information obtained on crustal thickness and upper mantle structure strictly 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:

2.2.1 Size and physical state of lunar core

As the Apollo seismic data were unable to constrain the size or physical state of the lunar core, such knowledge as 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 Wieczorek 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 remanent magnetisation of surface rocks, will 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.

2.2.2 Deep structure of the lunar mantle

One of the main contributions lunar science can make to planetary science more generally 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 be able to determine the initial depth of the magma ocean, and thus 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 in turn may be used to constrain both the bulk composition of the Moon (and thus its origin), and the crystallisation history of the lunar mantle and its implications for magma ocean evolution. Again, new, and more widely spaced, seismic data are now required if new advances are to be made over what has been learned from the Apollo data.

2.2.3 Thickness of the farside lunar crust

Re-interpretations 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 at all. Estimates based on gravity data are typically in the range 70-90 km (Wieczorek et al., 2006), although gravity data obtained by the Kaguya mission indicate that some farside areas (e.g. the South Pole-Aitken Basin (SPA) and Mare Moscoviense) have substantially thinner crust (e.g. Araki et al., 2010). However, many of these interpretations are non-unique, and in particular 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 in order 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.

There is considerable interest in the thickness of the crust (if any) remaining under the giant South Pole-Aitken impact basin – the largest impact structure currently known in the Solar System. Together with the nearside Procellarum 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). Part of the interest in the SPA lies in the possibility that it may have exposed lower crustal or upper mantle materials. Seismometers located within the SPA will, for the first time, be able to make a definitive measurement of the crustal thickness remaining under this important structure.

2.2.4 Studies of natural moonquakes

The Apollo seismometers detected four types of natural moonquake: (i) deep (700-1200 km), relatively weak, moonquakes which occur in 'nests' and which appear to have a tidal origin; (ii) shallow (5-200 km), relatively strong, moonquakes of unknown origin; (iii) thermal moonquakes due to thermal stresses in the near surface; and (iv) meteorite impacts (summarised by Vaniman et al. 1991). Of these (i), (ii) and (iv) may be used as sources of seismic energy to probe the lunar interior, and a better understanding of the causes and clustering of (i) will provide additional knowledge of the physical properties of the deep lunar interior.

However, it is the shallow moonquakes (ii) that are probably the most interesting scientifically. These were the strongest (up to magnitude 5) and rarest (only 28 recorded in 8 years), and currently their cause is unknown. Insofar as these result from unknown tectonic processes, our knowledge of present-day lunar geological activity will remain incomplete until their cause and locations can be identified (e.g. Nakamura 1979). Owing to the spatially restricted locations of the Apollo seismic stations, the Apollo data lacks the resolution to pinpoint the precise epicentres or depths pf these events, for which a global distribution of seismometers will 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 that 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.

2.3 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 the 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 2-1*) and may thus not be representative of the lunar heat-flow as a whole. Moreover, both these Apollo measurements have been subject to numerous re-interpretations over the years, owing 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).

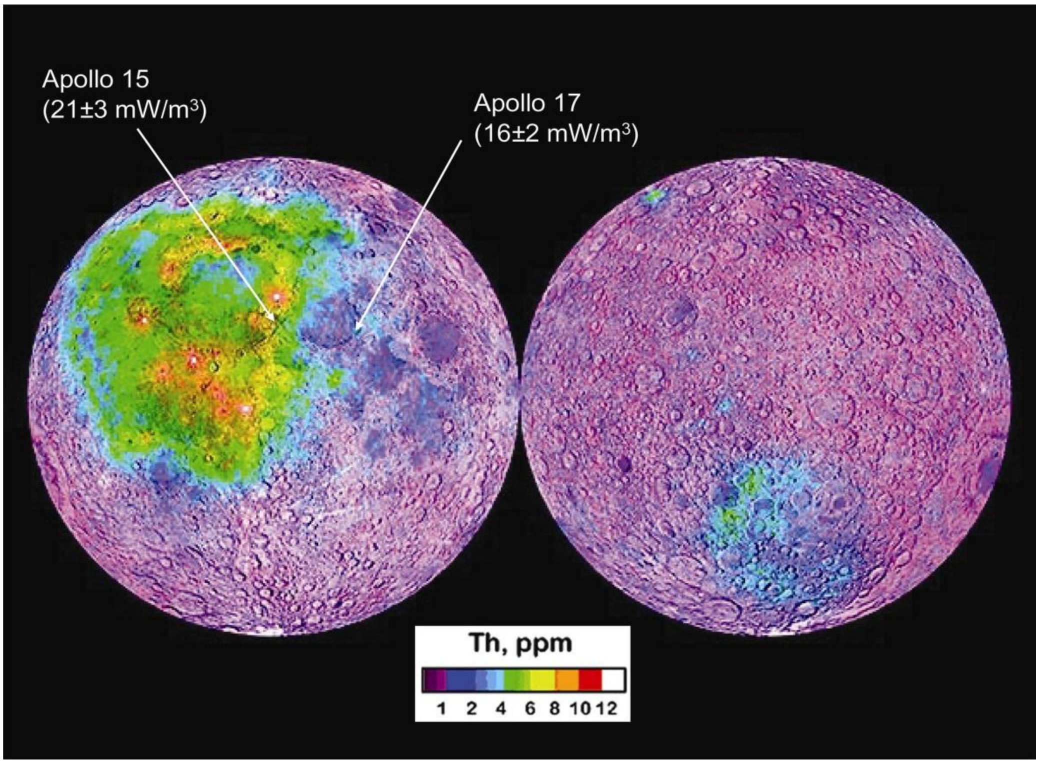


Figure 2-2: Concentrations of Th in the lunar surface, measured by the Lunar Prospector spacecraft. The PKT is the region of high Th concentrations around and to the south of the Imbrium basin on the nearside. The Apollo 15 and 17 heat-flow measurements are indicated.

One particularly important measurement would be to determine the heat-flow as a function of distance from the Procellarum KREEP Terrain (PKT) 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 2-2*), 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 indeed concentrated in the mantle below the PKT. The latter scenario would predict a much higher heat-flow in the PKT than elsewhere, and 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 do appear to indicate a decrease in heat-flow away from the PKT (21±3 and 16+2 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, ideally close to the centres of the three lunar terrain types [i.e. the PKT, the Felspathic Highland Terrain (FHT), and the South Pole-Aitken Basin (SPA)] identified by Jolliff et al. (2000). Such measurements would greatly aid in constraining models of lunar thermal evolution. Finally, we note that in situ measurements of both the temperature and the thermal conductivity of the regolith would help "ground-truth" temperatures obtained by radiometer observations from orbit (e.g. Paige et al., 2010). Penetrator deployment of a global heat-flow network would be an attractive means of achieving these objectives.

2.4 In situ geochemistry

Understanding the diversity of lunar crustal rock types was one of the highest scientific priorities identified by NRC (2007; see *Table 2-1*), and this requires the detailed chemical and mineralogical analysis of rocks and soils. The only places on the Moon from which samples have been collected *in situ* are the six Apollo landing sites) and the three Russian Luna sample return missions from near the Crisium basin on the eastern limb of the nearside (*Figure 1-1*). 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 140 or so known 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, at least of the abundances of the major rock-forming elements (e.g. Mg, Al, Si, K, Ca, Fe and Ti). In principle, various instruments would be capable of making such measurements, including X-ray spectroscopy, gamma-ray spectroscopy, and/or laser-induced-breakdown spectroscopy (LIBS). Depending on the sensitivity, some of these instruments may also be able to measure minor and trace elements and isotopes, many of which provide key diagnostic information regarding the origin and ages of geological materials. Penetrator-deployed instruments of this kind therefore have to potential to determine the composition of lunar materials in regions remote from areas sampled to-date. In addition such measurements would provide additional 'ground truth' for the calibration of remote-sensing observations performed by orbiting spacecraft.

The diversity of lunar crustal materials has been highlighted most recently by the detection of spectral signatures of "evolved" (quartz-rich) lithologies by the Diviner instrument on LRO (Greenhagen et al., 2010; Glotch et al., 2010). These rock types are very rare in the Apollo sample collection (occurring only as small clasts in brecciated rocks), and the discovery of quite extensive outcrops by LRO has important implications for understanding the magmatic evolution of the Moon. It is therefore important to (a) confirm the interpretation of the remote-sensing data (as no 'ground-truth' has yet been obtained for any of these localities) and (b) obtain measurements of minor and trace elements which cannot be detected by orbital remote-sensing instruments, but which would help discriminate between different suggested formation mechanisms for these materials (e.g.

Glotch et al., 2010). Targeting suitably instrumented penetrators to these localities, such as proposed here, would be an attractive (and certainly cost effective) means of obtaining these measurements, especially as dedicated sample return missions to these sites are unlikely to be realised in the near-term.

2.5 Polar volatiles

As noted in the NRC Report on the Scientific Context for Exploration of the Moon (NRC, 2007; *Table 2-1*), the lunar poles potentially bear witness to the flux of volatiles in the inner Solar System throughout much of Solar System history. The possibility of extensive volatile deposits at the lunar poles was highlighted in 1998 when the *Lunar Prospector* neutron spectrometer found evidence for enhanced concentrations of hydrogen at the lunar poles. This was widely interpreted as indicating the presence of water ice in the floors of permanently shadowed polar craters (Feldman *et al*., 1998). This now appears to have been confirmed by the LCROSS impact experiment, which found a water ice concentration of 5.6 ± 2.9 % by weight in the target regolith at the Cabeus crater (Colaprete et al., 2010). It seems likely that this water is ultimately derived from the impacts of comets with the lunar surface, although solar wind implantation and endogenic sources might also contribute. This is an important result, but the inferred quantity of water is sensitive to the calibration of the spectrometers on the LCROSS Shepherding Spacecraft, and a number of other assumptions (Colaprete et al., 2010). Ideally, therefore, it needs to be confirmed by *in situ* measurements, and a penetrator-deployed volatile detection package would be one means of achieving this.

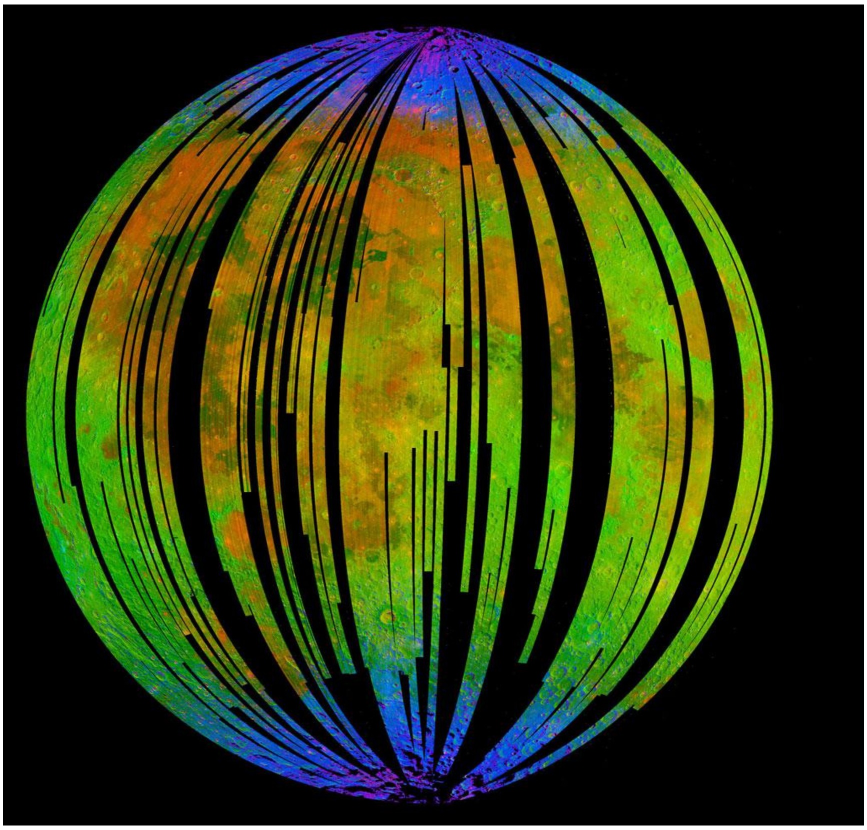


Figure 2-3: False colour rendition of the global mineralogical observations of the Moon conducted by the M^3 instrument on Chandrayaan-1 (Pieters et al., 2009). Here blue indicates the presence of absorption bands at wavelengths close to 3 μm attributed to OH and/or H_2O (Image: M^3/NASA/ISRO).

In addition to ice in permanently shadowed craters, infra-red remote-sensing observations from the M^3 instrument on *Chandrayaan*-1 have found evidence for hydrated minerals, and/or adsorbed water or hydroxyl molecules, over large areas of the high latitude (but not permanently shadowed) lunar surface (Pieters et al., 2010; *Figure 2-3*). Surficial concentrations of up to 800 ppm OH and/or H_2O were inferred from the spectra. This OH/H_2O cannot exist as ice, and is more likely due to the reduction of iron oxides in the regolith by solar wind-implanted hydrogen, with OH/H_2O being retained in the cold high-latitude regolith. However, it is possible that over time this high-latitude OH/H_2O may migrate to polar cold traps and contribute to ice deposits there. The concentration of this high latitude OH/H_2O with depth in to the regolith is currently unknown, and will require *in situ* measurements to determine. Again, penetrator-deployed instruments would be an efficient means of doing this.

Improved knowledge of the presence, composition, and abundance of water (and other volatiles) at the lunar poles is important for at least four reasons:

(i) It is probable that the ice in permanently shadowed regions is ultimately derived from comet impacts. Even though the original cometary volatiles will have been considerably reworked by impact vaporisation, migration to the poles, and subsequent condensation, it remains possible that some information concerning the composition of the original sources will 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).

(ii) Evidence for the creation, retention, migration, and destruction of OH and H_2O across the surface of the Moon with the lunar diurnal cycle is arguably one of the most important recent discoveries from the Moon. The processes involved are likely to be common on other air-less bodies, and quantifying it on the Moon will give us better insight into the volatile history and potential availability of water (ice) in the inner solar system.

(iii) 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 will have been continuously subject to irradiation by galactic cosmic rays and, as such, 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 much more accessible than any of these other locations.

(iv) The presence of water ice at the lunar poles, and even hydrated materials at high-latitude but non-shadowed localities, could potentially be a very 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, and determination of its abundance, would therefore make a significant contribution to the developing Global Exploration Strategy of which renewed human exploration of the Moon is a key element (GES, 2007).

Volatile detectors deployed on penetrators, and landed within permanently shadowed craters (and/or the surrounding non-shadowed but apparently nevertheless volatile enhanced areas), would be a powerful and economical means of determining whether or not scientifically and operationally valuable deposits of volatiles exist at the lunar poles. One of the implications of the LCROSS and other recent spacecraft results is that such volatiles may be distributed very inhomogeneously in the lunar polarregions, and a penetrator mission would enable additional sampling of this distribution which would be important in terms of understanding sources/sinks of polar volatiles.

2.6 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 LunarNet penetrators have the potential to make major contributions to lunar science. At the same time, they will provide knowledge (e.g. of lunar seismicity and polar volatile concentrations) that will be of central importance in the planning of future human missions to the Moon, and will also demonstrate a technology that will have wide applications for the exploration of other airless bodies throughout the Solar System (e.g. Gowen et al., 2010). A summary of the Science Requirements is given below:

#	**Science Requirement/Success Factor**
1	To measure the size and physical state of lunar core
2	To determine the deep structure of the lunar mantle
3	To measure the thickness of the farside lunar crust
4	To determine the origin of natural Moonquakes
5	To constrain the composition and thermal evolution of the lunar interior
6	To characterise the geochemistry at diverse lunar sites
7	To determine the nature and origin of lunar polar volatiles
8	To determine the presence and concentration of water ice in the permanently shaded craters (part of 7)

3 Mission profile proposed to achieve these objectives

3.1 Mission Design

The mission involves the delivery of a minimum of four penetrators into the Lunar surface at widely dispersed locations. It is anticipated that one of penetrators will be placed on the far side and at least one penetrator will be within a permanently shaded, polar crater. Therefore, direct communication between penetrator and Earth is not possible and a lunar polar orbiting relay communications satellite (Orbiter) is required. The Orbiter will carry the 4 Descent Modules into lunar orbit prior to their release.

Each Descent Module consists of a Payload Delivery System (PDS) and a Penetrator. The Penetrator includes both a scientific payload (see section 4) and services (see section 5). During the descent phase a camera (Penetrator Descent Camera) is used to provide impact site location and context information.

To meet the scientific Objectives the following high level requirements have been placed on the Orbiter, Descent Module and Penetrators:

The Orbiter shall:

- Carry the DMs into Lunar polar Orbit
- Release the DMs for descent to arbitrary locations on the Lunar Surface. Each DM shall be separately targeted.
- Provide a communications link (send and receive) between penetrator and Earth.

The Descent Modules shall:

- Provide continuous communications during descent
- Ensure penetrator impact as follows:
    - Impact within 2 km (tbc) of specified location

    - Impact velocity <300 ms^{-1}
    - Attack angle <8 degrees (angle between penetrator body axis and velocity vector)
    - Incidence angle <30 degrees (tbc) (angle between local vertical and velocity vector)
    - Impact spin rate <2 revolutions per second (around penetrator body axis)
- Measure impact location to an accuracy 100m (tbc).

Each Penetrator shall:

- Perform scientific investigations including sampling of the local regolith
- Communicate with orbiter during orbiter passages
- Operate for at least 1 year after impact

The Mission will comprise the following phases:

- Launch and transfer to a 100 km polar Lunar Orbit
- Deployment of Penetrators (requiring temporary reduction of periapsis to <40km for each release)
- Penetrator Operations with orbiter at 100 km (1 year)

3.2 Launcher requirements

Launcher requirements are to deliver a lunar network of 4 stations using 51.6kg descent modules, and supported by a communications orbiter. Since the mass of this is estimated to be 922kg (see section 5.6) a Soyuz 2-1b (Soyuz-Fregat) is baselined as the launch vehicle.

3.3 Orbit requirements

3.3.1 Transfer Options

The main trade-offs in this area are the launch vehicle delivery orbit and the trajectory employed to reach the lunar vicinity.

3.3.1.1 Launch Vehicle Delivery Orbit

This impacts both the subsequent trajectory and spacecraft design. The main options are releasing the spacecraft into a Highly Elliptic Earth Orbit (HEEO), such as a Geostationary Transfer Orbit (GTO), or inserting directly into a Lunar Transfer Orbit (LTO). The HEEO option is more efficient as the Trans-lunar Injection (TLI) manoeuvre is performed by the spacecraft and not the launch vehicle upper stage. This means an increased mass can be delivered to lunar orbit and the TLI can effectively be split into multiple smaller burns which are more efficient due to reduced gravity losses (effectively splitting the transfer into a series of intermediate orbits). However, a larger propulsion system (propellant volume) is needed on the spacecraft to perform this manoeuvre. The LTO option is slightly less efficient (the launcher upper stage has to accelerate its own mass and the spacecraft to achieve TLI) but will result in a more compact spacecraft design due to decreased propellant requirements.

3.3.1.2 Lunar Transfer

Numerous transfer options from Earth to lunar orbit exist. With a direct transfer (as used by the majority of lunar missions to date) the spacecraft is placed on an elliptical transfer orbit to the moon – either by its own propulsion system or by the launch vehicle upper stage as discussed previously. The main advantage of these trajectories is a short transfer duration (3-14 days), but they do require a high energy propulsion system. Other options include: a Weak Stability Boundary (WSB) transfer; a bi-elliptic transfer; and a low thrust spiral from an initial HEEO. From a preliminary assessment the direct transfer from an initial GTO orbit is baselined as this is a well understood trajectory which also maximises the available launch options. The overall delta-V can be minimised by selecting a number of phasing orbits before performing the final TLI manoeuvre. This approach has the added advantage of allowing gradual commissioning of the spacecraft and propulsion before performing the critical manoeuvres (TLI and LOI).

3.3.2 Orbit Options

Upon arrival in the lunar vicinity, the spacecraft will enter a ~ 100km circular, polar parking orbit. From this orbit the spacecraft will temporarily manoeuvre into a DM delivery orbit (100x40 km). It shall then circularise into the parking orbit before repeating this process for the remaining DMs. This ensures that any point on the lunar surface is potentially accessible for the penetrators.

A nominal deployment altitude of the Descent Modules (DM) of 100x40 km, slight modifications to these altitudes can be investigated (in conjunction with the other two studies – penetrators and descent systems) to ensure the optimal set of delivery conditions are achieved. For example, the most suitable propulsion system for the PDS may require a slightly lower delivery orbit to ensure the drop altitude is compatible with the maximum penetrator impact velocity of 300 m/s. In addition, there must be telemetry relayed back to the orbiter from the DM during its descent to the surface.

3.4 Ground segment requirements

Two ground stations would be suitable for LunarNet: E.g. :-

- SSTL (RAL Antenna): Lat: 51.5°; Long: -1.3°
- South Point (Hawaii): Lat: 19.0°; Long: -155.7°

The ground stations will be required to provide commanding for Orbiter orbit and attitude changes, descent module release operations (nominally 4 per mission, one every e.g. 2 weeks), and any non-nominal commanding. They will also be required for downlink of orbiter health and safety data, and penetrator science data.

The ground stations will also be required to provide commands to the individual penetrators via the orbiter. Such commands are needed to optimise the operation and data return from the payload. An externally referenced time signal is needed for operation of the seismometers to form a network.

A single Penetrator Control Centre will be created that monitors the health and performance of all penetrators and provides level 1 data products to the various instrument teams – who will perform downstream data analysis within their institutes.

3.5 Critical issues

While technological solutions are available for all mission aspects, the following are considered to be the most critical :-

- That the Penetrator Delivery System ensures a survivable attitude/velocity at impact
- That the impact sites are chosen and characterised appropriately
- That low temperature operation within permanently shaded craters can be sustained for >1 year.

4 Proposed model payload to achieve the science objectives

Described here are the various payload instruments – both as a baseline set and with additional options. The penetrator itself along with services including power, thermal control and command and data management are described further in section 5.

The study of a penetrator for a Jovian Icy Moon commissioned by ESA included the preparation by ESA of a Payload Definition Document (SCI-PA/2009.076, Gebler and Wielder, 2010) and much of the information included in this section is taken from this document. Of course the document itself was compiled with inputs from many of the proposers of LunarNet. Values given here have also been updated by consortium members in light of recent studies.

4.1 Overview of all proposed payload elements

Instrument	Acro-nym	Mass [kg]	Size [cm^3]	Power [W] *[Whr]*	Total Data Volume [kbit]	TRL* Heritage
Proposed Model Payload						
Accelerometer (8 sensors)	ACCL	0.07	2.4	0.8 to 1.2 *0.17*	1Mbit	TRL 6-8 Off-the-shelf components, Lunar A, Pendine
Descent camera	DC	0.160	9 3 x 3 x 3 cm	0.160 *0.015*	~ 10 Mbits after compression	TRL 7+ general camera technology TRL 2 for proposed design
Heatflow probe	HEAT	0.300	20	0.025 to 0.3	Max: 0.5 Mbit	TRL 7: Lunar A Mounting will be specific to mission
Magnetometer	MAG	0.07	200 10*10*2	0.15 - 0.4	~1Mbit (0.06 kbps)	TRL 5: Pendine trials
Mass Spectrometer	MSPC	0.75	1000 10x10x10	3-6	~0.2Mbits	TRL 4/5: Rosetta / Beagle2
Seismometer	SEIS	0.3	200	0.053 to 0.112 *500*	~5Mbit (720 bps)	TRL4-5, Netlander development, ExoMars, Pendine Trials
Engineering Tiltmeter	ETLT	0.010	25	0.1	1 kbit	TRL 6-8 Huygens, Mars 96
Water/Volatile Detector	BIOC	0.750	1000	3	TBD	TRL 4-8: DS-2, Huygens, ExoMars, Pendine
X-Ray Spectrometer	XRS	0.260	160	4 *24*	0.1Mbits	TRL 7 : Mars 96
Potential additional instruments						
Dielectric/permittivity sensor	PERM	<0.1	TBD	0.5	1kbit	Rosetta (Sesame-PP)
Engineering Tiltmeter	ETLT	0.010	25cm3	0.1	1 kbit	MoonLITE, Huygens
Microphone	MPHO	0.004 (TBC)	2.6x1 (TBC)	TBD	(0.46/s) (TBC)	Huygens, Rosetta (Sesame-PP)
Microscopic Imager	MICR	TBD	TBD	TBD	TBD	
Radiation Monitor	RADM	TBD	TBD	TBD	TBD	MoonLITE
Radio Beacon	RBEC	0.4	TBD	4 W		Huygens
Thermo-gravimeter	THERMO-GRAV	40	4*2.5*3	0.5 to 2	~ 4 Mbit	A-Rosetta

*Pendine refers to UK Penetrator trials (see Smith et al 2010).

Table 4-1: Proposed Penetrator Payload Instruments.

The Model Payload instruments are discussed in more detail below. Note that in addition a sample acquisition system is also described since this is necessary for the Mass Spectrometer and would be of value to other instruments.

4.2 Summary of each instruments key resources and characteristics

4.2.1 Accelerometer

The main goals of this experiment are:

- To derive mechanical properties of the Lunar regolith vs. depth. Important in its own right and to give context to the geochemistry and geophysical measurements.
- To determine the depth below the surface at which each penetrator comes to a rest and so provide important information for the interpretation of results from other experiments, including heat flow.
- To provide a full dynamic history of each penetrator impact, for comparison with results from ground testing and simulations.

4.2.1.1 Description and key characteristics

Two sets of 3-axis accelerometers will need to be located inside the penetrator close to its axis of symmetry. One set shall be mounted close to the penetrator tip, the other close to the penetrator's rear (upper) end. This is to derive the complete motion history of the penetrator (position and orientation) and compensate for the mechanical response of the penetrator structure. The accelerometers will operate during the impact event, sampled rapidly enough to achieve sufficiently fine spatial resolution of the motion. Such measurements are routine in military applications. Accelerations of up to ~15,000g can be expected during impact. The Endevco Model 7270A-60K Piezoresistive accelerometer is baselined as shown in Table 4-2.

Range:	+/-60,000 g peak	Over range limit	+/-180,000g
Sensitivity	3 micro-V/g typically	Warm Up Time	2 mins (max), 15 secs (typical)
Response	0 to 100 kHz (at +/-5%)	Op temp	-34 to +66 deg C
	0 to 136 kHz (at +/- 1dB)	Storage temp	-54 to +121 deg C
Transverse sensitivity	5% max	Materials	Stainless Steel (17-4 PH CRES) Stainless Steel (17-4 PH CRES)
		Weight	1.5g

Table 4-2: Endevco accelerometer parameters

The electronics circuit design would use the Huygens HASI Accelerometer PZR design, with a resistor value changed to modify the circuit gain. This uses an Analog Devices AD524 precision instrumentation amplifier.

4.2.1.2 Performance assessment with respect to science objectives

Precise determination of the penetrator motion and final depth requires each of the accelerometers to have range, sensitivity, noise, offset performance and frequency characteristics that are compatible with the impact event. For 3 mm spatial resolution at an impact speed of 300 m s^{-1}, a sampling rate of 100 kHz is required. While the accelerometer might be operational for up to 10 mins prior to impact by using a 0.1 second circular buffer the amount of data recorded and transmitted would be kept to <1Mbit.

4.2.1.3 Pointing and alignment requirements

The accelerometers and tilt sensors will be mounted internally, with axes aligned with those of the penetrator.

4.2.2 Descent camera

4.2.2.1 Description and key characteristics

The Descent Camera does not have to withstand impact and so general space qualified camera technology will be suitable. For this the space qualified Beagle-2 PANCAM which are also in development for ExoMars are quite possible at quite low resource of 160g and 900mw, (Griffiths et al 2006), though we propose a lower mass based on a 'camera on a single chip' 3 Mpixel CMOS detector coupled to a 45° objective lens (⅓" format) via minimal encapsulating structure. The camera will image the surface in RGB colour from 40 km down to ~ 1 km altitude to determine landing site location and context; thus supporting the achievement of the science objectives. Below 1 km the image blur due to motion exceeds the camera resolution.

The camera will interface directly to the penetrator DHU transferring up to 32Mbit bits per image Therefore, 4 images acquired during the 3 minute 42 second decent would require 128 Mbit of uncompressed storage. Binning (2x2 or 3x3) could be performed in the DPU to reduce the data volume and a further reduction a factor of 15 by using lossy compression (e.g. wavelet). The working value of data from the Camera is 10 Mbit.

4.2.2.2 Performance assessment

Expected camera performance (based on a COTS mobile phone camera module) is shown in the following table.

Size (l x w x h) (mm)	10 x 10 x 30	Linear Resolution (m/pixel)	120 (@ 40 km) 3 (@ 1 km)
Array Size (w x h) (pixels)	512 x 512	Pixel Size	2.2 x 2.2 µm
Output Format (Bayer Matrix)	10 bit RGB	Angular Resolution	0.3 mrad/pixel
Signal to Noise Ratio (dB)	42	Spatial Resolution	0.3 m at 1 Km
Diagonal Field of View (°)	45	Drive Voltage	2.8 V
Sensitivity (DN/s)/(W/m^2.str.µm)	168	Dynamic Range	50 dB

4.2.2.3 Pointing and alignment requirements

The optical axis to be within 1° of the penetrator axis

4.2.2.4 Calibration requirements

The camera would be radiometrically calibrated to better than 1% and geometrically calibrated so that the relative alignment of the optical and penetrator long axis is known to better than 0.1°.

4.2.3 Heatflow probe

For measuring planetary heat flow, two parameters are required: the subsurface thermal gradient and the thermal conductivity of the subsurface material (i.e. the regolith). The heat flow experiment will measure the temperature gradient in the Lunar regolith by using temperature sensors on the outside of the penetrators. These will be accommodated at several locations between nose and tail. The thermal gradient can be determined from temperature measurements once the orientation of the penetrator is known from the tilt-meter. A correction will have to be made to deduct the thermal effect of the penetrator from the temperature measurements. The thermal conductivity of the subsurface regolith will be measured in four locations using small plate heaters.

4.2.3.1 Description and key characteristics

The heat flow experiment will consist of a number of sensors located on the outside of the penetrator together with electronics (100gm). These are in detail:

- a suite of 8 relative temperature sensor (thermocouples) on the outside of the penetrator (each 12gm)
- 4 absolute temperature sensors (Pt-100 or NTC thermistors) on the outside of the penetrator (each 12gm)
- 4 miniature thermal conductivity sensors (e.g. heater plate with thermocouple, or miniaturized needle probe) (each 20gm)

4.2.3.2 Performance assessment

The feasibility of a penetrator-based heat flow experiment has been studied in detail (e.g. Tanaka et al., 2000). Based on thermal sensors with an accuracy of 0.01K Tanaka et al. (1999) estimated an accuracy of 10% for the gradient measurement. Using plate heaters, thermal conductivity can also be measured with an accuracy of 10%. Needle probes increase this accuracy into the 1-2% range.

4.2.3.3 Resources: mass, volume, power, OBDH and telemetry

	Heat Flow
OBDH	Temperature measurement: e.g. 1/hr., >18bit resolution, depending on chosen sensor. Thermal property measurement: 50Hz, 12bit resolution
Telemetry	< 0.5 Mbit for thermal property < 0.1Mbit for temperature

4.2.3.4 Operating modes

Temperature sensors: temperature measurement ~1 per hr, <0.1 Mbit data volume.
Thermal conductivity sensors: temperature measurement (low power) and thermal property measurement (high power), 50Hz during measurement, <0.5 Mbit data volume

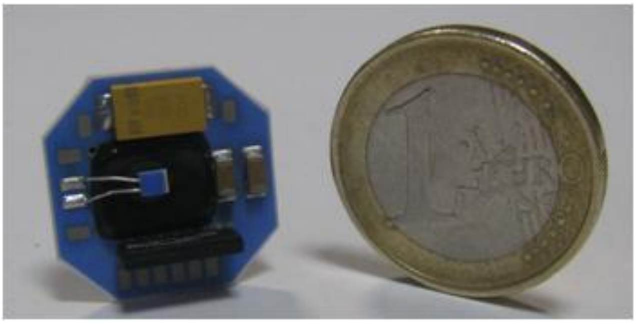
4.2.3.5 Current heritage and Technology Readiness Level (TRL)

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.

4.2.4 Magnetometer

4.2.4.1 Description and key characteristics

The magnetometer will measure the three components of the local magnetic field vector in the vicinity of the penetrator in the bandwidth DC up to a maximum of 10Hz (i.e. 10 samples per second). It consists of (at least) two tri-axial Anisotropic Magneto-Resistive (AMR) sensor heads connecting to a single card housing associated drive and signal conditioning electronics and a bus communication element. AMR sensors are proposed instead of the more traditional fluxgate implementation due to the much lower mass and volume (as well as superior robustness against high impact) of the MR device over the fluxgate as well as demonstrating broadly equivalent performance for a fluxgate core of equivalent volume.



The sensors and electronics card are assumed to be wholly contained within the penetrator shell. Centralised power and data handling is assumed via a common backplane connection. The sensor heads should be located in a region of the penetrator that is far away from magnetic disturbing sources and will connect to the magnetometer electronics via an ultra-light harness. The use of two (or more) sensors fitted at multiple positions within the penetrator will permit determination of the local penetrator background stray field thereby allowing separation of this perturbing signal from the scientific signal.

The sensors would be of similar design to those currently under development for the Trio-Cinema mission (a three spacecraft CubeSat constellation in LEO due for launch in 2011) and originally targeted for the UK MoonLITE mission. Driven closed loop electronics are used to extract an analogue measure of the magnetic field. The sensor is relatively low noise 100pT/√Hz above 1Hz and the instrument range would be set to ±1200nT with 50pT digital resolution. The standalone instrument accuracy would be <10nT although this figure would improve to around 2nT if the orbiter includes a high accuracy fluxgate vector magnetometer. Indicative resources are less then 5g for the sensor and 50g for electronics. Power consumption would be 0.15W average and 0.4W peak. A 2Hz cadence would require a data rate of 60bits per second. The design is currently at TRL5.

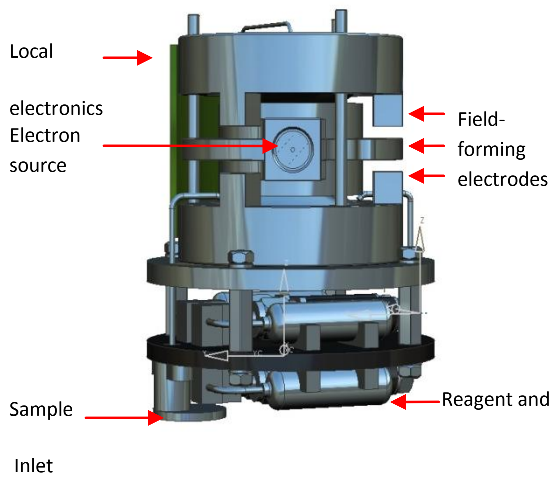
The magnetometer instrument requires only a small number of operating modes, and could be limited to power-on/power-off commands and data rate commands if required. Critical issues exist with respect to instrument calibration (for a sensor wholly enclosed within the penetrator shell) and absolute recovery of the magnetic vector direction post impact, due partly to the difficulty of acquiring knowledge of the azimuthal position of the impacted penetrator and partly due to the lack of sensor rotation after impact. Calibration will rely primarily on use of comparisons with lunar field maps/models together with in-situ data from a presumed orbiting magnetometer. The magnetometer sensors should be aligned along an axis within the penetrator with a knowledge and stability of 1^{o}.

4.2.5 Mass Spectrometer

The measurement of volatile content in the lunar regolith (both at polar and non-polar regions) is a key mission objective. The Lunar Evolved Volatile Ion Trap Analyser (LEVITA) is an instrument which through the identification and quantification of the volatile constituents in the lunar surface and subsurface aims to address outstanding questions regarding the distribution, origin and transportation of volatiles in the lunar system. The rationale for LEVITA is that the mass spectrometry analysis of evolved volatiles at penetrator impact sites will allow for the detection of volatiles and determination of their origin through isotopic analysis, and potentially the detection of other organic compounds to be found on the Moon.

4.2.5.1 Instrument conceptual design and key characteristics

The mass spectrometer system is based on the miniature state of the art quadrupole ion trap mass spectrometer used within the UK Ptolemy instrument on-board the ROSETTA lander Philae. This is a powerful yet simple device into which neutral gases are introduced into a cavity formed by three hyperbolic electrodes to which are applied suitable radiofrequency fields. A cold-cathode Field Emission Device (FED) is used to introduce electrons into the cavity to effect electron-impact ionisation of the gas molecules, and the resulting ions may become trapped within stable orbits within the cavity. Once trapped the ions are manipulated to fall upon an external electron multiplier detector to produce the mass spectra yielding information about the chemical and isotopic identity and abundance of the gas molecules.



Neutral volatiles are evolved from the sample material by either heating in a miniature oven, heating by a stand-off laser device or heating caused by thermal losses from the penetrator (in polar regions). The primary mode of operation relies on heating of samples within ovens. The oven is resistively heated, which liberates neutrals from within the sample in a stepwise manner. Stepped heating is an established technique which is commonly used to analyse extra-terrestrial materials. The temperature of each step is chosen to sequentially release more refractive components from the sample mixture, thus effecting a degree of separation before the released materials are further analysed in the mass spectrometer. Additionally, a calorimetric analysis method is incorporated into the heater oven. During the heating period, the power consumption required to achieve a pre-programmed heating ramp rate will be monitored, and thus the energy associated with phase changes in the sample will be reflected in the power profile.

The use of an oven would require a mechanism capable of delivering sample into the oven then sealing the oven. A de-scoped option would be to heat sample material upon a simple hot-plate, however with this arrangement lower sample temperatures would be achieved for a given amount of heating power. A number of types of analysis are possible depending upon the available resources. These include:

- Stepped heating / pyrolysis to evolve volatile components from the sample
- Analysis of isotopic composition of released water (i.e. D/H ratio) through use of on-board reagent gas
- Analysis of organic material
- Combustion (one step) of organic material with Oxygen at 500°C

An alternative heating method employing miniature, high powered solid state laser diodes could be used for material outside the penetrator body, either in a direct line-of-sight through an aperture in the penetrator body or via a deployable fibre optic cable. This approach might avoid the need for sample acquisition and will require further study. Finally, the presence of the penetrator will affect the local thermal environment resulting in an increase in the volatile sublimation rate which can be monitored. Operating the instrument in a 'background sniff' mode may give a contextual measurement to aid interpretation of results from other instruments e.g. gives understanding of changes in the external environment caused by impact event and penetrator presence.

The calibration system comprises of a number of miniature gas volumes containing reference and processing gases. These pressure vessels are sealed with in-house developed and patent-pending miniature high performance, high pressure valves which control the flow of gases to the mass spectrometer, allowing in-situ instrument calibration and sample processing.

4.2.5.2 Performance assessment

Instrument objectives are:

- Determination of surface compositions and chemistry, through the characterization of thevolatile content of surface and sub-surface material
- Measurement of the isotopic composition of organic material (D/H) to infer origin i.e. local or meteoritic.
- Determination of the organic compounds present.

Parameter	**Value**	**Comment**
m/z range	10 – 300 Da	molecular species from H_2O (~m/z 18) to organic molecules up to m/z 300
Mass resolution	Unit resolution i.e. >18 at m/z 18; >200 at m/z 200 etc	Baseline requirement.
Sensitivity	Sample size: 100 mg	

4.2.5.3 Operating modes

The following Science Modes have been identified:

Initialisation: Bring the instrument from a thermal cold start to operation temperature in preparation to start a science sequence. Heaters will be commanded to heat the mass spectrometer and parts of the system that come into contact with sample. Valves will be actuated to bring the required sub-systems up to pressure.

Background scan: Performs a background mass spectrum without sample. The background scan is essentially a diagnostic of out-gassing and off-gassing in the region of the penetrator and will allow volatile out-gassing of surface and sub-surface material surrounding the penetrator to be monitored over time as it warms up due to the presence of the penetrator.

Reference scan: Performs an in-situ calibration of the mass spectrometer with the on-board reference gas. The mode actuates and controls the flow of reference gas into the mass spectrometer cavity whilst a mass spectrometer scan is performed.

Oven sample: Requiring heater control, reference gas and pre-processing gases

Laser sample: The laser diode is run in constant power mode for a number of seconds to heat sub-surface material.

4.2.6 Seismometer

4.2.6.1 Description and Key Characteristics

The microseismometer elements are MEMS-based. A micromachined silicon suspension is used as the sensing element. This acts as a spring/proof-mass system, converting any external vibration to a displacement of the proof mass. This displacement is measured using a position transducer which consists of a series of electrodes on the proof mass and fixed frame forming a capacitive transducer together with sensitive readout electronics. The signal passes through a feedback controller and transconductance amplifiers to produce currents in a series of coils which form parallel electromagnetic actuators to maintain the position of the proof mass. There are two feedback loops, one producing the signal, and the second producing low-frequency integral control. One further coil is used to produce actuation from an external calibration signal.

Figure 4-1 shows the silicon suspension of the microseismometer fabricated at Imperial College, London. The suspension is formed by cutting through the 500µm thickness of a silicon wafer, using deep reactive-ion etching (DRIE). The clean profiles evident in the 30µm-wide flexures are the result of a concerted programme of DRIE optimization (Pike et al., 2004). In addition, the dynamics of the suspension are optimised to produce very good rejection of off-axis modes (Pike and Standley, 2005).

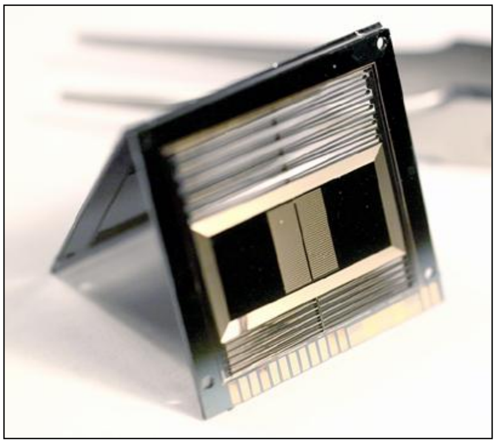


Figure 4-1: The silicon suspension of the microseismometer.
The die is 20mm square

The capacitance displacement transducer is of a novel design (Pike et al., 2006): the moving electrodes on the proof mass are in the form of an array which moves laterally over a similar array of fixed electrodes on the glass capping plate with the motion of the proof mass. Hence as the electrodes move in and out of registry with proof-mass motion, a periodic cycling of the capacitive coupling occurs. Optimisation of the design for this lateral capacitive array transducer, including the effects of stray capacitance, has been carefully studied and verified (Overmaat, 2005).

Finally, a magnetic circuit is mounted either side of the sensor-head sandwich. This provides the magnetic field for the feedback actuator. This circuit has been designed, modeled by finite element analysis, and tested against the modeling to a better than 90% agreement. The circuit consists of four rare-earth, rectangular magnets, four pole pieces and two soft-iron yokes which close the circuit.

Ruggedization against impact will be accomplished through the use of a highly pure volatile potting that sublimates after deployment (see Pike et al., (2009))

4.2.6.2 Instrument Performance

The requirements for a seismic investigation of the Moon (Table 4-3) are based on data recorded during the Apollo programme and lead to a need for: Low-noise; high-sensitivity; well-coupled, isolated from ambient noise; broad bandwidth; three matched components; Long operating time; Linearity. The microseismometer performance is shown in *Figure 4-2*.

Parameter	Requirement
Noise	< 1ng/√(Hz)
Bandwidth	0.03 to 80 Hz
Temp. coefficient	100 ppm full scale/K
Nonlinearity	<1% full scale
Range	0.05

Table 4-3: Microseismometer Performance Requirements

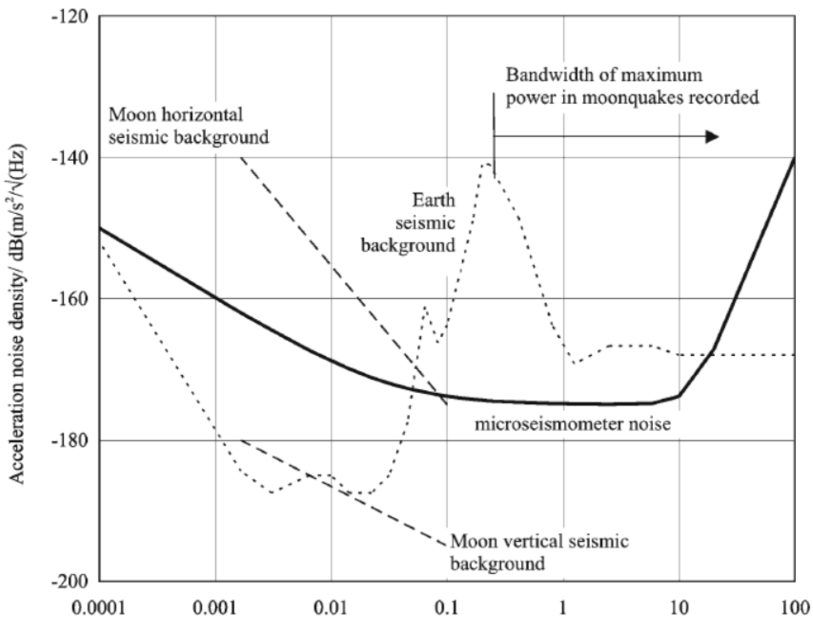


Figure 4-2: Comparison of the microseismometer's noise performance to horizontal and vertical axis background lunar seismicity measured during Apollo as calculated by Lognonné and Johnson (2007), and the Earth's background seismicity as determined by Peterson (1993), (after Wielandt, 1982).

4.2.6.3 Pointing and Alignment Requirements

In order that the components of the Moonquake-induced vibration map sufficiently to the axes of the microseismometer, the vertical microseismosmeter axis, and hence deployment, should be aligned to better than 10° to the Lunar surface normal. This requirement is only applicable during single, vertical-axis, operation. There is no absolute requirement on the azimuth, but knowledge of the azimuth will allow for complete vector determination of the vibration.

4.2.6.4 Operating Modes

Global network mode: 1-axis operation triggering 3-axis operation when a seismic event is detected. Lunar seismic events from Apollo showed that events had durations of up to 10s minutes and gave stronger signals in the horizontal axes compared with the vertical axis. This is typical for the Moon but unlike the Earth where the vertical axis normally dominates. It is therefore proposed to use a horizontal axis trigger. The S-P travel times of the phases are typically more than 100s (Nakamura, 1983, Lognonne, 2003) which implies a requirement to initialize the other axes within that time – the microseismometers will have an initialization time of 30s.

Full operation mode: 3-axis operation. For local seismic events the time-lag between axes will be less and so it is proposed to operate a higher power mode in which all axes are continuously active. To conserve power this mode will operate for one month at the beginning of the mission in order to characterize the local seismic environment. For the remaining mission the microseismometer will operate in a power-saving, 'global network mode'.

Sampling will be 10 24-bps with a bandwidth of 4 Hz, which covers most of the frequency range of moonquake energy. The baseline on-board data compression will be lossless and achieve an approximate three-times data volume reduction. For short periods a higher rate mode can be considered (200 24-bits samples per second)

4.2.7 Water/Volatile Detector

The measurement of volatile content in the shaded, polar Lunar regolith is a key mission objective and so in order to provide unequivocal results, whilst ensuring redundancy in this key area, an integrated suite of complementary instruments is proposed. The analysis techniques and sample requirements are listed below, while the description of a mass spectrometer is given elsewhere. Sample acquisition is also considered separately.

Technique	Method	Sampling requirements
Mass spectrometry	Direct	Sample ingress / laser stand-off
Spectroscopic	Direct	Sample ingress
Mutual impedance spectroscopy	Inferred	Touch sensor
Pressure sensor	Inferred	Sample ingress
Calorimetric	Inferred	Sample ingress

Table 4-4: Water and Volatile detection techniques

Note also that *in situ* measurement of regolith electrical properties is needed for interpretation of ground penetrating radar results from orbit.

4.2.7.1 Description and Key Characteristics

Mutual Impedance spectrometer: Laboratory studies of Lunar simulants have shown that a measurement of mineral dielectric constant is a suitable method of detecting water to levels of 0.1% (with possible lower detection limits of 0.001%). The sensors are physically small, simple devices and can be incorporated into the drilling mechanism allowing in-situ measurements.
Calorimetric analyser: The sample heater will be programmed to deliver a stepwise heating profile to elevate the collected regolith materials to above the sublimation point of ice, hold it there for a pre-determined time before turning the heater off and the sample allowed to cool. During the heating-and-hold period, the recorded temperatures and power profile will reflect sample cooling i.e. when ice sublimates more energy is required to maintain the programmed heating ramp so the presence of ice can be detected in the power profile of the heating cycle.
Pressure sensor: As the stepped heating profile is conducted, evolved gases expand into the analysis chamber and re-freeze when the heater power is switched off. The resulting pressure increase / decrease will be measured by a MEMS pressure sensor. The presence of water (and other volatile) ice will be detected in the temperature / pressure profile during sample heating and cooling.

Optical detection system: As the stepped heating extraction is conducted, evolved gases will expand into the analysis chamber. Spectroscopic analyses are conducted with a tuneable diode laser scanning across a single water line in the 1.37 µm region of the spectrum. The water vapour abundance in the chamber is calculated using Beer's law (e.g. May et al., 1993)

4.2.7.2 Operating modes (including mass spectrometer and sample handling)

A sequence of measurements is foreseen involving: Pre-impact checkout; Post-impact checkout Sample collection (drilling); Sample control (heating); Water detection 1 (Mutual impedance spectrometer); Water detection 2 (Heating / temperature); Water detection 3 (pressure/optical) ; Water detection 4 (mass spectrometer).

4.2.7.3 Current heritage and Technology Readiness Level (TRL)

The pressure sensors are devices which are in use on the Ptolemy instrument on Philae the Rosetta Lander (e.g. Wright et al., 2007) have TRL 8. The heritage for the optical detection system is based on the laser detection system which flew on the NASA Deep Space 2 instrument (e.g. Smrekar et al., 1999) which have TRL 6/7. The impedance spectrometer is based on proven mutual impedance probe which have been demonstrated on instruments flown on Philae the Rosetta (e.g. Trotignon et al., 2007; and Seidensticker et al., 2007) and Huygens (e.g. Fulchignoni et al., 2002) spacecraft at TRL 8. The subsurface element is based on mutual impedance probe being considered for mole deployment (e.g. Simoes et al., 2006) at TRL 4 and can be expected to increase as part of the HP3 instrument on ExoMars development.

4.2.8 X-Ray Spectrometer

4.2.8.1 Description and key characteristics

The aim of the geochemistry element is to greatly improve our understanding of global Lunar geochemistry by performing in-situ analyses at globally dispersed sites, and to provide contextual information for related payload elements such as the Polar Volatiles detector and accelerometer. The requirement is therefore for one or more techniques that can detect and quantify the major rock-forming elements e.g. Mg, Al, Si, Ca, Fe, Ti.

The selected technique is X-ray spectrometry, for which the Beagle 2 X-ray Spectrometer (XRS) provides the benchmark. Primary excitation was provided by two ^{55}Fe (emitting X-rays of 5.90 and 6.49 keV) and two ^{109}Cd sources (emitting X-rays of 22.16 and 24.94 keV). The fluorescent X-rays are detected by a Si PiN detector The instrument utilises excitation from radioisotope sources, identical to the Viking landers XRS, but uses the solid state detector as used by the APXS on Pathfinder. The instrument is sensitive to X-rays in the 1-27 keV range and the corresponding range of detectable elements is from Na to Nb.

The baseline XRS is based on the Beagle 2 instrument and comprises two parts: the detector head assembly (DHA) and the Back End Electronics (BEE). The XRS will view the sample of the Lunar regolith brought into the penetrator volume by the micro-drill. Alternatively, a small x-ray transparent window with shutter could be provided in the rear wall of the penetrator.

4.2.8.2 Performance assessment

Expected accuracies and detection limits are shown in *Table 4-5* below.

Element	Si	K	Ca	Ti	Fe	Rb	Sr	Zr
Accuracy	-	0.11	0.070	0.098	0.034	0.10	0.15	0.047
Detection limit (µg/g)	-	360	230	120	420	13	14	9.0

Table 4-5: XRS Accuracy and detection limit

4.2.8.3 Current Heritage and Technology Readiness Level

Heritage for penetrator-borne XRS is provided by the ANGSTREM instrument in the aftbody of the Mars 96 penetrators. The LunarEX penetrator benefits from Beagle 2 heritage. Hence we assign TRL = 7 but must bear in mind that the instrument will require qualification at high-gee levels.

4.2.8.4 Critical issues

View of micro-drill sample volume vs window and shutter trade-study to be performed.

4.2.9 Tilt Meter

The goals of this experiment is to determine the angle from the local vertical at which each penetrator is tilted. This is needed to determine the orientation of the seismometer axes and to help measure the vertical temperature gradient for the heat flow determination. It will be required to measure the attitude of the penetrator to better than 0.1°. A number solutions are possible including a device 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. Other possibilities include Spectron L-series, as used by The Open University group on *Huygens* and the *Mars 96* penetrators, Analog Devices ADXL320, and two-axis electrolytic inclinometer (e.g. from Fredericks Company).

4.2.9.1 Current heritage and Technology Readiness Level

Current TRL 6-8 depending on choice of sensor. Options to be evaluated include:

4.2.10 Sample Acquisition

The present baseline penetrator payload includes a requirement for sample acquisition. This can be achieved either through passive (such as a scoop) or active (such as a drill) means. In fact, options to achieve all mission goals without sample acquisition (through local remote sensing) are also to be evaluated. In this proposal we baseline a sample acquisition drill mechanism.

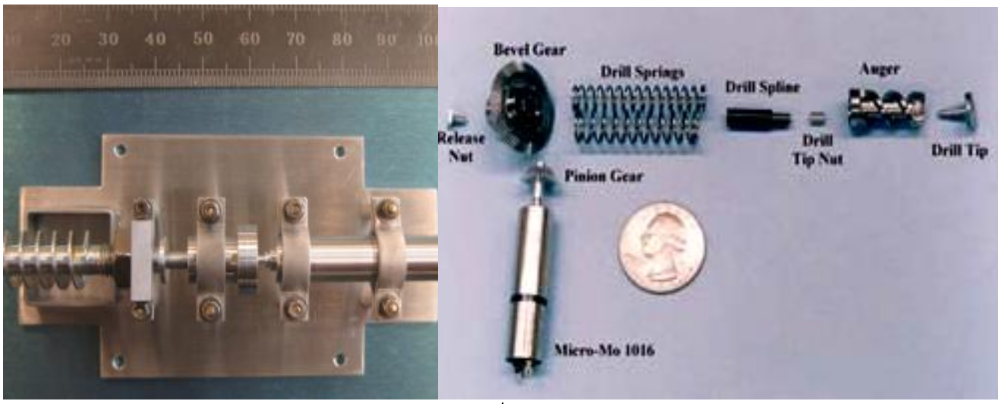


Figure 4-3: Left: SSC micro-drill at 1st Pendine impact trial Smith et al 2010; Right: DS2 probe drill (http://nmp.nasa.gov/ds2/tech/sample.html

4.2.10.1 Description and key characteristics

The major components of an active sampling mechanism include electric motor, gearbox, drill string and drill bit. Releasing/withdraw mechanism of the drill string is key to the design. Possible solutions include using a driven screw or loaded spring.

Figure 4-3 shows two drill prototypes for active sampling. The micro-drill developed in Surrey Space Centre uses screw-driven method and the DS2 drill used loaded spring.

Instrument design: The current baseline design for technology development is to use active sampling approach and build upon the Surrey Space Centre (SSC) micro-drill concept, which provides a simple and mechanically robust solution to acquire a sample. It has the advantage in terms of high controllability over the SAS operation and support multiple-time sampling in comparison to any passive methods. Basic structure of the first SSC micro-drill prototype has survived the 1st Pendine impact trial Smith 2010 and has since been further improved.

Drill Assembly: This consists of the drill bit, drive mechanism, an electric micro-motor, as well as mountings to the penetrator compartment (see illustration below).
The latest SSC micro-drill prototype has modified the mounting of the original design, since this is where the main failure occurred during the Pendine impact trial. It also enhances the drive mechanism by adding a spring driven function, which takes advantage of the ability to retract the drill of the screw driven and the function of the spring driven to chip away at hard materials. The drill is rotated using the micro-motor and propelled forward via the screw thread; the spring allows the drill to continue to rotate in order to chip away at any hard material without forcing the drill into it thus causing it to become jammed.

Outer shell penetration will be achieved either by drilling through a plug or with a door/flap/iris mechanism.

4.2.10.2 Performance assessment

The current requirements are summarized as follows:

Sample collection per deployment:	~200 mg
Number of sampling:	>=1
Sampling distance:	1-2cm from the shell
Mass: Power: Dimensions:	~ 50 g 1.5 W peak during operation Within one payload compartment which can be shared with another instrument
Working temperature:	70K
Operation duration per sampling:	In the range of a few minutes
Controllability over sampling (e.g. time, speed, sample quantity, location, etc):	High

Prototype build and testing with a lunar soil simulant at SSC involved a SAS Mass (incl. micro-switches and wiring) of 79.9g, a dimension of 90x25x20 mm. The average operating power during sampling was 0.64 W with a peak of 1.19 W. The average sample collection per deployment was 336.8 mg (+-20mg) while the average time for sample collection, including withdrawal of the drill, was 15 +/-1s. The sampling distance was 1cm. From this the total power usage during sample acquisition is estimated as ~0.003 Whrs

4.2.10.3 Heritage

A similar drill was flown on Deep Space-2 (TRL 6). The SSC design is currently at TRL 3-4, parts having been tested during the Pendine trial and within the laboratory

4.2.11 Proposed procurement approach

It is proposed that the Penetrator together with its payload be provided from national agencies. The various payload elements will be procured from collaborating instrument consortia. The baseline proposed here is an exemplar based on the current state. Actual procurement will be a mixture of COTS acquisitions (e.g. Accelerometer) and bespoke developments (e.g. Micro-seismometer, Mass Spectrometer, Sample acquisition). The majority of payload elements will come from international consortia and expertise in penetrator technology is available within Europe, the USA, Japan and Russia. Canada and China have also instigated penetrator research and development programmes.

5 System requirements and spacecraft key issues

5.1 Basic spacecraft key factors

One Lunar **orbiter** spacecraft is required, which carries the 4 descent modules. Each **descent module** consists of a single **penetrator** attached to a payload delivery system (de-orbit motor and attitude control system**)** which is ejected prior to impact.

5.2 Orbiter

The Orbiter will include for each descent module - accommodation, commanding and telemetry communications (health status), power, and ejection mechanism.

5.2.1 Attitude and orbit control required

The AOCS system of the LunarNet orbiter is required to perform 3-axis pointing for such tasks as orienting the spacecraft during the propulsive mission phases, antenna pointing for communications, directing solar panels towards the sun and launching penetrators towards the desired locations on the Lunar surface. After the deployment of the penetrators on the surface, the orbiter will continue to operate and communicate with the surface instruments and with Earth until the end of the mission. During this time ΔV orbit maintenance will be performed to ensure adequate visibility with the surface instruments and the Earth ground station. The basic AOCS system requirements are summed up as below:

3-axis pointing accuracy:	1 degree
Array pointing accuracy (all phases):	5 degree
Lunar insertion pointing accuracy:	1 degree
Mission lifetime:	1.2 years

5.2.2 On-board data handling and telemetry

Prior to penetrator deployment, the orbiter will need to provide commanding and power to each onboard descent module for a limited number of occasions to enable health checks. During deployment the orbiter will be required to accept descent module health checks, and if possible descent camera images. After deployment the orbiter will need to provide regular (e.g. every 15 days) communications with the penetrators for commanding and uplink of data, and to relay this information to Earth. The orbiter will also need to accept commands from Earth and telemeter to Earth a small amount of housekeeping data to support its own orbital manoeuvres and sub-systems. To support these requirements an orbiter data handling system is envisaged to consist of two redundant on-board computers (OBCs). On-board data handling for the 15 communication slots with the penetrators is described in section 5.4.2 and 5.4.3.

5.3 Penetrator Delivery System

There will be four descent modules, each comprising of a penetrator and aft de-orbit and attitude control system which is ejected from the penetrator prior to penetrator impact. A descent camera will be mounted on the descent module. Table 5-1 provides the mass budget for the equivalent

MoonLITE case (courtesy Astrium) indicating an overall mass with 15% system margin of 38.6 kg for the PDS.

Subsystem	Item	Unit Mass [Kg]	#	Basic mass [kg]	Margin [%]	System Mass [Kg]
Propulsion	SRM	5.200	1	5.200	10%	5.720
	RCS	2.744	1	2.744	10%	3.018
Atttitude control	MEMS IMU/gyro	0.100	1	0.100	20%	0.120
	Sun sensor	0.330	1	0.330	20%	0.396
Mechanisms	SUEM with orbiter	0.100	1	0.100	20%	0.120
	Penetrator / PDS Release	0.400	1	0.400	20%	0.480
Interfaces and harness	Harnessing/umbilicals	0.650	1	0.650	20%	0.780
Power	Battery	0.300	1	0.300	5%	0.315
Data Handling	OBC	0.400	1	0.400	20%	0.480
Structure	PDS Carrier Structure	1.000	1	1.000	20%	1.200
Communications	Antenna	0.200	1	0.200	20%	0.240
PDS Dry Mass						12.87 kg
System Margin					15%	
PDS Dry Mass Including margin						14.80 kg
Solid Propellant mass						23.68 kg
RCS Propellant mass incl.residuals						0.129 kg
PDS TOTAL MASS						38.607 kg
Penetrator mass						13.000 kg
DESCENT MODULE TOTAL MASS						**51.607 kg**

Table 5-1: MoonLITE Descent Module Mass Breakdown

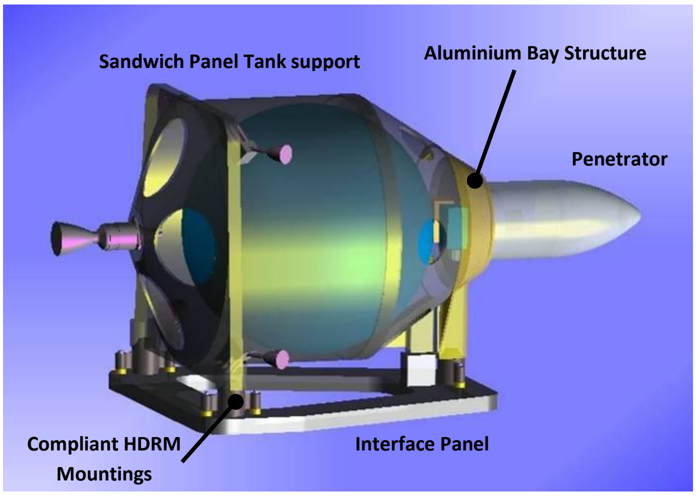


Figure 5-1: Penetrator Descent Module (Europa example)

[The preliminary MoonLITE PDS design was based on a solid fuel de-orbit rocket and a liquid fuelled system for other manoeuvres. Analysis following the ESA Europa study (Astrium, 2010) shows that a liquid fuelled de-orbit and reaction control system would be feasible for LunarNet with some mass savings.]

A value of 50kg is assumed here for LunarNet Descent Module including margins. The Europa Descent Module is shown in *Figure 5-1*, and a provisional timeline for the Descent Module is given in Table 5-2 and sequence in Figure 5-2.

Event	Label	Total Time (s)	Delta Time (s)	Altitude (m)	Horizontal Velocity (m/s)	Vertical Velocity (m/s)	Spin Rate (rpm)	Description
Release + Drift	t1	0.0	10.0	24815	1700	0	TBD	Release of DM, drift
Spin-up	t2	10.0	2.5	24815	1700	0	100	Spin up to give nutational stability.
De-orbit	t3	12.5	31.6	24815	1700	0	200	Perform de-orbit manoeuvre.
Spin-down	t4	44.1	2.0	24323	120	-43.5	200	Spin down with active denutation.
Calibrate attitude	t5	46.1	2.0	24233	120	-46.9	0	Calibrate attitude with sun sensor.
Re-orientation	t6	48.1	20.0	24136	120	-50.1	0	Re-orient to target attitude.
Take photos	t7	68.1	20.0	22812	120	-82.6	0	Take photos, if required.

Spin-up	t8	88.1	3.0	20839	120	-115.0	0	Spin-up to give gyroscopic rigidity.
Separation	t9	91.1	95.6	20487	120	-119.9	100	Passive separation (spring).
Impact	t10	186.7	N/A	0	120	-275.0	100	Impact on lunar surface with total velocity <300m/s.

Table 5-2: Provisional Descent Timeline

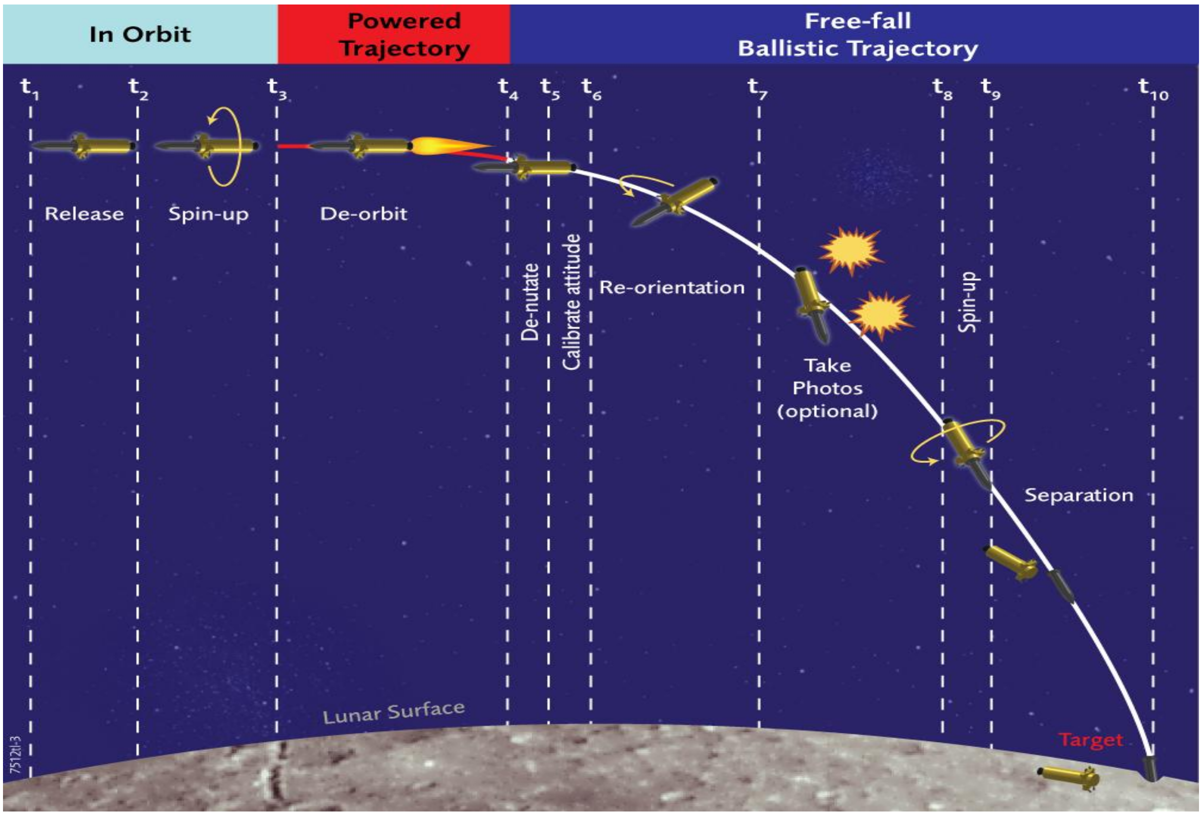


Figure 5-2: Provisional Descent Sequence (Courtesy Astrium)

A preliminary trade study of propulsion options for the PDS, including Full Mono-prop system, Full Bi-prop system, Solid Rocket + Mono-prop system RCS and Solid Rocket + Cold gas RCS. The Solid Rocket + Mono-prop RCS was selected as the baseline. The Solid Rocket Motor is used for the deceleration and a mono-prop (hydrazine) system for the remaining manoeuvres. This is primarily due to the mass/volume saving over a cold gas system and the simplicity of a single propulsion system for all phases (excluding deceleration burn) opposed to solid/mono-prop combinations.

A 3-axis control approach is baselined for the attitude control based on its lower risk and relative simplicity. The sensors used must be small, inexpensive, and provide adequate attitude data. The most convenient choice of primary sensor is a 3-axis Inertia Measurement Unit (IMU) which combines a gyroscope with an accelerometer. The gyro gives rate information which then can be integrated to give attitude data. The accelerometer can be used to measure the residual horizontal component of velocity after the de-orbit burn. This knowledge can then be used to calculate the target impact attitude and any necessary rate correction for the RCS. Many COTS Micro-Electro-Mechanical System (MEMS) IMUs with good performance are now available. These can be lightweight, small, and inexpensive and the technology is improving rapidly.

Separation of the Penetrator from PDS is foreseen prior to impact, 90s will give 5m between Penetrator and PDS impact locations.

5.3.1 Heritage and Technical Readiness Levels

A Lunar-A PDS was fully developed prior to mission cancellation implying a generic TRL of the technology of TRL 6. All proposed technologies within the PDS are flight proven at component level.

5.4 Penetrator

Some general characteristics of a penetrator and its requirements on the penetrator delivery system are provided in *Table 5-3*. Each penetrator will be ~0.5m long and ~13kg mass (similar to Lunar-A) and will be a simple "single-body" type (as opposed to fore-/aft-body types such as Deep Space-2). They will each consist of a supporting structure, a power system, comms system, data handling system, and payload.

Mass (at impact)	13kg
Impact deceleration	Up to 20,000 g.
Impact angle (between impact velocity vector and tangent to surface)	~90° (not critical)
Attack angle (between penetrator long axis and impact velocity vector)	~<8° (critical)
Penetration depth into regolith	2 to 5m.
Ambient penetrator operating temperature:	-20°C to -50°C. (50K to 100K in shaded polar craters)
Mean penetrator power (subsystems & payload)	60mW.
Mission duration	1.2 years (1 year on surface)

Table 5-3: Penetrator characteristics

A preliminary study of penetrator structure options has been carried out by QinetiQ (Church, 2007). Four alternative materials were considered, steel, aluminium alloy, titanium alloy and carbon composite. A summary of results from this study are shown in Table 5-4.

Penetrator Shell Material (for 720mm length)	Wall Thickness (mm)	Projectile Internal Volume (cm^3)	Projectile Filling Mass (kg)	Projectile All-up Mass (kg)
Aluminium Alloy	6.5	6500	7.44	13.0
Steel	11.5	5700	6.5	27.4
Titanium	2.5	7300	8.46	10.8
CFRP Compression Moulding	7	6400	7.33	10.5

Table 5-4: Penetrator Structure options

These figures should be compared with an estimated payload volume requirement of:
Scientific payload elements - 1477 cm^3
Batteries - 1000 cm^3
Electronics - 1500 cm^3
Total - 3977 cm^3

This leads to an occupancy factor of 61% for an Aluminium shell (the selected baseline).

The Laplace study led to an internal design as indicated in Figure 5-3. Note that this design is similar to that used during the Pendine trials except that snubbers are used to separate the inner bays from the outer shell – an approach which radically eases the thermal control issue.

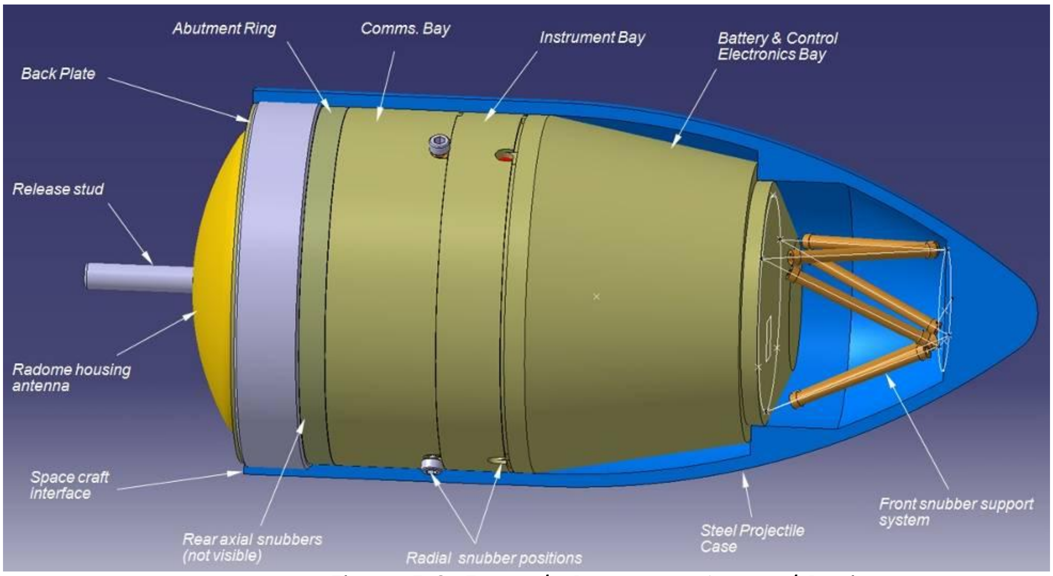


Figure 5-3: Example Penetrator Internal Design

5.4.1 Power

Because the penetrator will be completely buried under the Lunar regolith power will be entirely supplied to the penetrator systems by batteries. Initial studies for this proposal (Wells 2007) indicate the use of Lithium thionyl chloride primary cells, as planned or adopted for DS-2 and Lunar-A, with an energy density of ~275Wh/kg. The Lunar-A team report an energy density of 430Wh/kg (Mizutani et al., 2005). For these batteries, both the operating temperature and g-force survival levels have significant margins over the LunarEX requirements. The initial study indicates a battery mass of the order of ~2.5Kg/penetrator, corresponding to a capacity of ~550W.hr (depending upon operating temperature). For non-shaded sites, operation of a penetrator comparable to Lunar-A dimensions should achieve a similar 1-year operational lifetime. For the shaded polar sites, where there are much lower temperatures, extended operations will require careful consideration of insulation and could greatly benefit from use of RHUs.

5.4.2 Onboard data handling and telemetry

Because of the expected infrequent communication contacts with the orbiter, (> 2 per month depending upon penetrator latitude) each penetrator will need to operate autonomously, collecting, compressing, and storing data until each uplink opportunity. A small commanding capability is necessary to allow optimization of seismic data selection and data volume reduction. Because of the low radiation environment an FPGA, small micro-controller or micro-processor solution will be strong candidates for this mission with relatively high density memory. The nature of the scientific payload will naturally allow for a high degree of sequential operation with initial uplink of descent camera images and accelerometer data collected during impact. This will be followed by geochemical and temperature data. Heat flow measurements will not be possible until after thermal stabilization possibly after a whole Lunar cycle or more. Seismic data will be the only instrument required to operate more or less continuously throughout the whole mission. This will allow, as resources permit, a significant processing and memory storage saving via natural prioritisation. In addition it will be planned to select only the most significant seismic data for transmission.

Assuming a 90 sec uplink window within a single 12 minute contact period/penetrator every 15 days, an uplink rate to the orbiter of 5 kbits/s will be sufficient to return an estimated total data volume of 12 Mbits (with a 40% margin) within the 1 year lifetime. The data return is dominated by the seismometer for which approximately half of the telemetry is allocated. The recent ESA Europa study (Astrium,2010), indicates that this is feasible as a minimum capability, and with potential for a factor 4 or more higher depending the penetration depths and signal attenuation levels which are expected to be low for both these worlds. For 4 penetrators this requires the orbiter to relay an average of 120 kbits/day from the penetrator to the orbiter and from the orbiter to the Earth.

5.4.3 Communications

One contact/penetrator every 15 days, corresponds to a total of ~2W.hr for the necessary 90sec transmission contacts (in a general 12 minute window). A similar amount will be required for the receiver leading to around 4W.hr which is <1% of the total power budget, with ~99% of the power left for payload and data handling.

The baseline communication design is a body antenna mounted at the aft (trailing) end of the penetrator. The antenna would be conformed to the surface of the penetrator, to ensure a smooth, projection free surface. As the body diameter is quite small for a UHF antenna, a helical or similar antenna may be needed; alternatively dielectric loading could be employed at the expense of mass. The dielectric properties of the regolith would need to be taken into account in designing the antenna in order to optimise performance when buried. Testing would also need to replicate these conditions. The ruggedised UHF transceiver built by QinetiQ for the Beagle 2 mission to Mars, is proposed as a starting point. Its mass is approximately 600g, and its design is based on the highly successful MELACOM transponder, still in operation in Mars Orbit. MELACOM would be a logical unit to deploy on the Orbiter. The design could be updated and miniaturised for the LunarNet mission, with an emphasis on the engineering to survive the high gee environment. Study of the link budget shows that a 0.5W omni-directional UHF transmitter on the penetrator can transmit 15 days of data to the orbiter in ~90s with a more than adequate ~30dB of margin. The composition of the Lunar regolith will have a significant impact on the achieved margin of the link for which a minimum margin of 20dB has been assumed to account for possible regolith attenuation on the link.

5.4.4 Heritage and Technical Readiness Levels

a. **Shell:** for a shell with no apertures there is extensive Earth based defense sector heritage at impact velocities in excess of 300m/s, and space implementation heritage with DS2, Lunar-A, Mars-96. For a shell requiring apertures, heritage exists via the DS2 implementation of a drill which drilled through the side of the penetrator wall. A new element of shell design is use of titanium alloy material.
b. **Vacuum Flask bay system**: No heritage.
c. **Communications:** based around the Beagle-2 and MELACOM UHF design.
d. **Power** (Batteries): Commercial batteries are baselined with Li-$SOCl_2$ which has extensive space heritage, but not impact heritage.
e. **Penetrator Management System**: This will be an adaption of data processing and control units that MSSL has built for many space systems, and of the particular development for the successful Pendine impact trial design.

Penetrator Item	TRL	Comments
Shell	4-5 1-2	No apertures: Design modelled, and similar designs have survived impact with gee forces we expect. Apertures: Concept developed.
Vacuum flask Bay system	2-3	Concept designed and analysed.

Communications	4-5	Modification of existing communications systems with extensive space heritage, and impact hardened.
Power (batteries)	3	Commercial provided.
Management system (DPU, PCU)	4-5	Modification of existing technology with extensive space heritage, and Pendine impact trial impact survival.
Sample Acquisition & Handling	3 1-2	Drill assembly. Outer shell penetration

5.5 Mission operations concept (ground segment)

For the relatively brief mission phases comprising operations from launch to the moon; the 4 penetrator deployment events; and commissioning will require significant human operator monitoring, whilst the majority of the 1 year mission could be operated with minimal human intervention. Ground reception and commanding facilities would only be required for the majority of the time to cover short e.g. 30 minute periods for the penetrator once in 15-day data uploads and commanding with the orbiter occur. Operations with the orbiter outside these periods could be performed autonomously. Suitable ground station networks could comprise a mixture of UK and other commercial ground stations (such as used by SSTL for the Giove-A mission) and ESA facilities.

5.6 Estimated overall resources

(a) Mass: Preliminary LunarNet mass estimates are provided in *Table 5-5*.

ITEM	Mass (Kg)
Structure	131.0
Communications	8.4
Power	28.7
Solar Panels	15.3
AOCS	44.1
Propulsion	66.1
OBDH	6.5
Environmental	16.6
Harness	30.0
Payload (4 penetrator descent modules)	206.4
System Margin (platform)	34.7
Total (Dry)	**587.8**
Propellant (Transfer, LOI, OM) AOCS Propellant	323.2 11
Propellant (Total)	**334.2**
Total (Launch)	**922**

Table 5-5: LunarNet Mission Mass Estimate for nominal 4 penetrator payload (extrapolated from Gao et al 2008).

Since the available mass into Lunar Orbit with a Soyuz-Fegat is 1250kg then a margin of 328kg is available.

(b) Power: Power for the landed penetrators will be supplied by primary batteries providing 550 W.hr (See 5.4.2). Power for the orbiter is modest as there is no orbital payload. It is envisaged that the orbiter power will be provided by solar cells supplemented by batteries. The provision of suitable solar power and battery capacity will need to take into account large (e.g. 40%) solar eclipse in a low lunar polar orbit. Because of the difficulty of locating solar cells on the walls of the orbiter due to the accommodation requirements of the descent modules, a deployable solar array system is envisaged.

Comparing power requirements with Mars Express leads to a preliminary estimate of ~450 Watts for the orbiter.

5.7 Specific environmental constraints (EMC, temperature, cleanliness)

5.7.1 EMC/EMI

No unusual requirements are foreseen in this area. Detailed requirements will be developed during phase A.

5.7.2 Radiation

The spacecraft will most likely be injected into an initial GTO orbit, using its own propulsion to transfer onto the desired Lunar Transfer Orbit (LTO). Even so, the spacecraft will spend very little time traversing the Van Allen Belts. Therefore, the total dose induced will be small (<2 krad(Si)) for transfer and a mission lifetime of 1 year in lunar orbit and still less than 5 krad (Si) for 5 years in orbit.

The probability of single event latch-up damaging the mission must also be quantified. In the Lunar environment the heavy ion spectra density will be similar to the MEO environment (GIOVE-A orbit). Therefore, the units with GIOVE-A heritage are suitable for this mission without the need for increased radiation protection (have experienced m = 7 solar flare). In addition, this spacecraft is protected with redundant systems and current monitoring at suitable locations. Over-current conditions lead to the automatic shutdown of the system. This approach has proven to offer robustness at a system level.

The penetrators themselves will be buried below >2m of regolith and so relatively well shielded.

5.7.3 Thermal

The spacecraft thermal environment has been assessed with the spacecraft in its operational orbit. With the spacecraft in yaw steering mode heat can be dissipated via conventional passive radiative surfaces. Heating in cold case conditions (i.e. eclipses) will require the use of electrical heaters.

The penetrator thermal environment depends upon their location but can be as cold as 70K in a permanently shaded crater. For this reason a vacuum flask concept has been proposed by MSSL (and reported in the Laplace study (Astrium, 2010). RHUs for heating will be evaluated as part of a Phase A study.

5.7.4 Cleanliness

Some limitations may be imposed upon lunar impact sites related to planetary protection. However, given the wide choice of sites available and the history of impact of man-made objects onto the lunar surface (more than 70) it is not likely to be an issue.

5.8 Proposed procurement approach

- Spacecraft: Prime contractor
- PDS: Sub-contractor
- Penetrator: National agencies
- Ground operations: Prime contractor or Third Party

6 Science Operations and Archiving

It is assumed that the agency will be responsible for spacecraft operations support including telemetry, immediate health and safety monitoring, and any commanding that may be included. The scientific consortium will be responsible for detailed specification of agency operation requirements, more detailed health and safely analysis, calibration, scientific data analysis, and command generation.

6.1 Science Operations Architecture and share of responsibilities

Science operations for this mission are envisaged as follows :
(a) **Orbiting support spacecraft** – Intense operational support will be required for the launch, and early post launch phase, orbital manoeuvre changes, and then at a low level for regular spacecraft health and safety (housekeeping) monitoring throughout the nominal 1 year mission.
(b) **Penetrators** – It is envisaged that there will be intense operational support for pre-deployment health and safety checks, follow by orbital deployment, and impact. Deployment of penetrators will occur approximately every 2 weeks. Contact with each penetrator is expected every 15 days (more frequently for polar penetrators). After the initial 1-2 contacts only the seismometer and heat flow experiments will be operating, and operational support will be reduced.

In summary, operational support during the first 3 months will be relatively intense with a co-located science team assessing data and optimising the payload operations. For the latter part of the mission (following 9-12 months) operations will be relatively routine.

6.2 Archive approach

All scientific data should be archived. It is to be noted that the total penetrator data volume is expected to relatively small at ~30kbytes/day, generating 11Mbytes/yr * 4 penetrator mission = 44Mbytes for a complete 1 year mission.

6.3 Proprietary data policy

All the scientific data shall be made public 6 months after the end of the mission. However, data of public interest from the descent cameras will be made publicly available immediately.

7 Technology development requirements

7.1 Payload technology challenges and technology development strategy

All payload instruments are based upon proven space applications or are under development for other space missions. However, relatively few high velocity impact missions have been flown, the majority of the payload must be ruggedized. The Pendine trials indicated that this was an entirely feasible approach given the level of experience in such impacts available to the team. The general approach to ruggedization of payload instruments involves the following (Church et al., 2009) :-

- Lunar regolith properties determination from available source material and geological considerations
- Impact modelling to determine likely shock loading and shock-induced stress
- Small scale modelling and impact trials (e.g. at the Cavendish Laboratories in Cambridge, UK)
- Full scale design qualification at Pendine

Within the payload instruments the following are the most critical developments :-

- Impact hardening of micro-seismometer through the use of a volatile packing material
- Drill (with option to use passive sample acquisition or aperture if necessary)
- Heat flow feasibility through modelling of the thermal disturbance of the regolith.

To permit flexible trials and facilitate AIV, the strategy of using an inner-bay design (see Smith et al 2010) will be continued. This approach allows clear interface definition and permits sub-system testing in isolation.

Within the Penetrator the following areas require short-term development or study:

- Snubbered shell approach – thermal and impact modelling and trials
- Penetrator Aperture – impact modelling and trials
- Power system (battery) performance at low temperatures
- Penetrator packing material behaviour at low temperatures
- Communication system demonstration and modelling of the effects of the overlying regolith

7.2 Mission and Spacecraft technology challenges

The Penetrator deliver system is a spacecraft in its own right, albeit with a lifetime of only a few minutes. Following the EADS Astrium study of MoonLITE the following technological challenges were identified:

Guidance, Navigation & Control

- Location / Attitude detection and algorithmic handling
- Control to reach the impact zone
- Rotational dynamics of the Descent Module

De-orbit stability and rocket motor accuracy

- To ensure a predictable de-orbit burn within the requirements

Mass, Cost, and Risk

- Technology selection /TRL level de-risking
- Resource sharing with the Penetrator and Orbiter

Validation Testability

- Ensuring that the design can be validated before flight

On-orbit Testing and Reconfiguration

- Enabling adequate testing and reconfiguration prior to release at the Moon
- Analysis of descent communications

8 Preliminary programmatics/Costs

8.1 Overall proposed mission management structure

LunarNet is proposed as an ESA mission with international collaboration only occurring at the level of the penetrator and payload. *(Possible involvement in EJSM mission could produce cost savings via bilateral arrangements and development of the penetrator delivery system)*

8.1.1 Basic integration & verification approach and model philosophy

The verification and validation approach for penetrators is :-

a) Component level verification and validation through modelling, and small scale impact testing, and performance testing.
b) Integrated level verification through large scale (Pendine) impact trials, including, during trial and post impact performance testing.

Model philosophy and schedule (relaxed from the Europa TDA study) is provided in Table 8-1 for a late 2020 launch. A later launch will provide more contingency.

Model		Schedule		Comments
BB	Breadboard Model	2014	1yr	Phase A/B1.
STM	Structural & Thermal Model	2014-2015	1yr	Depending on when required.
EM	Engineering Model	2015-2016	2yr	Impact survival - flight quality parts.
QM	Qualification Model	2017	1yr	Functional and environmental performance model.
FM	Flight Model	2018 2019 Start 2020	1yr 1yr -	Fabrication and unit testing. Penetrator AIT followed by PDS AIT. PDM delivery to Orbiter
FS	Flight Spare	2018-2019	2yr	Possible refurbishment of QM.

Table 8-1: LunarNet Model Philosophy and Schedule

8.2 Mission Schedule Drivers/Risks

- Timely provision of funds to complete TRL5 Technology developments by end 2014. (In particular to extend demonstration of impact survival of all penetrator elements, beyond MoonLITE subset involved in successful initial Pendine full scale impact trial. Expect imminent follow on ESA funding to demonstrate impact survival of payload elements)

- Timely agreement and definition of bi-lateral arrangements on penetrator technology, to allow partition of elements to contributing nations. Risk of insufficient national funding support for penetrator. (Bi-lateral discussions between UKSA and JPL and currently underway with regard to penetrator inclusion on proposed mission EJSM JEO).

8.3 Payload/Instrument Cost

It is proposed that the penetrators should be provided by ESA nations with non-ESA collaboration, while the Penetrator Delivery System should be funded by ESA.

8.3.1 Assumed share of payload costs to ESA

It is assumed that all payload costs will be provided by national funding.

8.3.2 Estimated non-ESA payload costs

Estimated non-ESA payload costs are 75 MEuros, which assumes selection of the most capable but expensive mass spectrometer of ~15M Euros. (*(Using payload cost estimates provided to the recent ESA TDA (Technical Development Activity) studies, a reasonable instrument suite composed of 5 instruments is estimated to cost ~20 MEuros. Assuming a 25% cost saving on replication of build costs of instruments for 4 penetrators, plus 1 instrument spare, leads to a total cost of 75 MEuros.)*

8.4 Overall mission cost analysis

Table 8-2 shows a simple comparison between Mars Express and LunarNet. MEX and LunarNet appear similar in that both involve a planetary orbiter element and a surface element.

Aspect	Mars Express	LunarNet
Launch Mass (kg)	1223	922
Launcher	Soyuz Fregat	Soyuz Fregat
Mission Duration	>4 years	1.2 year

Mass of Surface Element	71 kg (33kg Beagle-2)	206kg (descent modules) (4 x 13kg penetrators)
Mass of orbiting payload	116kg	0kg
Mass of fuel	426kg	334kg
Launch dry mass (i.e. launch mass - fuel)	797kg	588kg
ESA Costs (M€)	204	204*
National Costs (M€)	~100	~75

* Reductions can be envisaged from reduced operations costs from 1 year mission only. Additional cost of de-orbit and attitude control units is offset by the savings from the absence of an orbiter scientific payload.

Table 8-2: Mars Express – LunarNet comparison

Assuming operation costs for 1 year at 50M Euros, the total cost to ESA is 254M Euros.

9 Communication and Outreach

The Lisbon European Council Meeting in March 2000, in the celebrated "Lisbon Declaration" recognized the important role of education as an integral part of economic and social policies for strengthening Europe's competitive position worldwide. The meeting set the strategic objective for the European Union to become the world's most dynamic knowledge-based economy.

However in summing up the outcome of the recent Space Education Forum held in June, 2007 at the international Space Science Institute in Bern, the Executive Director Professor Roger M. Bonnet remarked "that the aims of the Lisbon Declaration are pursued energetically in the USA but apparently no longer in Europe"

Europe is critically short of young scientists and engineers. Of all the domains that have the potential to inspire, Space remains at the forefront. Within the Space domain, planetary science and exploration is probably the most engaging to the public.

LunarNet has the potential to be a very high profile mission. It will be novel and exciting and will take place at a time when Lunar exploration has re-emerged in the public eye. A general sense of 'Man returning to the Moon' is growing and we can expect to see a dramatic increase in interest. This will improve public awareness of the issues that the mission seeks to address (origin of the Earth, implications of water ice on potential for manned planetary exploration and the origin of life).

The relatively short duration of the first phase will include a number of significant events (Launch, orbit insertion, four surface deployments and four 'first light's plus potential water discovery and, later Lunar core discovery) which should maintain public interest and media coverage. While comparisons with Apollo will be made, it will also be noted that at least two penetrators will impact in locations which were not accessible to Apollo (Far Side and shaded craters): thus it will be easy to communicate significant advances being made by LunarNet.

Within this context it is proposed to plan an outreach programme linked to key mission milestones. Live coverage of impacts and first transmission is a strong possibility since through ESA ownership, confidence will be very high. Descent images transmitted in near real time will be reminiscent of the first Ranger photographs.

Moreover, the high technology, and apparently highly challenging nature of the penetrator concept offers a showcase for European technology.

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