MoonLITE: A UK-led mission to the Moon

1: Farside view of the Moon as seen by the Clementine spacecraft. Penetrators launched by the MoonLITE orbiter would allow surface investigations in areas not visited by Luna, Surveyor or Apollo missions. (NASA/JPL/USGS)

Ian Crawford and Alan Smith discuss the scientific objectives of the proposed MoonLITE mission.

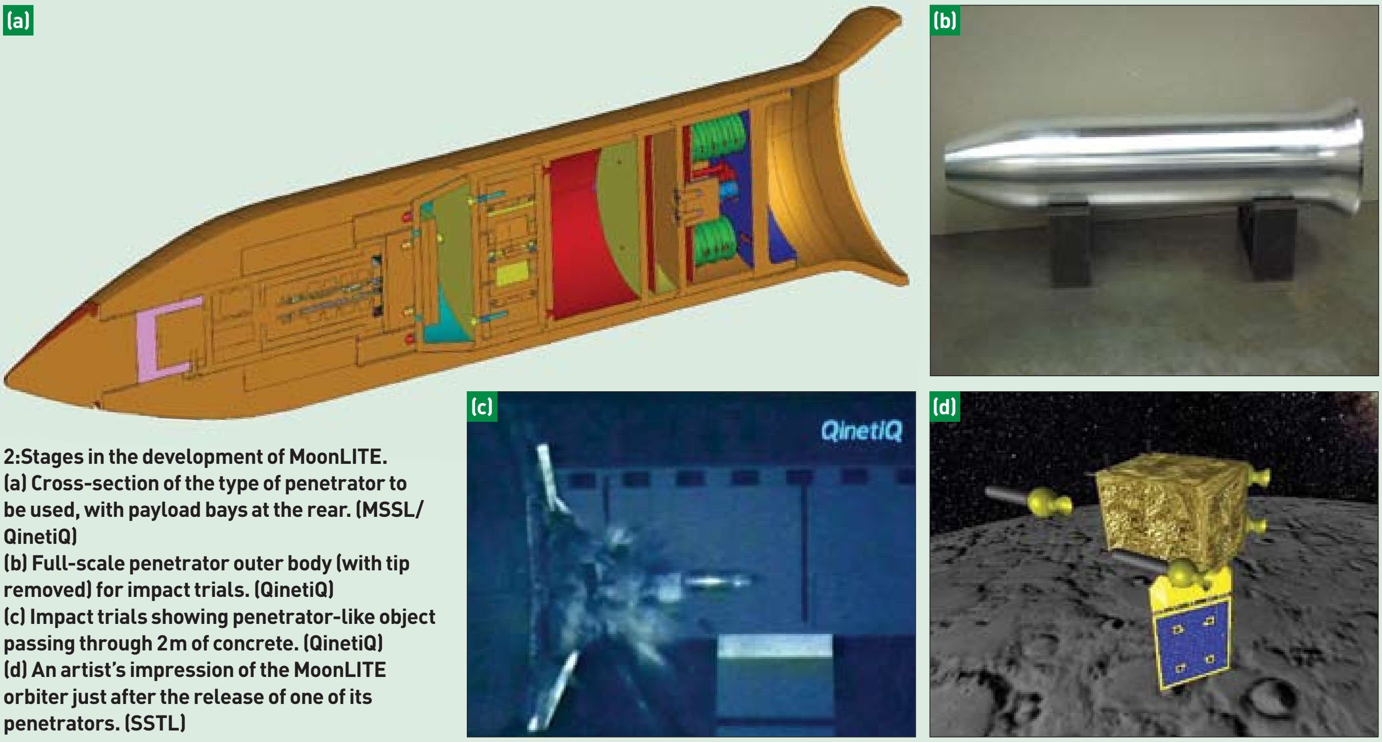
Abstract

MoonLITE is a proposal for a UK-led mission to the Moon that will place four penetrators in the lunar surface in order to make geochemical and geophysical measurements that are impossible from orbit. It has the potential to make major contributions to lunar science, while at the same time providing knowledge that will be of central importance in planning future human missions to the Moon. Plus, MoonLITE will demonstrate technologies that will have wide applications for the exploration of other solar system bodies.

While the surface missions to the Moon of the 1960s and 1970s achieved a great deal, scientifically much 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 recorder of the early history of the Earth–Moon system and of the interplanetary environment 1 AU from the Sun (e.g. Spudis 1996, Crawford 2004, Jolliff *et al*. 2006, NRC 2007). Although the Clementine and Lunar Prospector missions have greatly added to our knowledge of the geochemical and mineralogical makeup of the lunar surface, and these observations will soon be supplemented by results from Kaguya, Chang'e-1, Chandrayaan-1 and Lunar Reconnaissance Orbiter, our knowledge of the lunar interior is limited and relies largely on geophysical measurements made during the Apollo programme (see Wieczorek *et al*. 2006, for a review). Moreover, the recent remote-sensing missions have themselves raised questions that will require new surface measurements for their resolution, of which one of the most important is the circumstantial evidence for water ice, and by implication other volatiles, within permanently shaded craters at the lunar poles (Feldman *et al*. 1998).

In order to make significant further progress in lunar science, and to make better use of the lunar geological record to understand solar system evolution more generally, it will be necessary to return to the surface. It will be especially important to make geophysical and geochemical measurements from areas not visited by previous missions, including the poles and the farside. MoonLITE (Moon Lightweight Interior and Telecommunications Experiment) is a

THROWING LIGHT ON MOONLITE



2:Stages in the development of MoonLITE.
(a) Cross-section of the type of penetrator to be used, with payload bays at the rear. (MSSL/QinetiQ)
(b) Full-scale penetrator outer body (with tip removed) for impact trials. (QinetiQ)
(c) Impact trials showing penetrator-like object passing through 2 m of concrete. (QinetiQ)
(d) An artist's impression of the MoonLITE orbiter just after the release of one of its penetrators. (SSTL)

proposed UK-led lunar science mission that will contribute to these objectives by emplacing four scientific penetrators at widely spaced localities on the lunar surface (Gao *et al.* 2008). In addition, a telecommunications experiment (the "TE" in "MoonLITE") will be used to develop expertise in Moon–Earth communications that will benefit UK involvement in future lunar missions.

In 2007 MoonLITE was considered by the BNSC–NASA Joint Working Group (JWG 2008), which was established to explore avenues for UK–US collaboration in space exploration following the signing of a statement of intent in April. This report strongly endorsed the MoonLITE concept, describing it as an "inspirational" project and "the primary mission for potential [UK–US] cooperation". Cooperation with other partners is also a possibility. In the coming months, MoonLITE will undergo an assessment of the science case by an international peer review panel and a formal Phase-A technical study. If approved for implementation it will fill an important gap within the proposed international lunar mission portfolio and help facilitate the future scientific and ultimately human exploration of the Moon.

Scientific objectives

The principal scientific objectives of the MoonLITE penetrator mission are:

- To further understanding of the origin, differentiation, internal structure and early geological evolution of the Moon;
- To obtain a better understanding of the origin and flux of volatiles in the Earth–Moon system;
- To obtain "ground truth" geochemical data to complement orbital remote-sensing observations; and
- To collect *in situ* surface data that will help in the planning of future lunar exploration.

These top-level science objectives require that the penetrators emplace instruments capable of contributing to at least four different areas of scientific investigation: seismology, heat-flow, geochemical analysis, and volatile detection/characterization. These are discussed in more detail below.

Seismology

Seismology is the most powerful geophysical tool available for determining the interior structure of a planetary body. However, the only object other than the Earth where it has been successfully applied is the Moon, where the Apollo seismometers yielded important information on the Moon's natural seismic activity, and the structure of the lunar crust and upper mantle (Goins *et al.* 1981, Lognonné 2005). However, the deep interior of the Moon was only very loosely constrained by Apollo seismology because the network was geographically limited (essentially an equilateral triangle on the centre of the nearside between the Apollo 12/14, 15 and 16 sites; figure 3), so the information obtained on crustal thickness and mantle structure may not be globally representative. There is now a pressing need for a more widely spaced network of lunar seismic stations, including stations at high latitudes and on the farside. Penetrators delivered from orbit are ideally suited as a means of emplacing a global seismometer network, which would address the following scientific questions.

- **Size and physical state of the lunar core.** Such knowledge of the lunar core as we have has been obtained from studies of the Moon's moment of inertia and physical librations, and electromagnetic induction studies (Wieczorek *et al.* 2006). These studies favour a small ($R < 400$ km), partially liquid core, with suggested compositions ranging from iron–nickel, Fe–FeS alloy, to molten silicates. Confirmation of 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. For these reasons, constraining the nature of the Moon's core is a top scientific priority of the penetrator-deployed seismic network.
- **Deep structure of the lunar mantle.** One of the main contributions lunar studies can make to planetary science is an enhanced understanding of the internal differentiation processes that take place immediately after the accretion of a terrestrial planet. Magma oceans are likely to have been a common phase in the early evolution of 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 by constraining the initial depth of the magma ocean and its mineralogy (Lognonné 2003). Again, new, and more widely spaced, seismic data are required if this record is to be deciphered.
- **Thickness of the farside lunar crust.** Reinterpretations of the Apollo seismic data have

now constrained the thickness of the nearside anorthositic crust to between about 30 and 40 km (e.g. Wieczorek *et al.* 2006, Lognonné 2003). However, the thickness of the farside crust has not been seismically constrained. Estimates based on gravity data are typically in the range 70–90 km (Wieczorek *et al.* 2006) but these are non-unique, and farside seismic measurements are required to determine the average lunar crustal thickness, which has significant implications for understanding the bulk composition, and thus origin, of the Moon.

- **Studies of natural moonquakes.** Understanding natural lunar seismicity, and especially the relatively strong (up to magnitude 5) shallow moonquakes, is important both for our knowledge of lunar geophysics and the planning of future exploration activities (Neal 2006).

Heat-flow

Measurements of surface heat-flow provide valuable constraints on the composition and thermal evolution of planetary interiors. The lunar heat-flow was measured at the Apollo 15 and 17 sites (Langseth 1976). However, these measurements have been subject to numerous reinterpretations (Wieczorek *et al.* 2006), and in any case may not be representative of lunar heat-flow as a whole. An important measurement would be to determine the heat-flow as a function of distance from the Procellarum KREEP Terrain (PKT) on the northwestern part of the lunar nearside (Jolliff *et al.* 2000). Remote sensing measurements have determined that the heat-generating elements (U, Th, K) are concentrated at the surface in this region, but the question remains whether this is a surficial effect (owing to excavation of a global underlying KREEP-rich layer by the Imbrium impact), or whether these elements are indeed concentrated in the mantle below the PKT (Wieczorek *et al.* 2006, Hagermann and Tanaka 2006). The latter scenario would predict a much higher heatflow in the PKT than elsewhere, and would have major implications for our understanding of mantle evolution (Wieczorek and Phillips 2000). There is thus a need to extend these measurements to new localities far from the Apollo landing sites (e.g. the polar regions and the farside highlands) and penetrator deployment of a global heat-flow network would be an attractive means of achieving this.

Geochemistry

The only places on the Moon from which samples have been collected *in situ* are the six Apollo landing sites and the three Soviet Luna sample-return missions. No samples have been returned from the polar regions or the farside, greatly limiting our knowledge of lunar geological processes. Although additional sample-return missions are desirable, 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, Ca, Fe and Ti). This could be achieved by penetrator-deployed X-ray fluorescence spectrometers. As well as teaching us much about the geology of the sites that have yet to be sampled, such measurements would provide additional "ground truth" for the calibration of remote-sensing instruments on forthcoming lunar orbital missions.

Polar volatiles

As is well known, the Lunar Prospector neutron spectrometer found evidence for enhanced concentrations of hydrogen at the lunar poles, which has been widely interpreted as indicating the presence of water ice in the floors of permanently shadowed craters (Feldman *et al.* 1998). If water ice is present, it is most likely to have been derived from comets hitting the lunar surface. The confirmation of water ice (and other volatiles) at the poles would be important for what it will reveal about the flux and composition of cometary volatiles into the inner solar system (which is of significant astrobiological interest), and also because such volatiles could be a very valuable resource in the context of future human exploration of the Moon. We consider that volatile detectors, deployed on penetrators and landed within permanently shadowed craters, would be a powerful and economical means of determining whether or not scientifically and operationally valuable deposits of volatiles exist at the lunar poles.

Development methodology

MoonLITE is envisaged as both a lunar science/exploration mission and as a "penetrator demonstration mission" and the development methodology reflects both of these aspects. While it is essential that the mission achieves its scientific objectives, it is also anticipated that the technological developments therein will have direct application to other solar system bodies. The adopted development methodology is characterized by the following:

- A scalable, modular design around a core data and power distribution network;
- Model-based impact stress prediction, validated through impact trials, leading to a well-defined payload element environment;
- Inclusion of well-proven technologies brought in from outside of the space domain;
- "Pick-and-mix" payload selection to match specific mission opportunities.

Impact

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 a polar orbiting communications relay satellite, followed by release, de-orbit and descent (Gao *et al.* 2008). Each penetrator will have an attached de-orbit motor and attitude control systems, both of which will be ejected before impact.

Each penetrator will impact the lunar regolith at a speed of ~300 m s^{-1} (equivalent to a free fall from 30 km onto the lunar surface). It is entirely feasible for an instrumented package to survive an impact at such speeds and a vast amount of resource has been devoted to such conditions within a defence context. "Penetrators" are common-place within that sector and a (limited) range of components are available off-the-shelf that will survive impacts of >50 000*g* (MoonLITE expects up to 10 000*g*). This expertise is by no means purely empirical in nature; a very sophisticated predictive modelling capability also exists. The MoonLITE project will tap this capability for a scientific end. Moreover, Mars 96 (Surkov and Kremnev 1998), Deep Space-2 (Smrekar *et al.* 1999, 2001), and Lunar-A (Mizutani *et al.* 2001) penetrator development programmes have overcome many key problems and demonstrated survivability in ground tests.

Lifetime

Each penetrator will be designed to operate for one year below the lunar surface. This has significant consequences for total energy requirement. It is not proposed to have a detached body surface element (unlike DS-2), therefore all power must be generated internally. Moreover, the temperature 3 m below the lunar surface is estimated to be between 250 K and <100 K depending upon location – the latter figure referring to permanently shaded polar craters. Lithium-based batteries (providing 500 Watt-hours) together with radioactive heating units (RHU) are proposed. Very-low-power electronics and power-saving operation strategies will also be employed.

Communications

A polar orbiting satellite will be used for two-way communications between ground control and each penetrator. For penetrators located away from the lunar poles, communication passes will occur every 15 days with ~90 s of contact at each. For polar penetrators the frequency of contact will be much higher, but in this case the amount of information is still limited by the available transmitter power. Each penetrator will be able to transmit 10 Mbits of data during its one-year lifetime. A Lunar-A study (Mizuno *et al.* 2000) has analysed the likely communication effects of the overlaying lunar regolith and associated impact crater.

Payload

In accordance with the scientific objectives laid out above, the baseline MoonLITE scientific payload comprises:

- **Accelerometers and tilt-meter.** Three-axis accelerometers will be mounted at the head and tail of the penetrator to provide a complete motion history (position and orientation) during impact. A tilt-meter will be essential to provide for the interpretation of heat flow and seismic data.

- **Seismometer.** A three-axis MEMS-based microseismometer is proposed, based on novel micromachined technologies being developed at Imperial College (e.g. Pike and Standley 2005). These will have a sensitivity and bandwidth comparable to that provided by the Apollo missions (see fig. 5 of Gao *et al.* 2008).
- **Geochemistry package.** A miniaturized X-ray fluorescence spectrometer is proposed that will detect and quantify the major rock-forming elements in the local regolith (e.g. Na, Mg, Al, Si, K, Ca, Ti and Fe) together with diagnostic minor and trace elements. A drill is proposed to bring samples of the local lunar regolith into a common analysis chamber for both the geochemistry and volatile detection instruments.
- **Water/volatile experiment.** Several techniques are proposed as options for this important measurement, including: neutron spectroscopy, mutual impedance probe; calorimetric analyser; pressure sensor; optical spectrometer; and miniature ion-trap mass spectrometer.
- **Heat flow experiment.** To measure the heat flow in the lunar regolith, both thermal gradient and thermal conductivity measurements are required. The current baseline choice for penetrator structural material is aluminium, which represents a major challenge to thermal gradient measurements since the penetrator itself is manifest as a thermal "short". Alternative approaches are being studied to overcome this problem, including a trailing thermal probe, external thermal insulation and deployed needle probes.
- **Descent camera.** Part of the descent module to provide context images prior to impact.

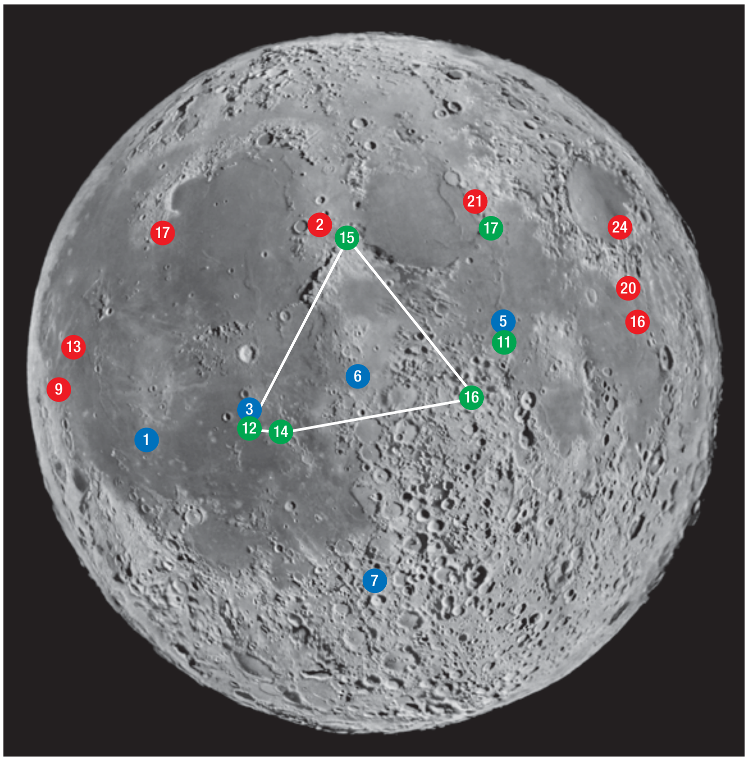
Additional instruments (e.g. to measure surface magnetic and electrical properties) may also benefit from penetrator-deployed instruments, and will be considered during the Phase-A study.

Public engagement

MoonLITE has already received significant public and media interest. Lunar exploration by its nature is accessible to all and inspirational to many. MoonLITE offers many opportunities for public engagement and these will be pursued throughout the programme. For instance, the MoonLITE penetrators will remain relatively undisturbed under the lunar surface for a vast period of time (probably hundreds of millions of years) and so represent the ultimate time capsules. One possibility would be to engage the public (both within the UK and abroad) in deciding what legacy we might wish to leave on the Moon in the form of information encoded on microchips carried in the penetrators.

Conclusions

By deploying a range of instruments (including seismometers, heat-flow probes, X-ray spectrometers and volatile detectors) to diverse locations on the Moon from which geochemical and geophysical measurements have not yet been obtained (including the poles and the farside), the MoonLITE penetrators have the potential to make major contributions to lunar science. At the same time, they 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. Last, but not least, MoonLITE offers the potential for enhancing public interest in science and technology.●



3: The approximate landing sites of Apollo (green), Luna (red) and Surveyor (blue) on the nearside of the Moon. The Apollo seismic network (white) was deployed by Apollos 12, 14, 15 and 16; heat-flow measurements were made by 15 and 17. Note the geographically restricted nature of these measurements; MoonLITE would extend coverage to the poles and the farside. (Moon photograph Ken Florey)

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