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Lunar science with affordable small spacecraft technologies: MoonLITE and Moonraker

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Abstract

Returning to the Moon has been advocated by a large number of international planetary scientists in order to answer several key scientific questions. The UK also has an active lunar science community keen to support (robotic) lunar exploration missions. However, for several years these interests have been eclipsed by the drive to Mars. Recently there is a renewed global interest in the Moon demonstrated by the Vision for Space Exploration in the USA, the evolving Global Exploration Partnership, and new lunar missions from Europe, Japan, China, India and the USA. The ESA Aurora programme may also broaden its focus to embrace the Moon as well as Mars—realizing that the risks associated with many of the major technical challenges that are faced by Mars missions could be reduced by relatively inexpensive and timely lunar technology tests. Surrey Satellite Technology Ltd. (SSTL) and Surrey Space Centre (SSC) have been preparing a 'smallsat' approach [Sweeting, M.N., Underwood, C.I., 2003. Small-satellite engineering and applications. In: Fortescue, P., Stark, J., Swinerd, G., (Eds.), Spacecraft Systems Engineering, third edition. Wiley, New York, pp. 581–612] to achieving a low-cost lunar mission for more than a decade—including various activities, such as the earlier LunarSat study funded by ESA and a current hardware contribution to the Chandrayaan-1 mission. With the recent successes in GIOVE-A, TOPSAT and BEIJING-1,[1] alongside participation in Aurora and Chandrayaan-1, Surrey have developed capabilities for providing affordable engineering solutions to space exploration. Recently, SSTL/SSC was funded by the UK Particle Physics and Astronomy Research Council (PPARC) (now subsumed into the UK Science and Technology Facilities Council) to undertake a study on low-cost lunar mission concepts that could address key scientific questions. This paper presents some major results from this study [Phipps and Gao, 2006. Lunar mission options study. UK Particle Physics and Astronomy Research Council Report Reference No. 118537, pp. 1–104] and provides preliminary definitions of two mission proposals.

Keywords: The moon; Mission definition; Lunar science; Spacecraft design

1. Introduction

Since the last Apollo landing on the Moon in 1972, our knowledge of the Solar System has expanded immeasurably,

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[1]Recent Earth satellite missions built and launched by SSTL.

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raising questions that cannot be answered from Earth (Phipps and Gao, 2006). There is now a global renewed interest in returning to the Moon, driven both by the demands of science and as a stepping-stone for human exploration of the Solar System (Crawford, 2004; ESA, 1992; Jolliff et al., 2006). In terms of science, the Moon provides a *unique* record of processes affecting evolution of terrestrial planets during the first Giga-year or so of Solar System history. This includes internal processes of geological evolution (e.g. differentiation and crust formation) and external processes caused by the environment (e.g. meteoroid and asteroid flux, interplanetary dust density, solar wind flux and composition, galactic cosmic ray flux) that are not as easily examined anywhere else in our Solar System (Ball and Crawford, 2006; National Research Council, 2007; Spudis, 1996; Stern, 2005). So far, all the *in situ* measurements of the lunar surface have been obtained by soft landings on the near side of the Moon, from Apollo, Luna and Surveyor missions. Actual samples have been returned from only 9 locations from mid- to low-latitudes on the near side, the 6 Apollo and 3 Luna landing sites, although the sample collection has been supplemented by the discovery of 40+ lunar meteorites (see http://meteorites.wustl.edu/lunar/moon_meteorites_list_alumina.htm and http://curator.jsc.nasa.gov/antmet/lmc/index.cfm for details). There is little doubt that returning to the Moon could, with sustained effort, vastly enhance our knowledge of the Solar System and of our own planet. The UK for instance already plays a significant role in lunar science research by participating in the Clementine, SMART-1, Chandrayaan-1 and LRO missions, as well as through geological studies using remote sensing and lunar meteorite data as inputs to theoretical modelling.

During 2006, PPARC funded SSTL to carry out a pre-phase-A study of a UK-led small-scale lunar mission. A fundamental driver in the study was that any UK-led mission must (1) be affordable[2]; (2) satisfy key science objectives not yet addressed; (3) offer the opportunity for educational outreach; and (4) stimulate UK industrial capability in space exploration. Initially, the study assessed the scientific and technological requirements of three mission options, namely orbiter, lander and sample-return. The design and cost drivers in terms of science performance and required technology were identified. First-level system design and trade-offs were performed. Finally, two mission proposals were established, namely MoonLITE and Moonraker. This paper presents a preliminary mission definition, including the science and technology, of the two mission concepts, as well as a science comparison with forthcoming approved missions.

[2]The low-cost concept is basically reflected in low launch mass. The ROM cost estimate of MoonLITE is 100 million pounds. Such a costing exercise is not yet done for Moonraker but it is deemed more expensive due to higher development cost.

2. MoonLITE (Moon Lightweight Interior and Telecom Experiment)

2.1. Mission rationale

The MoonLITE mission concept comprises a small orbiter and four penetrators (see Fig. 1). The orbiter will demonstrate communications and navigation technologies aimed at supporting future exploration missions, whilst the primary scientific goal is to investigate the seismic environment and deep structure of the Moon including the nature of the core, by placing a network of seismometers via penetrators on the lunar surface. The four penetrators would be widely spaced over the surface, with a pair on the near side (a preference for one being in the same area as one of the Apollo seismic stations for calibration purposes) and the other pair on the far side. In addition, heat flow experiments will be conducted. If possible, one penetrator would be targeted at a polar cold trap and equipped with an experiment to detect water and other volatiles. The surface mission is proposed to last 1 year at least, driven by the maximum life expectancy of the seismic network constrained by power source likely to be available. Other science experiments do not require so long (a few lunar diurnal cycles for heat flow, and much less for volatiles). Provision for penetrator descent imagery would be desirable for both science context and outreach purposes.

The demonstration of instrumented penetrators for the Moon, using non-aerodynamic attitude stabilization, would prove a technology relevant to the scientific exploration of other destinations such as Mercury, Europa and Enceladus. The basic technology for penetrators has

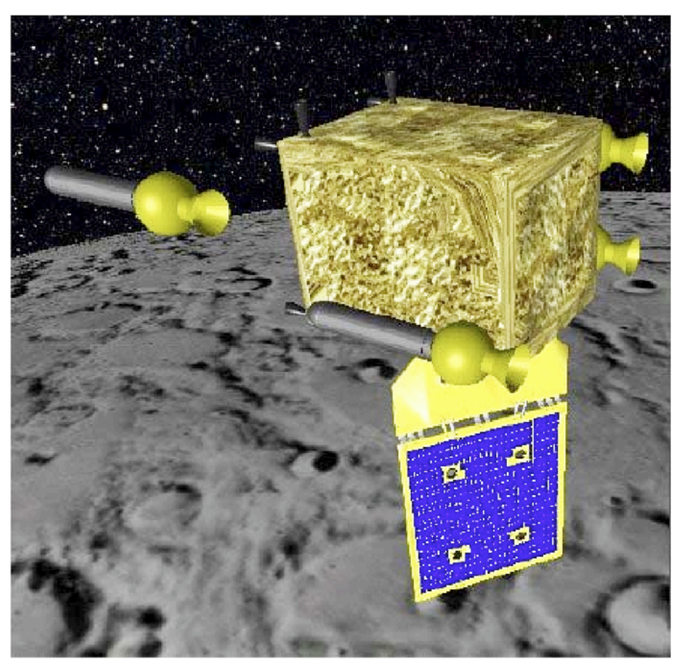
Fig. 1. MoonLITE orbiter carrying four penetrators.

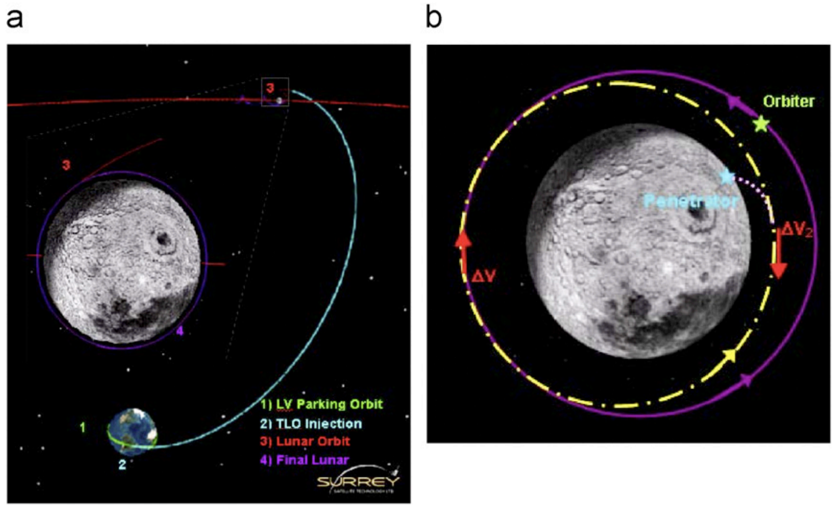

Fig. 2. (a) Orbiter transfer trajectory and (b) penetrator deployment trajectory.

existed for several decades, based largely on military heritage (e.g. Simmons, 1977; Murphy et al., 1981; Bogdanov et al., 1988); however, only in the mid-1990s did proposals for their use in Solar System exploration begin to be adopted for flight. In the USA, Mars penetrators were studied for several years and, indeed, field tested as part of a possible post-Viking mission. NASA sent its *Deep Space 2* microprobes to Mars on *Mars Polar Lander* (Smrekar et al., 1999, 2001; Lorenz et al., 2000), but no signals were received after separation. In the Soviet Union, planetary penetrator studies had started in the mid-1980s, and two penetrators were launched with *Mars 96* (Surkov and Kremnev, 1998), which failed to leave Earth orbit. Russia also continues to study its Luna-Glob mission, which would include penetrators and landers (Surkov et al., 1999; Galimov, 2005; Covault, 2006). Japan's planned Lunar-A penetrator mission (Mizutani et al., 2001, 2003) was cancelled in 2007, although the penetrators had by that point been built and tested successfully. The UK too has an interest in penetrator technologies, which are gathered into a national consortium comprising major academic and industrial players (Smith and Gao, 2007; Smith et al., 2006, 2007; Gown et al., 2007; see consortium website http://www.mssl.ucl.ac.uk/planetary/missions/Micro_Penetrators.php for details).

The primary purpose of the orbiter after the deployment of the penetrators is to provide a telecommunications relay for the penetrators and to demonstrate high-rate communication links from the lunar surface. It would be a pathfinder for a permanent high data rate lunar telecommunications infrastructure operating at Ku band (as anticipated in NASA long term requirements for lunar exploration). As far as possible, the telecom capability should be compatible with other lunar orbiters and future robotic landers. If feasible, some form of navigation payload might also be included. These aspects of the mission concept offer opportunities for bilateral or multilateral cooperation and cost sharing, while reducing risk for future lunar and martian missions.

2.2. Mission profile

MoonLITE is technically compatible with a launch in 2010–2011 and capable of operating on the lunar surface for 1 year. In order to minimize trajectory ΔV requirements and hence launch costs, a direct injection into trans-lunar orbit (TLO) by the Polar Satellite Launch Vehicle (PSLV)[3] is used as the baseline (although other launchers will be considered for the final mission). A transfer trajectory that combines a low ΔV (reduced propulsion system costs), short Earth-Spacecraft distances (simpler communications system) and short transfer times (lower operations cost during transfer) is desirable. After considering a number of possibilities (e.g. direct transfer, bi-elliptic transfer and weak stability boundary transfer), we chose a direct transfer trajectory to the final lunar orbit, as illustrated in Fig. 2(a). This transfer takes about 3 days. The final orbit is set to be a 100 km circular polar orbit because it provides a sensible balance between orbiter/penetrators ΔV requirements and the visibility of the penetrators for data relay purposes. The proposed total ΔV budget including mid-course correction, lunar orbit insertion and orbit maintenance for a 1-year mission is 1217 m/s with 10% margins.

For penetrator deployment (see Fig. 2(b)), an initial manoeuvre places the penetrator on a trajectory with periapsis near the lunar surface (40 km altitude, for example). A large second burn is performed to slow the penetrator down to near zero velocity to allow it to drop to the surface. Additional attitude control manoeuvres are required during the final drop to the surface to ensure that the penetrator impacts the lunar surface vertically.

[3]We understand a configuration like PSLV-XL can launch 1200 kg to GTO, but it has not been possible to establish the precise capacity of PSLV for insertion into TLO. A launch mass limit of 810 kg is assumed.

2.3. MoonLITE spacecraft

The basic configuration of the MoonLITE spacecraft is shown in Fig. 3. The concept is based on the GIOVE-A spacecraft (Benedicto et al., 2006) but only one solar array is required, which remains stowed until after penetrator deployment and then rotates. Penetrators for payload delivery are bullet-shaped vehicles designed to penetrate a surface and emplace experiments at some depth. The four penetrators of the MoonLITE are attached in two pairs on opposite sides of the orbiter body. Each cylindrical penetrator is to carry and deliver a science payload package to the lunar surface. Table 1 gives specifications of a strawman payload such as the seismometer and heat flow probe for the primary science objectives of the mission. For example, the 3-axis microseismometer is proposed by members of the UK Penetrator Consortium from Imperial College London using novel micromachined technologies (Pike et al., 2004, 2006; Pike and Standley, 2005). Performance of such a micro-instrument is compared to Apollo, Viking and terrestrial seismometers in Fig. 5. The proposed heat flow package will measure the temperature gradient and thermal conductivity of the lunar regolith. This may, for example, include a number of sensors located on the outside of the penetrator, such as a suite of 8 relative temperature sensor or thermocouples, 4 absolute temperature sensors (Pt-100 or NTC thermistors), and 4 miniature thermal conductivity sensors (e.g. heater plate with thermocouple, or miniaturized needle probe). More descriptions of the proposed payload can be found in an ESA Cosmic Vision proposal called LunarEX (see http://www.mssl.ucl.ac.uk/planetary/missions/LunarEX_CV_bid-Modified_Dec07.pdf for full report).

A conceptual design for the MoonLITE penetrators is shown in Fig. 4. Each is assumed to have a total mass budget of 36 kg-including 23 kg of propulsion and 13 kg of actual penetrator carrying a science payload mass of ~2 kg. The penetrator is expected to impact the lunar surface at around 300 m/s. The data rate from the penetrator to the orbiter is assumed to be 30 kbits/day. Because of the infrequent communication contacts with the orbiter (e.g. every 15 days), each penetrator will need to operate

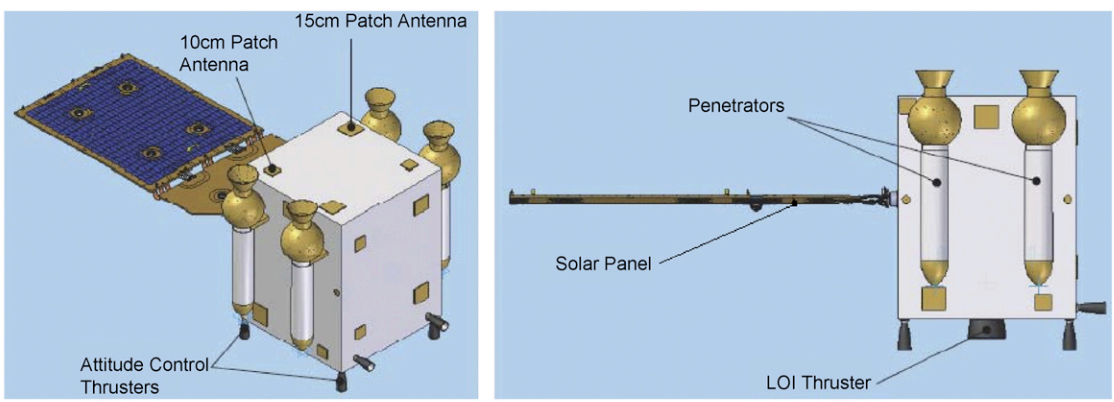

Fig. 3. MoonLITE spacecraft configuration.

Table 1
MoonLITE penetrator strawman payload

Science instrument	Mass (g)	Volume (cm^3)	Power (mW)	OBDH	Telemetry
Micro-seismometer (3-axis)	300	200	112	10 samples/s/axis and 24 bit each; Total data rate of 720 bits/s	6 Mbits (corresponding to ~0.5% time during events)
Heat flow package	300	20	25 (Normal) 300 (peak)	Temperature measurement at 1/h at >18 bit resolution; Thermal measurement at 50 Hz at 12 bit resolution	<0.1 Mbit for temperature; <0.5 Mbit for thermal
Water/volatiles detector	750	1000	3000	50 Mbits of data in series of operations	<2 Mbits
Geochemistry package (XRS)	260	160	4000	No special requirement	50 kbit per spectrum (two spectra)
Accelerometer (8 sensors)	56	~8	<500	100 kHz sampling (equivalent to 3 mm spatial) with 12-bit resolution for 8 axes	0.1 Mbit in total
Tilt-meter (2-axis)	10	25	<100	1 Hz sampling with 12-bit resolution for each of 2 axes	1 kbit in total
Descent imager	10	3	160	Offline × 10 data compression on 21 images (32 Mbits each)	2 Mbits over 28 days; some over descent (TBD)

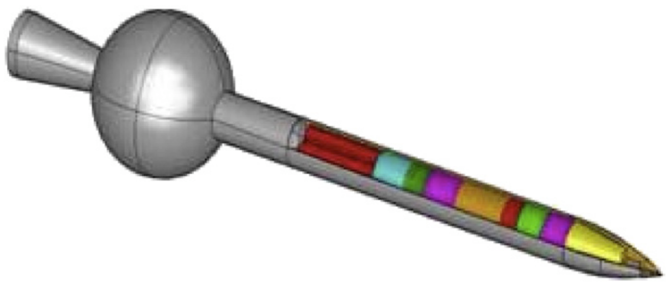

Fig. 4. Concept for lunar kinetic micro-penetrator.

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 and/or micro-processor solution will be strong candidates for this mission with relatively high density memory. Each penetrator is buried beneath the lunar regolith, and the communication relies on transmission through the regolith (as for Lunar-A penetrators). However, a detailed study will be made of regolith communication transparency properties, and the possibility of a trailing antenna especially for the case of immersion into regolith containing a significant proportion of ice. The baseline 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 optimize performance when buried. The UK penetrator consortium is currently investigating the key design issues and penetrator sub-systems including AOCS, material, communication, power, payload operations, etc. The LunarEX proposal outlines the recent progress.

The spacecraft contains low and medium gain antennas (10 and 15 cm patch) on all faces to provide omni-directional communication coverage. The orbiter has two S-band ranging receivers (0.5–4 kbps using a 10 cm patch antenna) and transmitters (0.4–2 kbps using a 15 cm patch antenna) for communication with Earth ground stations[4] and penetrators. To provide uplink at high speed for other surface activities on the Moon, the orbiter is also equipped with one Ku-band receiver (10 Mbps using an omni-directional antenna).

A chemical propulsion system is adopted based on a bipropellant solution using monomethyl-hydrazine (MMH) and nitrogen tetroxide (NTO) that gives the most

Table 2
MoonLITE mission mass budgets (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 (penetrators)	144
System margin	49.1
Total (dry)	539.7
Propellant (transfer, LOI, OM)	296.4
AOCS propellant	10
Propellant (total)	306.4
Total (launch)	846.1

mass-efficient solution.[5] A single centrally mounted 400 or 500 N thrust engine (see Fig. 3) is used to perform the main ΔV manoeuvres. Four 10 N thrusters, located at the corners of the same panel, are used for attitude control during the orbit manoeuvre firings. Together with two others on the side, all thrusters would be used for the full range of attitude control functions during the mission.

Attitude determination is performed using sun sensors and star cameras, combined with 3-axis gyros utilized during manoeuvres. Three-axis attitude control is executed using four orthogonal reaction wheels and a set of 12 redundant thrusters. The on-board propulsion system mentioned above is used for control during orbit manoeuvres and wheel de-saturation.[6]

2.4. Mass budget

The mass budget of MoonLITE is shown in Table 2. The total launch mass is 846 kg including an overall average margin of 10%. Further mass reduction trades are being explored to reduce the orbiter mass to match the performance of the PSLV, such as reduced redundancy of sub-systems (currently everything is dual redundant) and mass minimization of SSTL sub-systems, etc.

3. Moonraker

3.1. Mission rationale

The Moonraker mission consists of a single propulsive soft-lander (see Figs. 6 and 8) aiming to provide a low-cost

[4]The Earth ground station baseline is the Rutherford Appleton Laboratory (RAL) 12 m aperture antenna.

[5]SSTL is developing a bipropellant engine using high test peroxide (HTP) and kerosene that would potentially reduce the recurring costs further (Coxhill, 2002).

[6]De-saturation is the process of unloading angular momentum from the reaction wheels (i.e. when the wheels have reached maximum speed). The wheels are slowed down and the corresponding rotation of the spacecraft is cancelled out by thrusters to maintain 3-axis pointing.

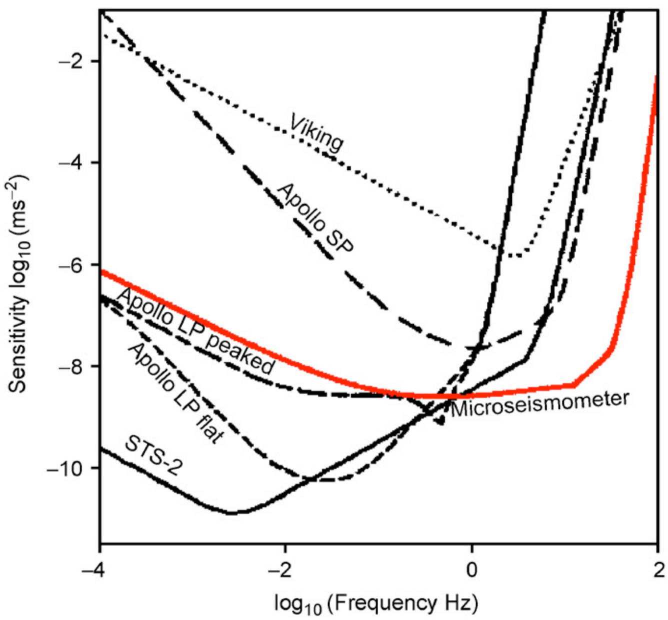

Fig. 5. Comparison of microseismometer, Apollo, Viking and terrestrial (STS-2) seismometers (after Lognonné and Mosser, 1993).

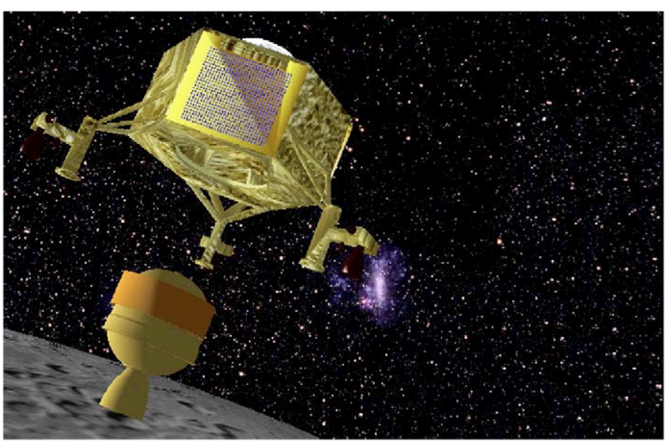

Fig. 6. Moonraker lander jettisoning solid motor.

European lander capability for robotic exploration of the lunar surface in preparation for subsequent human expeditions. The first mission is targeted to the lunar near side, which allows direct-to-Earth communications. The primary science goal is *in situ* dating of the young basalts at northern *Oceanus Procellarum*, both for understanding lunar evolution and for better calibrating the lunar cratering rate that is used with assumptions for dating solid surfaces throughout the whole Solar System (Crawford et al., 2007). The envisaged *in situ* method involves a K–Ar dating technique being investigated at the University of Leicester and the Open University, building upon previous work (Swindle, 2001; Swindle et al., 2001). This combines data from both an X-ray spectrometer and a mass spectrometer derived from Beagle 2 and Rosetta heritage. The *in situ* dating is at present un-proven and has been met with scepticism in some quarters (Taylor et al., 2006), but if successful, it could be of general use at other rocky planets, and could be used to help select samples for return-type missions (e.g. Mars Sample Return (MSR)). Even if *in situ* dating proves not to be feasible, the X-ray spectrometer derived from Beagle 2 (Sims et al., 1999) would still be suitable for general geochemistry work, which would also be scientifically very valuable if performed at sites from which samples have not yet been returned.

Technologically, the robotic lander could embody greater intelligence than ExoMars (e.g. vision-based guidance for the terminal phase) to allow landing autonomously on the ejecta blanket of a suitable crater such as Lichtenburg at *Oceanus Procellarum*. This capability would be novel but is essential for future precision robotic landers (Mars, asteroids, Europa, etc.). Surface sample acquisition may involve robotic arms, miniaturized drills, possibly including a 'rake' to extract small rock fragments of interest from the regolith, giving rise to the mission name, 'Moonraker'. The mission concept could be implemented driven by the need

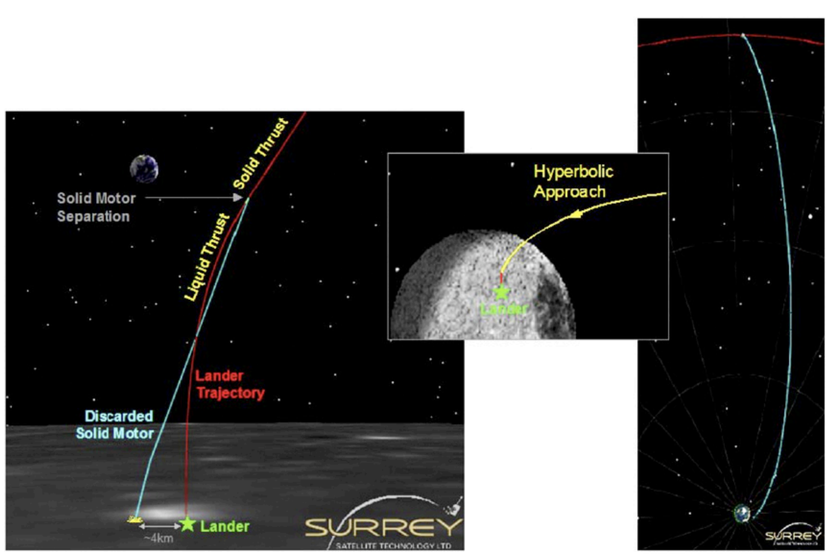

Fig. 7. Lander trajectory.

to test vision-based precision terminal guidance using active hazard avoidance.

3.2. Mission profile

Moonraker is proposed to launch in 2013. The spacecraft is placed directly into a TLO by the PSLV launcher. A direct hyperbolic approach is used to land on the northern region of *Oceanus Procellarum*, which has direct visibility to the Earth. This transfer duration is approximately 5 days. The entire transfer trajectory is shown in Fig. 7 illustrating the direct interplanetary transfer, hyperbolic arrival and final descent to the surface. The descent phase starts with a spin-stabilized solid motor firing to decelerate the approach velocity from 2.5 km/s when the lander is about 70 km above the surface. It takes less than 1 min for the lander to reach 10 km above the surface and its velocity to be reduced to about 80 m/s. The lander then jettisons the solid motor, fires the liquid motor and continues to decelerate. From this point until landing, the target duration is 4 min. The lander subsequently enters despin and transitions to a 3-axis stabilization mode, followed by a 3-axis controlled descent mode, a free fall for

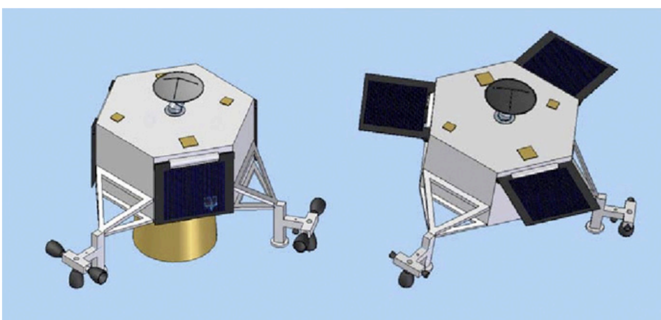

Fig. 8. Moonraker spacecraft configuration: cruise (left) and on-surface (right).

Table 4
Moonraker mission mass budgets (kg)

Science payload	23.6
TTC comms	19.1
Structure	45.1
ADCS	14.7
OBDH	4.3
Power	9.4
Propulsion (hydrazine)	30.8
Harness	9.9
Thermal control	3.1
Landing gear	16.2
System margin	17.6
Lander (dry)	193.8
Descent liquid propellant	58.0
Lander (total)	251.8
Solid motor stage	493.3
Liquid propellant during cruise transfer	28.1
Propellant (total)	521.4
Total (launch)	773.2

Table 3
Moonraker lander strawman payload

Science instrument	Mass (kg)	Power (W)	Data rate/volume	Duration	Science objectives
Gas analysis package (incl. sample ovens and electronics)	8 (excl. sample acquisition)	Idle: 5–10 Peak: 30–50	1 Mbyte/sample; Min. 10 samples	Per sample: 30 min per step × min. 10 steps, Min. 10 samples	Age dating
X-ray Spectrometer	0.14 per detector (2 off) plus 0.2 electronics (excl. sample acquisition)	2.7	32 kbits per measurement	Min. 3 h (for arm-mounted head) but could be up to 2 wks during lunar night (for lander-based head examining sample to be dated)	Age dating/geochemistry
NIR Vis/NIR imaging spectrometry microscope	1 (excl. sample acquisition)	2	~10 Mbit per measurement (data cube); assume 30 samples	Seconds per measurement; Assume 30 samples	Geochemistry (would duplicate some of the capabilities of the XRS and volatiles detection)
Infrared spec (IRS)	0.5 (excl. sample acquisition)	1.5	~32 kbits per measurement; assume 30 samples	Seconds per measurement; Assume 30 samples	
LAMS (laser ablation mass spec)	0.5 (excl. sample acquisition)	3	~32 kbits per measurement; assume 30 samples	Seconds per measurement; Assume 30 samples	
RAMAN/LIBS	1.5 (excl. sample acquisition)	3	~32 kbits per measurement; assume 30 samples	Seconds per measurement; Assume 30 samples	
Seismometers-short period and broadband	2.3 (for broadband plus short period)	0.6	2.5 Mb/day	~1 yr continuous buffered and filtered for downlink	Seismology
Heat flow package	2	10 peak	<1 kbps mean	Periodical data generation	Heat flow

Table 5
Science comparison of lunar missions planned by 2015

Science	Selene	Chandrayaan-1	Chang'e-1	LRO/LCROSS	MoonLITE	Moonraker	LEO	Luna-Glob
Image mapping	x	x	x	x			x	
Gravity mapping	x						x	
Radiation field	x	x	x	x			x	
Topography mapping	x	x	x	x			x	
Mineralogical composition	x	x		x		*	x	
Chemical element composition	x	x	x			*		
SPA water detection	x	x	x	x *	*		x	*
Basalts age dating						*		
Seismometry					*	*		*
Heat flow					*	*		

x: Remote sensing. *Surface in situ.

the last few metres, and finally terminates with an impact at ~3 m/s. The surface operating lifetime is about 3 months (i.e. 3 lunar days).

3.3. Moonraker spacecraft

The Moonraker spacecraft is configured as shown in Fig. 8. A hexagonal structure is selected, providing facets for the landing gear and for 3 solar panels. The solar panels are deployed after landing, their angles being set to optimize solar power generation once the orientation of the lander on the surface has been established. There is generous internal volume for accommodation of the lander avionics, power conditioning and science instruments. The strawman science instruments include an XRF spectrometer, multispectral imaging system, Raman/LIBS, seismometer and heatflow probe (Sims et al., 2003; Bibring et al., 2007; Mall et al., 2005; Wurz et al., 2004; Ahlers et al., 2007; Mimoun et al., 2007; Spohn et al., 2001). The sample acquisition system would be mounted on the underside of the lander. The total science payload including sample acquisition package is estimated at less than 22 kg (see Table 3).

The top facet provides support to the 50 cm diameter parabolic high-gain antenna used for transmission of science data direct to Earth (see Fig 7). There are also 10 and 15 cm patch antennas mounted on the top offering omni-directional communications coverage. One S-band receiver (4 kbps and a 10 cm patch) and transmitter (2 kbps and a 15 cm patch) are used for TT&C with an Earth ground station. An S-band transmitter of 38.4 kbps is used to transmit the science data back to Earth.

The baseline concept for the propulsion system is to use a solid motor (e.g. ATK Thiokol's STAR 30BP) to provide 84% of the total deceleration ΔV. The remaining deceleration, trajectory correction and targeting, spin-up/despin and attitude control velocity increments are provided by a liquid propulsion system. The hydrazine blowdown monopropellant system used comprises two 60 ℓ propellant tanks each containing ~86 kg of hydrazine, filters, latch valves, pressure transducers and 3 identical thruster modules, one on each leg. Each thruster module has a nominal 150 N engine for deceleration and three 20 N nominal engines for spin and down, attitude control and lateral movement. For reliability and robustness, each thruster has redundant valve seats.

Attitude determination is performed using sun sensors, a star camera, a 3-axis inertial measurement unit (IMU) and an Earth and Sun Sensor (ESS).[7] AOCS actuation is provided by monopropellant thrusters.

3.4. Mass budget

The mass budget of Moonraker is shown in Table 4. An overall average margin is 10%. Some specific units have higher margins than 10%, since we understand precisely some SSTL-built units that can therefore have very small margins. The overall launch mass of 773 kg is within the assumed capacity of the nominal PSLV including an allowance for the launch vehicle adaptor.

4. Future missions science comparison

Countries including the US, China, Japan India and Russia have plans for robotic missions to the Moon, which involve orbiters, landers and rovers. These missions will prepare the way for crewed excursion missions and eventually a human-tended outpost on the Moon. Table 5 summarizes the internationally planned robotic missions over the next 10 years and compares the scientific objectives of these missions. It is clear that the MoonLITE and Moonraker missions would be focusing on *in situ* science and are complementary in terms of addressing some of the niche areas such in situ age dating.

[7]Radar and/or vision package using modern technologies can be further investigated to improve the performance of gravity turn descent.

5. Conclusion

The Moon remains scientifically appealing and has generated revived interest in recent years (e.g. Jolliff et al., 2006). Despite the large number of planned missions, there still remain significant gaps in science that can be addressed by low-cost lunar missions. Small, low cost missions have become highly successful in recent years, with outstanding results and many scientific and commercial users. The capabilities of small satellites have also seen drastic improvements, and have matured to the point where such missions offer huge potential within space exploration. The MoonLITE and Moonraker missions provide a stepwise approach to space exploration, using the Moon as a proving ground for technology that is essential for robotic exploration of Mars and reducing risk for de-risking larger programmes such as ExoMars and MSR.

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