

L-VRAP

Lunar Volatile Resources Analysis Package for Lunar Exploration

Executive Summary

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1 Introduction

A key scientific question to be addressed by a Lunar Lander is the extent, nature and distribution of volatile species within the regolith. Such volatiles, and in particular water, are of interest because of their potential for In Situ Resource Utilisation (ISRU). Volatiles are particularly pertinent for a mission to the South Pole, because it might be expected that volatiles are cryogenically trapped and hence concentrated in cold shaded regions at such localities.

A study has been undertaken to define a so-called Lunar Volatile Resources Analysis Package (L-VRAP) as a candidate payload element for the first European Lunar Lander. The resulting L-VRAP design presented herein is a flexible powerful instrument to detect, identify, quantify and characterise volatiles in Lunar regolith and Lunar atmosphere.

2 Objectives and Requirements

The overall objectives for L-VRAP concerning regolith volatiles are to:

- Extract volatiles from regolith samples obtained from known (and ideally, characterised) localities including from depth and from the surface (top ~1 mm)
- Identify the volatiles released
- Quantify the volatiles released
- Isotopically characterise the volatiles released
- Relate all of the above back to the original nature of the components in the regolith

With respect to atmospheric volatiles the objectives are to identify and quantify and as far as possible isotopically characterise volatile neutral species.

3 Contamination

During its descent to the lunar surface, Lunar lander will consume around 1000 kg of propellant, producing an exhaust plume of volatile-rich species similar in composition to the target indigenous volatiles which L-VRAP seeks to study. Moreover, a significant fraction of these exhaust products will be released close to the eventual landing site. As part of the current study, a preliminary investigation has been undertaken aimed at understanding the nature and extent of contamination and alteration of the lunar surface resulting from the action of the Lunar Lander's motors during descent. The initial findings suggest that contamination may not be as problematic as might be first envisaged from a simple observation of Apollo landings; the Lunar Lander descends more abruptly in the final near-surface stages which is where contamination and alteration effects are most prevalent and hence these effects are reduced. Nevertheless it is possible that the Lander's robotic arm will not be able to access unaltered surficial regolith material (unless it is shielded by

serendipitous local topography e.g. rocks which of course cannot be relied upon). Hence it is considered that the approach most resilient to delineating the effects of contamination comprises a combination of

- measuring volatiles as a function of lateral distance from Lander (to investigate decline in alteration with distance)
- measuring volatiles as a function of depth
- measuring volatiles as a function of time (to investigate any transients caused by the landing event)
- being able to recognise contamination effects in acquired data

4 L-VRAP Conceptual Description

The L-VRAP concept derived through this study is a development of the MODULUS (Methods Of Determining and Understanding Light elements from Unequivocal Stable isotope compositions) philosophy which was initially developed for the ESA Rosetta mission and further refined for Beagle2. The MODULUS approach has been specifically tailored for a lunar polar lander set of objectives. It incorporates the following elements:

- Means for collecting and analysing exospheric samples
- Means for receiving regolith samples from Platform's robotic arm
- Means for metering and/or determining the mass of regolith sample
- Means for extracting volatiles from samples
- Means for cleaning up/separating evolved gases
- Means for qualitative, quantitative and isotopic analysis of volatiles

The functional schematic of L-VRAP produced during this study is shown in Figure 1; the concept overview is shown in Figure 2 and the preliminary design in Figure 3.

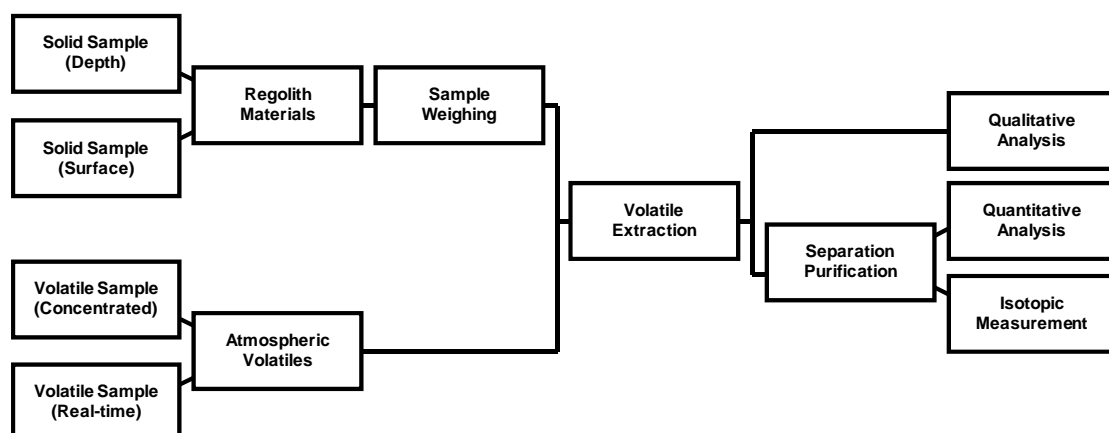


Figure 1 L-VRAP Functional Schematic

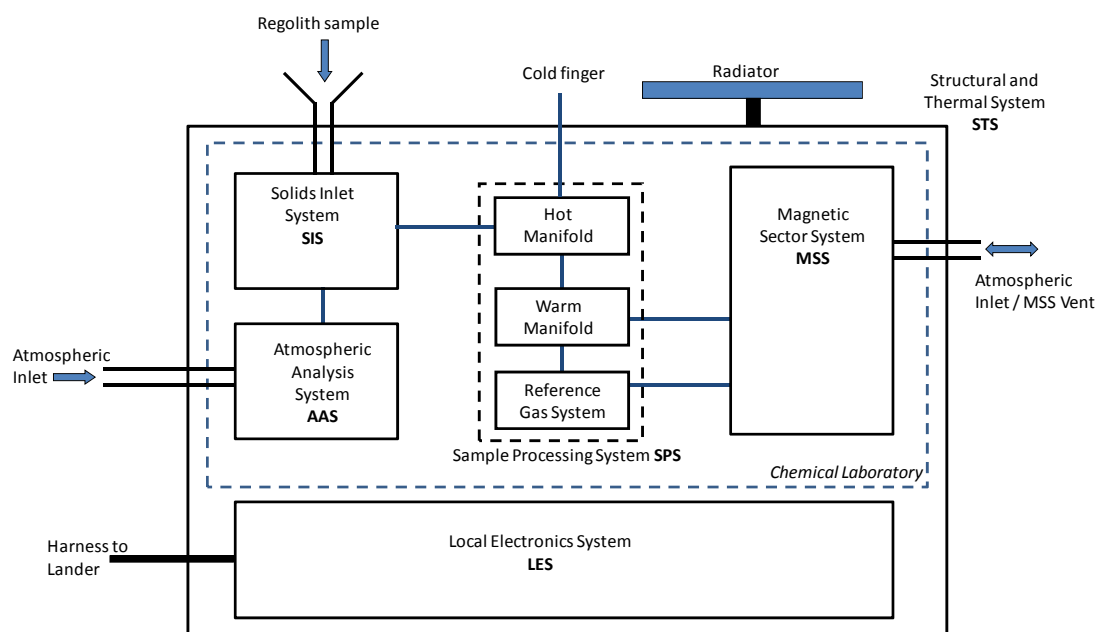


Figure 2 L-VRAP concept system diagram

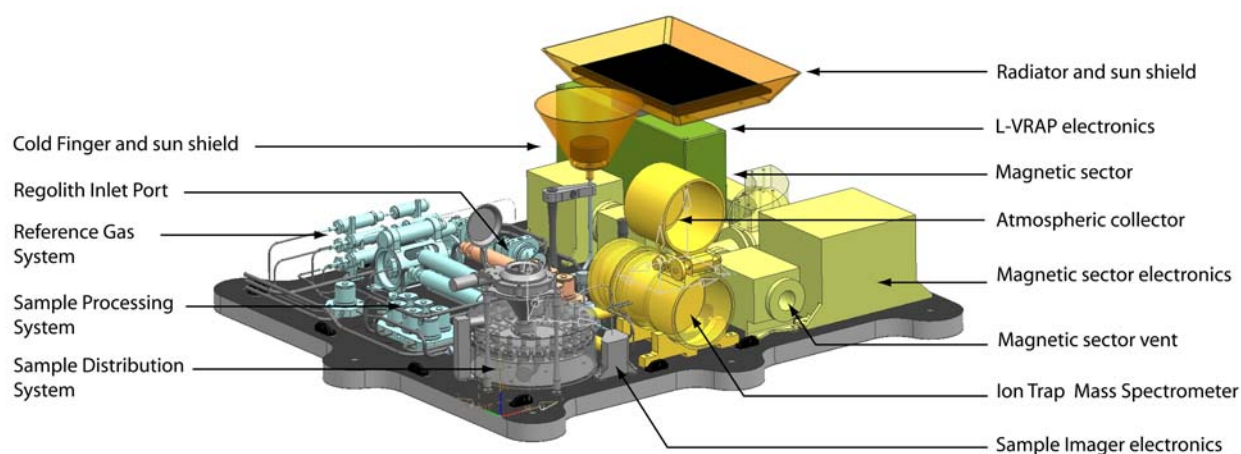


Figure 3 L-VRAP preliminary design. Not shown is the outer MLI cover and support frame

4.1 Structural & Thermal System STS

The STS performs the following functions:

- Provides overall structural basis for the L-VRAP hardware
- Provides protection from dust and micrometeorites
- Provides a barrier against chemical contamination from the lander and environment (including residual fuel vented by the lander)
- Affords thermal control of overall instrument box (local control may also be effected within the various subsystems/components)

It is currently foreseen that the instrument baseplate shall be constructed from a CFRP-aluminium honeycomb-CFRP sandwich sheet. This provides a very stiff baseplate whilst providing some favourable thermal properties. Firstly this provides the required thermal isolation (low conductive thermal links) into the Lander structure. Secondly this allows the various subsystems of L-VRAP to be thermally isolated (to a certain extent) from each other allowing their independent thermal control at their operational temperatures. The individual L-VRAP subsystems are mounted to the baseplate using thermally isolating mounts to reduce thermal conduction into the Lander and to help isolate parts of the L-VRAP, one from another.

The thermal control subsystem uses passive means to control the upper temperatures of sensitive equipments. The instrument is wrapped in MLI except for designated radiator areas on the top surface. Internal equipment will be connected to a radiator via conductive coupling through a mechanical link to the radiator. The radiator rejects heat directly to space, and is sized so as to maintain the upper temperature of equipments towards the top of their allowable range. To ensure the efficient sizing of the radiator it is assumed that surface will be shadowed from direct solar illumination by a baffle (sun shield) around the radiator/instrument. The back surfaces of the shadowing surfaced will have a low emissivity finish to minimise heat radiated to the radiator surface. Additionally due to the potential solar aspect angle one side of the baffle will be illuminated by solar flux. To perform this function effectively the baffle surfaces shall be angled such that any incident solar flux shall be reflected away to space rather than to the radiator.

The minimum necessary heating is applied by direct electrical resistance heating in the cold cases so that the lower temperature of each unit is maintained towards the bottom of its allowable range. By using the full design temperature range of each unit in this way, the required heater power is minimised. Internal equipment is decoupled from the external environment during cold conditions by conductively decoupling the radiator using a wax actuated heat switch. This reduces the steady state heating power demand to a total of ~1.5 W distributed throughout the instrument. The use of a Pre-Warm strategy (e.g. 16 W over 10 hours) enables L-VRAP to remain within safe temperature limits for ~38 hours before the ~1.5 W heating is required.

4.2 Local Electronics System LES

At this stage the LES design is only at a conceptual level. The functionality requires will be split across three printed circuit boards (PCBs). At this stage it is envisaged that the PCBs will be as follows:

- Instrument controller and space-craft interface
- Control of valves, heaters, pressure sensors etc
- Mass spectrometer control

The design architecture is similar to that used in the Ptolemy (Rosetta) GC-MS and the board area currently provided (160 mm x 100 mm per PCB) is informed by that experience. The PCBs are housed in a local electronics box in aluminium alloy which affords some protection against radiation.

4.3 Solid Inlet System SIS

Regolith samples are introduced into L-VRAP via the Solids Inlet System (SIS), the baseline concept for which is based on the Beagle2 inlet port in which a funnel is used to receive sample from the sampling system. A cantilever sample retention and inspection platform allows direct imaging of deposited sample prior to insertion into the sample inlet funnel (Figure 4 (a) and (b)). A piezoelectric actuator aids sample transfer into the sample ovens from the sample inlet funnel (Figure 4 (c)) under the influence of gravity; a charge neutralisation device may additionally be required to reduce electrostatic effects during transfer. Once the necessary sample is introduced into the SIS it is deposited into one of 24 (TBC) small “ovens” mounted on a rotary carousel (Figure 4 (b)). The rotary drive mechanism is located below the carousel in a dust proof enclosure to minimise the effects of dust ingress on the mechanical drive systems (Figure 4 (c)). The carousel can rotate to place the sample oven below one of three functional stations:

- Sample imaging station
 - provides direct confirmation that sample has been successfully deposited into the oven;
 - provides contextual information on the nature of the sample prior to destructive analysis by L-VRAP
 - allows for an optical estimation of sample mass
- Oven clean-up station
 - allows the clean-up of the sealing surface at the top of the oven prior to sealing
- Oven docking station
 - enables a gas-tight seal to be made between the oven and the sample transfer pipe

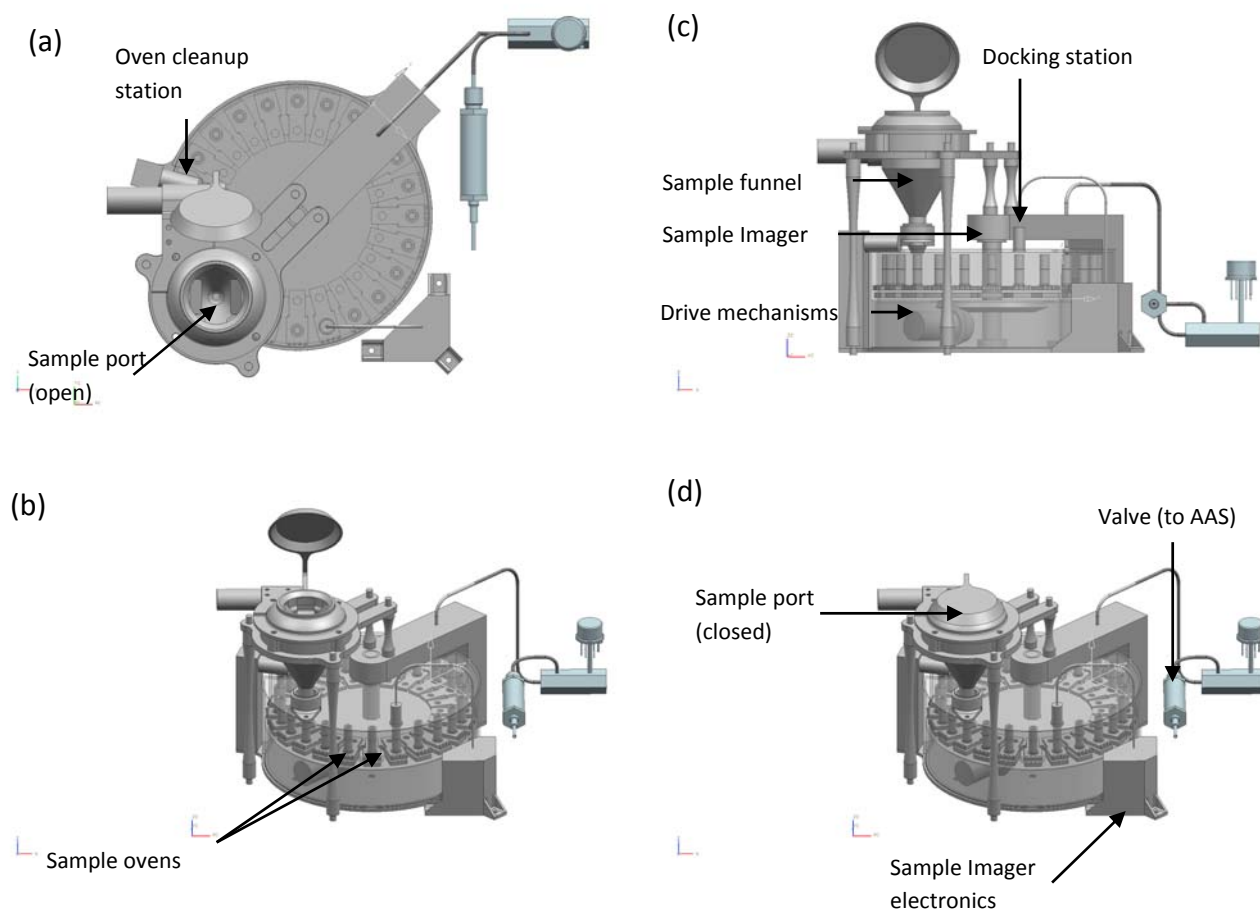


Figure 4 CAD representation of the SIS

4.4 Atmospheric Analysis System AAS

The Atmospheric Analysis System (AAS) is based around an ion trap mass spectrometer which is capable of measuring incident neutral volatile species in real time. A second mode of operation involves use of a cooled adsorbent material to collect and concentrate neutrals for a period of time prior to releasing them into the ion trap for analysis; this offers increased sensitivity and the ability to collect samples over extended durations for zero power consumption. The ion trap is also used to directly measure a small aliquot of the volatiles as they are released from the Solids Inlet System and before chemical processing. The ion trap can analyse a mixture of volatiles over the full mass range in a few seconds.

The AAS design is shown in Figure 5 and includes a collector material which can be exposed to the atmosphere. A drive mechanism can move the collector out of the atmosphere and seal it against a volume into which the ion trap mass spectrometer is housed. Heating the collector releases volatiles for analysis in the ion trap. In addition there are localised electronics and a supply of reference gas for ion trap calibration.

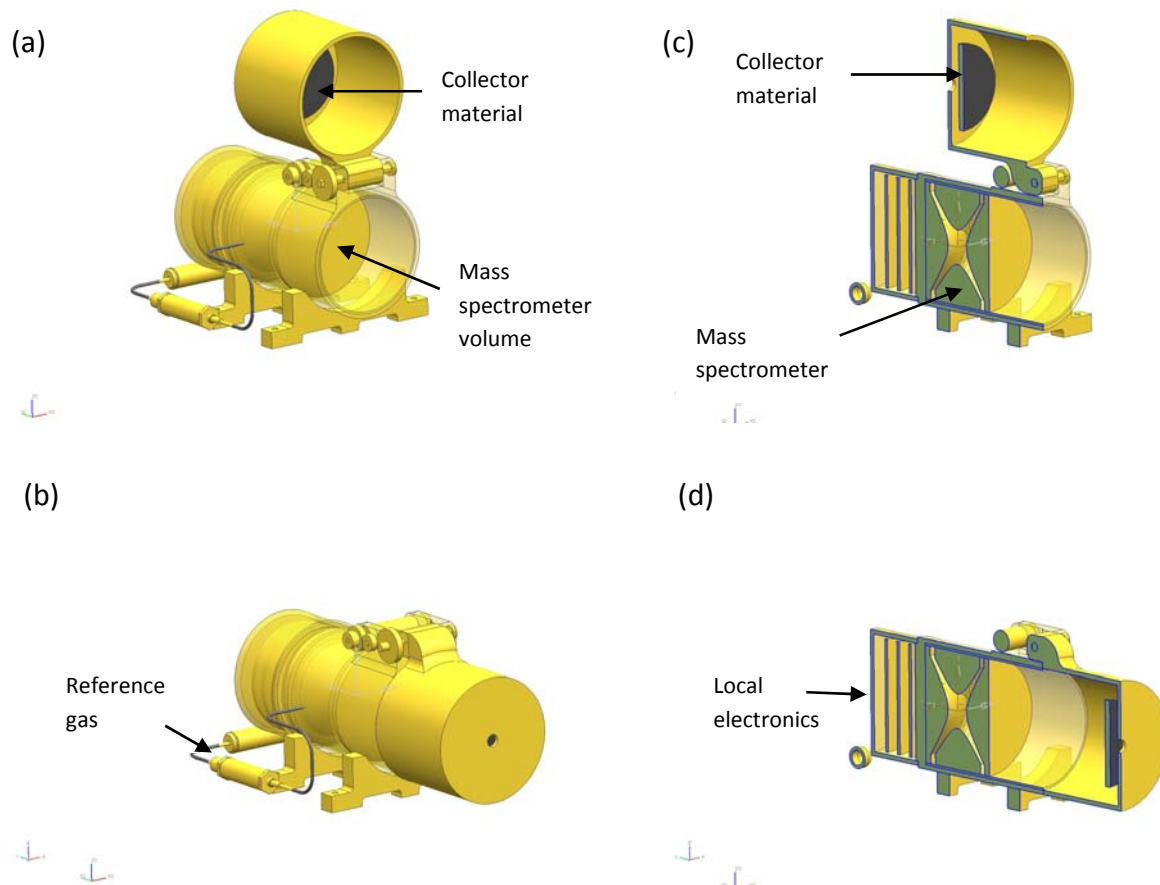


Figure 5 CAD representation of the AAS: (a) the collector exposed to the atmosphere (b) cut away view. The collector is shown in the closed configuration (c) with cut-away view in (d)

4.5 Sample Processing System SPS

The Sample Processing System is used to physically and chemically process volatiles into species suitable for isotopic analysis by the MSS. The SPS consists of a number of discrete subsystems:

- Hot manifold
 - runs at an elevated temperature to allow processing of samples rich in water vapour water without associated “memory effects”
- Warm manifold
 - processes “dry” samples i.e. having had water removed
- Reference Gas System
 - stores and releases precise amounts of reference gases into the SPS and AAS.
- Cold Finger Assembly
 - to separate volatiles using cryogenic focusing techniques

4.6 Magnetic Sector System MSS

The MSS performs the following functions:

- Receive sample and reference gases from the SPS
- Receive atmospheric samples from AAS via SPS (TBC) and/or direct from lunar atmosphere (TBC)
- Perform qualitative, quantitative and isotopic characterisation of reference and sample gases

The core sub-system of the MSS is the isotope ratio mass spectrometer. In order to achieve accurate isotopic analysis (better than 1‰) this will be a magnetic sector mass spectrometer which can operate in two modes:

- dynamic in which rapid switching between analysis of sample and reference gases allows good isotopic precision ($\sim 0.1\%$) but requires μmol quantities of sample
- static in which the mass spectrometer is sealed from the pumps and the entire sample enters the mass spectrometer for analysis over a period of up to several minutes. This achieves greater sensitivity ($\sim \text{nmol}$ sample size) but at a cost of reduced isotope precision ($\sim 1\%$) as the gas pressure reduces during the analysis and it is not possible to make a contemporaneous comparison with the reference gas. Further, the ionization source can degrade reactive gases during the analysis so this technique is only suitable for gases such as noble gases, CO_2 , CO , N_2 and CH_4 .

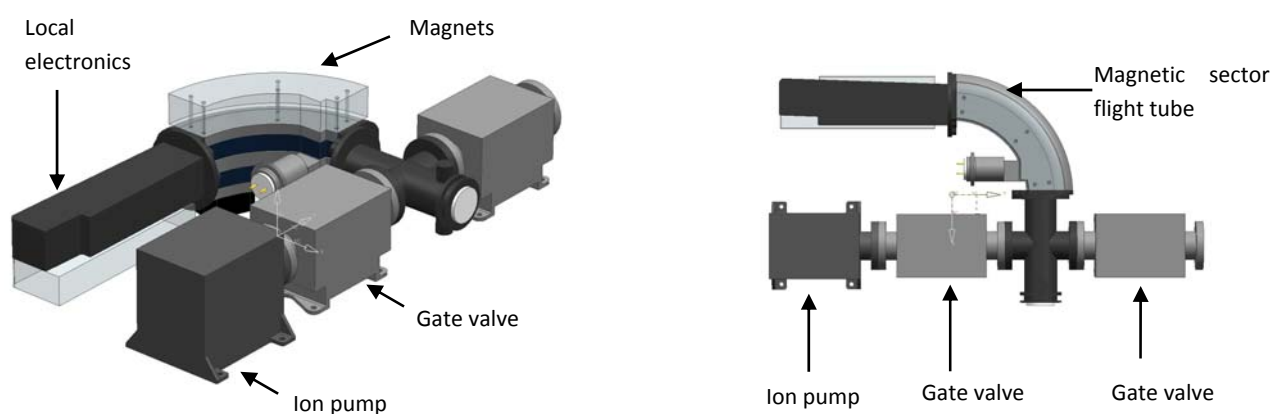


Figure 6 MSS Magnetic Sector System

5 L-VRAP operations

5.1 Regolith Analysis

In order to achieve its primary science objectives L-VRAP depends upon the delivery of appropriate regolith samples by the Lander's Solids Sampling System (SSS). As a baseline this comprises a simple scoop mounted upon a robotic arm, which can collect a surface or subsurface from an accessible zone up to around 2 m from the Lander, and deliver it into the solid sample inlet on the upper surface of L-VRAP. There are a number of likely limitations in the performance of such a scoop:

- Fidelity with which a desired sample location (lateral, depth) can be targeted
- Size of sample collected by scoop (of order ~few gram?) is likely to exceed sample size required by L-VRAP (few 10s of mg)
- Potential loss of volatiles from collected samples due to lack of containment and potential heating/insolation effects
- It is unlikely such a device could determine the size of sample delivered to L-VRAP (though in any case it may be preferable to carry out this function within L-VRAP itself).

The presence of a Mobile Payload Element (MPE - e.g. mini-Rover) would present the opportunity to collect samples from a greater distance from the Lander and so avoid most of the contamination associated with the Lander's descent motors. The MPE sample collection method may also involve a mole type device which may also give a sample size more in keeping with the current L-VRAP Sample Inlet System.

Once the regolith sample has been loaded into the sample inlet system it is characterised by the imaging system. Volatiles are extracted in incremental temperature steps. For each temperature step the volatiles are characterised by the ion trap mass spectrometer and may be processed by the SPS into forms appropriate for isotopic analysis in the MSS. Temperature steps will depend upon resources available and results from previous samples. Initially only a few temperature steps may be selected and emphasis may be placed on quantitative analysis (so called "quick regolith analysis"). Later experiments may concentrate on particular volatiles released from chosen temperature steps and will likely include full isotopic characterisation – i.e. "detailed regolith analysis".

5.2 Atmosphere/Exosphere Analysis

L-VRAP is more self-sufficient in terms of analysing the lunar atmosphere/exosphere, this being undertaken by the Atmospheric Analysis System (AAS) either in real time or after pre-concentration. It should be recognised that making measurements of the tenuous lunar exosphere in close proximity to a landed spacecraft will be complicated by the outgassing and offgassing of the spacecraft itself, and in particular any release of volatiles by the spent fuel system. In such circumstances it is anticipated that it may be beneficial to focus upon differential "before and after" measurements enabled by perturbations in the external environment: for instance the approach of the terminator, or the change in illumination conditions. It may also be feasible to take advantage of artificial perturbations that may be induced either by the digging

action of the Lander's robotic arm or by the action of the MPE traversing across the regolith and releasing trapped volatiles. It is anticipated that through a combination of these measurements, undertaken throughout the relatively extended time of the lander on the surface, it will be possible to build up a detailed understanding of the nature of the lunar exosphere and its temporal behaviour at the Pole, as well as the effect of the lander and hence by extension future human exploration on the Moon.

6 Scientific Performance

The ultimate performance of L-VRAP will be dependent upon a number of external factors including the local contamination environment and the capability of the Lander's sampling systems. Nevertheless, based upon previous flight hardware and laboratory experience it is possible to describe below the anticipated technical and scientific performance of L-VRAP.

The key mass spectrometer performance parameters can be summarised as follows:

Mass-to-charge ratio (m/z) range (corresponding to the types of species that can be analysed – i.e. “what species are present”):

- the instrument will have a mass range $m/z \sim 2-150$ corresponding to identification of species of molecular weight from hydrogen to more than xenon

The quantitative analytical capability (i.e. “how accurately is the abundance of each species measured”)

- the quantitative determination accuracy is estimated at ± 40 weight % and is currently limited by the accuracy of the method to determine the mass of sample analysed (i.e. not limited by the accuracy of the mass spectrometry).

The isotopic characterisation (“what is the precision of isotopic measurement”).

- the isotopic performance is species and sample size dependent. All target species can be measured with the required precision with the exception of oxygen-17 which is difficult to measure even with Earth-based instruments. The instrument's performance for various species is tabulated below (Table 1).

Table 1 Estimated isotopic precision of the L-VRAP magnetic sector with sample size, analyser mode to achieve measurement requirements

Isotope	Species	Analyser mode	Sample size	Precision (‰)
δD	H_2	dynamic	1 μmol	10
$\delta^{13}\text{C}$	CO_2	dynamic	1 μmol	0.1
		static	1nmol	1
$\delta^{15}\text{N}$	N_2	dynamic	1 μmol	0.1
		static	1nmol	1
$\delta^{18}\text{O}$	CO_2	dynamic	1 μmol	0.1
$\delta^{17}\text{O}$	CO_2	dynamic	1 μmol	2.2

7 L-VRAP Resource Requirements

7.1 Mass Budget

The current mass breakdown is shown in Table 2. The current estimated mass is 8 kg including maturity margins as specified by ESA.

Table 2 L-VRAP mass budget. CBE=Current Best Estimate. Maximum Expected Mass included margins as specified by ESA

Item	CBE Total Flight Mass (g)	Maximum Expected Mass [g]
STS Structural & Thermal System	1223	1363
LES Local Electronics System	900	990
AAS Atmospheric Analysis System	761	880
SIS Solids Inlet System	546	644
SPS Sample Processing System	1426	1596
MSS Magnetic Sector System	2314	2522
L-VRAP total	7170	7994

7.2 Instrument Volume

The instrument's maximum dimensions are 432 x 416 x 161 mm, which includes protrusions for mounting feet etc. Excluding such appendages, the volume envelope is 425 x 345 x 161 mm. The volume could be reconfigured to occupy a different footprint (e.g. smaller base footprint, but taller). No volume margins are specifically included, as the dimensions are generated from a detailed CAD model of the instrument.

7.3 Power Budget

The L-VRAP power budget is flexible as the instrument can be operated in a “slow, low power philosophy” or in a “fast, high power” regime. Average powers per experiment type are shown in Table 3. In all cases the maximum (peak) power will be limited to less than 56 W. Additionally, ~1.5 W of heater power is required at night (beyond ~38 hours' darkness)

Table 3 L-VRAP power budget.

Experiment	Average Power	Duration (minutes)	Data Volume (kBytes)	
			Science	Housekeeping
Exosphere real time analysis	Medium (7.9W)	611	242	306
Exosphere Passive Collection (NB L-VRAP on for only 59 minutes)	Low (0.015W)	659	63	30
Regolith Quick Analysis	Medium (8.0W)	74	553	37
Regolith Detailed Analysis	Medium (9.3W)	412	2258	206

7.4 Energy and Data Budget

The L-VRAP power and energy budget is flexible and can be tailored to resource availability (effectively at any mission stage – from the design stage through to during actual on-surface operations phase). For the purposes of this study, a baseline science operations scenario has been assumed with the resulting power and energy budgets shown in Table 4.

Table 4 L-VRAP baseline resource requirement. Duration % is % of mission phase for which L-VRAP is operative

Mission Phase	Duration	L-VRAP Operational Resources				
		Duration		Energy	Data vol.	Ovens
	(days)	(hours)	(%)	(Wh)	(kBytes)	(#)
Descent and Landing	0.042 (1 hour)	0	0.0	0.0	0	0
Lander Checkout	2	9.3	19.3	109.3	3247	0
Initial SS	30	199.6	27.8	1754.8	41947	17
Main SS	90	381.6	17.7	3166.0	26204	6
Extended SS	28	245.5	36.5	1991.1	9496	0
Total	150	836.0	23.2	7021.2	80894	23

8 Summary

The L-VRAP design described herein is a powerful instrument to detect, identify, quantify and characterise volatiles in Lunar regolith and Lunar atmosphere. Two mass spectrometers are involved – the first a wide mass range ion trap device to analyse the atmosphere and the second a magnetic sector to make precise measurements of volatiles released from regolith through heating up to 1000°C or more in sealed ovens.

A baseline operations scenario has been established allowing estimation of overall resource requirements. L-VRAP requires to be provided with at least 12 regolith samples although 24 would be preferable and should be seen as a target. The current maximum anticipated mass of the instrument is 7.99 kg. Data volumes are modest. A peak of 56 W power is required though some flexibility is possible if long/low power operations are found to be preferable at Lander level over a short/high power scenario (experience suggests the latter can be preferable in terms of energy and complexity). During extended periods of darkness, the Lander should provide ~1.5 W heating power to L-VRAP: the requirement can be forestalled for ~38 hours using a pre-heat before nightfall.

The majority of L-VRAP operations may occur during day time, though necessarily if L-VRAP is to study the behaviour of Lunar volatiles as a function of illumination, then some night time operations are preferable. The need to minimise night time energy demand has been recognised and taken into account; furthermore, night operations can be scheduled only towards the end of night to be implemented by a decision in the Lander only when survival of the Lander till upcoming dawn can be assured.

It is emphasised that L-VRAP is a flexible instrument that can be further refined in terms of performance, mass and power requirements as the mission definition matures.