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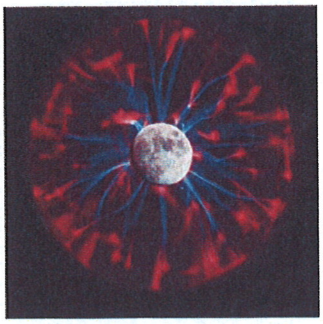

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1 Introduction

1.1 Background and Motivation

The Earth's Moon, our closest and most easily-accessible neighbor in space, is currently the subject of great international scientific interest. One of the key players in this is the European Space Agency, which is at the moment preparing its Lunar Lander mission. For a number of reasons including the expected presence of volatiles in shadowed areas and the potentially constant availability of solar power over a longer period, the mission's target is the Lunar south pole.

The goal of the Lunar Lander mission itself is to enable sustainable exploration in the future. The first step in this is the development of the highly accurate and automated lander itself. However, future exploration faces more questions and challenges than landing alone. One major hazard expected is that of the Lunar dust. This can be best illustrated by the following quote by Apollo 17 mission commander Gene Cernan (see [RD 06]):

"I think probably one of the most aggravating, restricting facets of Lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on. For instance, the simple large tolerance mechanical devices on the Rover began to show the effect of dust as the EVA's went on. By the middle or end of the third EVA, simple things like bag locks and the lock which held the pallet on the Rover began not only to malfunction but to not function at all."

This comment becomes especially relevant when taking into account that future missions to the Moon will last much longer than the Apollo missions – and require correspondingly higher reliabilities of mechanisms and seals.

While the dust distribution experienced by the Apollo astronauts was triggered mainly by man-made disturbances, there are also natural mechanisms responsible for dust transportation on the Moon. However, these still need significant further investigation to be understood. Delivering the necessary data for this is the main goal of the here described Lunar Dust Environment and Plasma Package (L-DEPP).

As far as future scientific use of the Moon in concerned, it has frequently been proposed to place large arrays of low frequency radio telescopes on the far side of the Moon. These scientifically extremely interesting wavelengths cannot reach the surface of the Earth due to its ionosphere. The advantages of such a telescope on the Moon as opposed to a free-floating array of spacecraft are the stable mounting ground and the protection from Earth-based interference by the Moon. However, it still needs to be confirmed that the dusty plasma around the Moon does not inhibit the transmission of low frequency radio signals in a way similar to the Earth's ionosphere. This also is a goal of L-DEPP.

1.2 Study Team and L-DEPP Concept

The Lunar Dust Environment and Plasma Package presented in this document has been developed by an international team of scientists lead by the space engineering company Kayser-Threde of Munich, Germany. Principle investigators are Priv.-Doz. Dr.-Ing. Ralf Srama from the Institute of Space Systems in Stuttgart, Germany, for dust particle science, Dr. Jan E. S. Bergman from the Swedish Institute of Space Physics, Uppsala, for plasma science and Prof. Dr. Heino Falcke from the Radboud University Nijmegen, The Netherlands, for radio science.

L-DEPP is projected to consist of two dust trajectory sensors, a set of three Langmuir probes and a radio antenna. When working together, these separate instruments provide a comprehensive insight into the mechanisms governing the dusty plasma on the Moon. To save precious resources, a common Package Support System is foreseen for power conversion, communications with the lander, instrument control and thermal control. Figure 1-1 shows the package mounted on an otherwise bare Lunar Lander.

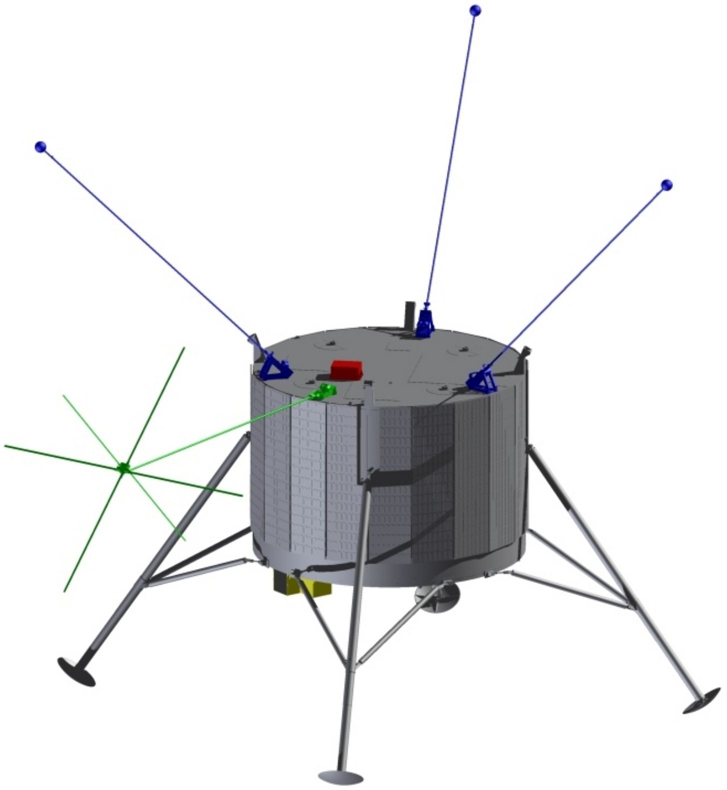

Figure 1-1 – L-DEPP mounted on the Lunar Lander

More detailed information on all relevant aspects of L-DEPP can be found in the L-DEPP documents listed in section 2.1 and 2.2.

2 Documents, Abbreviations and Definitions

2.1 Applicable Documents

[AD 01] Lunar Environment Specification [LLB1-LES-ESA(HSF)-0001: Issue 2, Revision 1]

[AD 02] Lunar Lander Mission Summary and Interfaces [LLB1-SUM-ESA(HSF)-0001]

[AD 03] Technology Readiness Levels Handbook for Space Applications [TEC SHS/5551/MG/ap. 2008]

[AD 04] L-DEPP proposal [KT proposal no. 402843 A, 08 April 2011]

[AD 05] L-DEPP Statement of Work [LDEPP-SOW-ESA(HSF)-0001, Issue 1, Revision 4, 27 Sept 2010]

2.2 Reference Documents

[RD 01] L-DEPP Requirements Specification and Concept Recommendation [LDEP-KT-TN-0001, Issue 3, 03 February 2012]

[RD 02] L-DEPP System Design Report [LDEP-KT-TN-0003, Issue 2, 23 August 2012]

[RD 03] L-DEPP Instrument Design Report [LDEP-KT-TN-0004, Issue 1, 25 June 2012]

[RD 04] L-DEPP Science Performance Report [LDEP-KT-TN-0005, Issue 1, 02 July 2012]

[RD 05] L-DEPP Development Plan and Breadboard Definition [LDEP-KT-TN-0006, Issue 1, 15 November 2012]

[RD 06] NASA Training Office and Crew Training and Simulation Division, 1973: Apollo 17 Technical Crew Debriefing (U), MSC-07631, pp. 27-27

2.3 Abbreviations and Definitions

Abbreviation	Meaning
AC	Alternating Current
AD	Applicable Document
ADC	Analog-to-Digital Converter
DC	Direct Current
DCN	Document Change Note
DPU	Data Processing Unit
ESA	European Space Agency
EVA	Extra-Vehicular Activity

Abbreviation	Meaning
FPGA	Field-Programmable Gate Array
IRF	Institutet för rymdfysik (Swedish Institute of Space Physics)
IRS	Institut für Raumfahrtsysteme Stuttgart
KT	Kayser-Threde GmbH
L-DEPP	Lunar Dust Environment and Plasma Package
NASA	National Aeronautics and Space Administration
PSS	Package Support System
RD	Reference Document
RP	Report
RUN	Radboud University Nijmegen
UHECR	Ultra High Energy Cosmic Rays
UV	Ultraviolet

3 Scientific Requirements

The objective of the Lunar Dust Environment and Plasma Package (L-DEPP) is to characterize the dust-plasma transport mechanisms, in situ, on the Lunar surface, and their relations to the global plasma and radio environment of the Moon.

This objective addresses long-standing questions of how the charging, levitation, and transport processes of Lunar dust work; how Lunar dust interacts with plasma and the electric fields that drive these processes; what the properties of the Lunar ionosphere and radio background are; and what the interactions between these large scale phenomena and the dusty plasma on the surface are. To answer those questions and so to obtain a far better knowledge of the Lunar dust-plasma environment than present, future robotic and human exploration of the Moon are important. The same is true for evaluating the Moon's potential to serve as a platform for scientific investigations in the future, not only of the Moon but also from the Moon.

To meet this objective the determination of the following physical characteristics is required:

- Dust
  - Directionality/origin
  - Speed and mass distribution
  - Charge
- Plasma
  - Density
  - Temperature
  - Ion drift speed
  - The Lunar ionosphere: cut-off frequency, physical extent, total electron content and spatial density distribution
- Electric Fields
  - Strength
  - Direction
  - Electric surface potential
- Lunar Radio Environment
  - Lunar radio background
  - Radio emissions caused by local transient events: Moonquakes, meteorite impacts, high speed dust particles, and ultra high energy cosmic rays (UHECR)
  - Exploring the potential of the Moon as a site for astronomical ultra-long wavelength radio observations that could open the last unexplored frequency regime to radio astronomy

4 Instrument Design

4.1 Lunar Dust Explorer

The detection principle for individual dust particles is charge induction onto three planes of charge sensing grids. The design driver for the selected instrument configuration is the requirement to provide reliable data. Surface charges in the instrument aperture are generated by UV light of the sun (direct sunlight incidence or indirect incidence). It is therefore the goal to suppress this effect as much as possible by a reasonable small instrument aperture. Therefore at least two separate sensors are required: One sensor (LDX-S1) pointing sideward, and one sensor (LDX-S2) pointing downwards to the surface. Furthermore, surface plasma can disturb the sensitive charge induction process, and therefore wall electrodes shield the interior sensing electrodes.

The ambient plasma electrons are shielded from the sensor inside by an electron reflector set to 300 V at the instrument aperture (3 grids). Fast surface ejecta particles and interplanetary dust particles are detected by a separate impact target using impact ionization at the bottom of sensor LDX-S1. The sensors have three planes with segmented electrodes, each of which is connected with a charge sensitive amplifier. The particle trajectory is derived from charge induction signals of individual channels. Dust particles with speeds between 1 m/s and 3 km/s are detected.

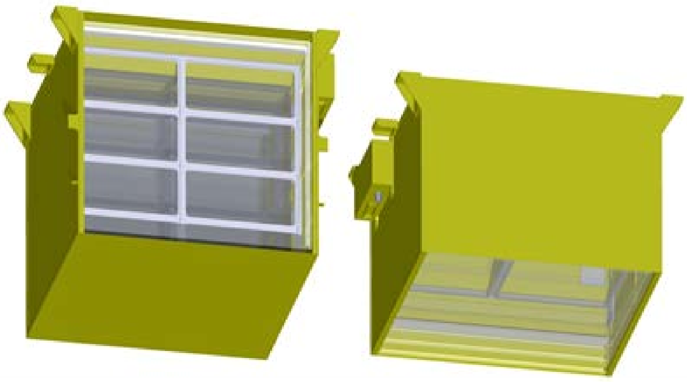

Figure 4-1 – LDX sensors S1 (left) and S2 (right)

4.2 Lunar Plasma Explorer

The LPX Langmuir probes can be operated either in current mode or in voltage mode, to measure plasma parameters or the electric field, respectively. To measure the electron number density and electron temperature, the standard measurement technique is the Langmuir probe voltage bias sweep. The probe potential with respect to the spacecraft, is varied from negative to positive and the current collected by the probe is sampled by an analogue-to-digital converter (ADC). Hence, for negative bias voltages, the ion number density and temperature can also be measured by this method during favorable plasma conditions. For ion flow speeds above the thermal speed (supersonic), the average ion drift velocity can be derived. If the flow speed and the ion charge are known, an estimate of the effective ion mass can be calculated. Keeping the probe bias voltage constant, variations in the probe current caused by plasma waves can be measured. The relative electron density fluctuations can then be determined. By using three probes, the propagation properties of plasma waves in the horizontal directions can be studied by means of interferometry. LPX will use this method to derive the plasma flow velocity components by time-offlight measurements. The LPX probes can also be operated with a controlled bias current, which allows the potential between the probes and the spacecraft to be measured. The difference in potential for two probes provides one component of the electric field, when divided by the probe separation distance. Using three probes yields the two horizontal components. The vertical component is determined from the spacecraft (surface) potential that is measured by all three probes in combination. The instrument can perform wave measurements up to 1 MHz, thereby complementing the LRX instrument in the low-frequency regime.

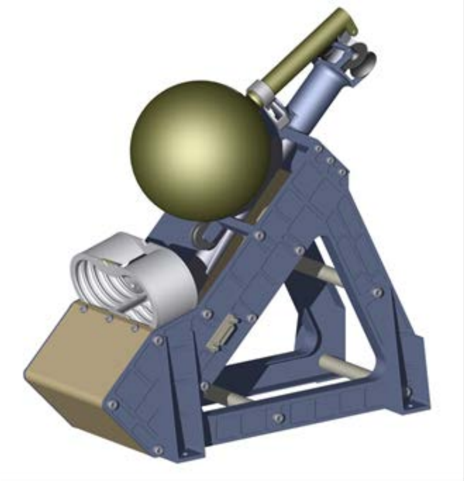

Figure 4-2 – LPX probe deployment unit (stowed for launch)

4.3 Lunar Radio Explorer

The active tripole antenna consists of 3 individual dipoles, each 2.5 m in length. The tripole shall be mounted on a boom so that its arms are symmetrically aligned in the xyz directions (see Figure 4-3). Due to the symmetry, the radiation pattern is omnidirectional. The tripole antenna will have its own LNA’s, filter and amplifier in the tripole center. An ADC then digitizes data. The digital data go to the DPU which includes an FPGA module and a microprocessor for triggering, processing and analysis. This system has to operate with 3 channels and up to 200 MHz sampling rate. The study will need to show whether that can be satisfied given the mission constraints. For optimizing the dynamic range, taking into account the increase in background noise towards the lower frequencies, the low and high frequency regime will be processed separately.

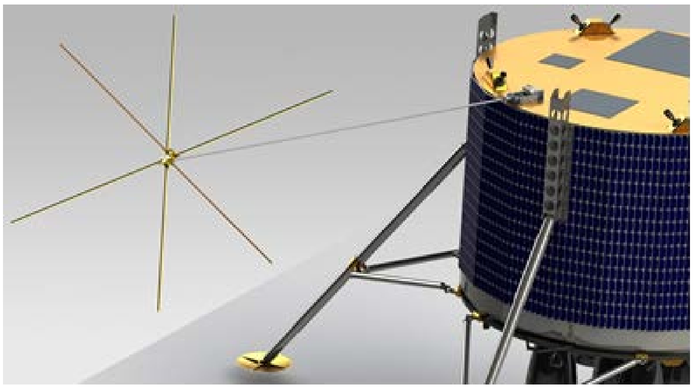

Figure 4-3 – LRX boom and tripole antenna (deployed)

5 System Design

5.1 Synergies

One key element of the L-DEPP study was the search for commonalities between the three instruments LDX, LPX and LRX as these may allow major reductions in mass, power consumption and complexity of the overall package. For many elements, a definite answer on this cannot yet be given at this time because a more detailed design is required for such statements. However, so far the following possible commonalities have been identified:

- Power conversion
- Instrument control
- Back end electronics thermal control system
- Analog-to-digital converters in LRX and LPX
- Deployment mechanisms for LPX and LRX.

The first three of these commonalities are to be exploited by having them performed by the Package Support System (PSS). The exception from this rule is the LDX high voltage generation, which will be under the responsibility of its user, the LDX.

5.2 Package Support System

To support the instruments of the Lunar Dust Environment and Plasma Package, the Package Support System (PSS) consists of several elements:

- Power conversion electronics providing the electrical interface to the Lunar Lander
- Instrument control electronics managing the package and providing the data interface to the Lunar Lander
- Mechanisms actuation electronics for centralized control of all L-DEPP mechanisms
- An electronics box housing all instrument Back End Electronics and the PSS boards
- A thermal control system for the PSS electronics box

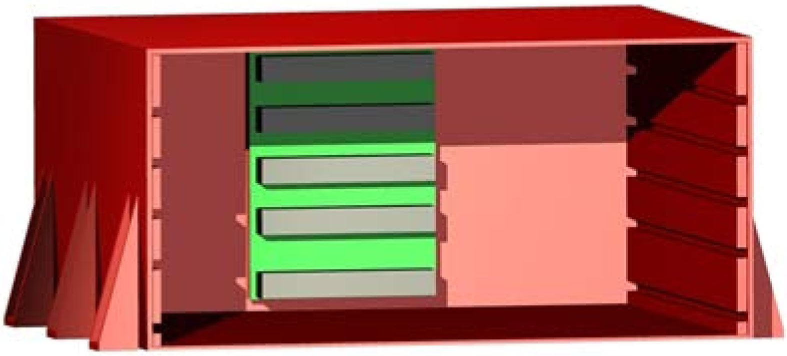

Figure 5-1 – PSS electronics box (front open)

5.3 Accommodation

Of the L-DEPP instruments, LDX requires two separate sensors and LPX requires three. When also taking into account LRX and the PSS, L-DEPP as a whole is made up of seven separate elements. Due to the different scientific requirements to the mounting locations, these elements must all be mounted separately. Figure 5-2 and Figure 5-3 below show the baseline accommodation of the L-DEPP study. In these images, the two LDX boxes are visible at the bottom of the lander. LPX consists of the three long boom units with Langmuir probes at their end while LRX is the antenna extended to the side of the lander. In Figure 5-3, the PSS box can be seen on top of the lander's deck between a plasma boom and the LRX boom unit.

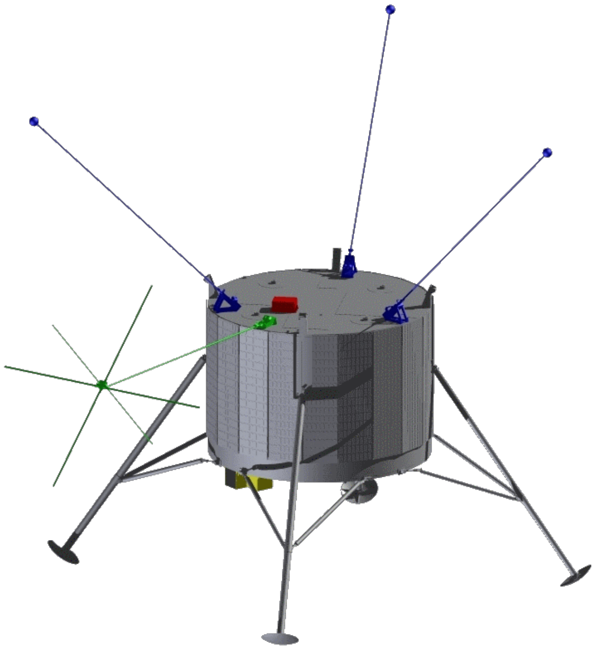

Figure 5-2 – L-DEPP accommodation

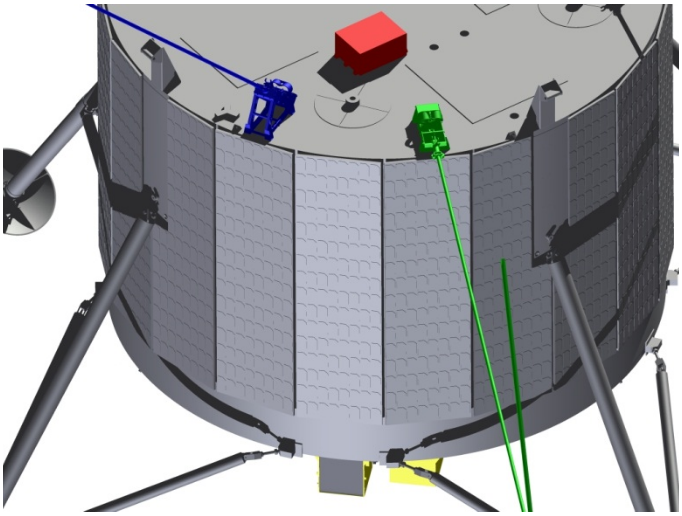

Figure 5-3 – L-DEPP accommodation (close-up)

6 Budgets

6.1 Mass

Table 6-1 – L-DEPP mass budget

		Mass Budget L-DEPP			22.08.2012	
Instrument	Item	Item Mass [kg]	Margin	Remarks	Item Mass incl. Margin	Total Mass [kg]
LRX						1,68
	1 Boom incl. Deployment Mechanism	0,500	20%	incl. cable from LNA to boom unit	0,6	
	Tripole Antenna	0,350	10%	0,12 (6 antenna arms) + 0,15 (6 antenna housings) + 0,03 (3 thermal knifes); 0,05 (all LNAs)	0,39	
	1 Double-Eurocard PCB	0,375	20%		0,45	
	harness to BEE	0,200	20%	estimated	0,24	
LDX					0,00	3,10
	Dust Sensor LDX-S1	0,831	20%	Sensor including Front-End Electronics	1,00	
	Dust Sensor LDX-S2	0,691	20%	Sensor including Front-End Electronics	0,83	
	1 Double-Eurocard PCB	0,376	20%	Event acquisition board (ADC's and trigger logic for real-time analysis), HV generation	0,45	
	harness S1 to BEE	0,425	20%	assuming 3m cabling between sensors and PSS, + 150g tbc for the connectors; shorter distance to PSS would decrease mass	0,51	
	harness S2 to BEE	0,259	20%	assuming 3m cabling between sensors and PSS, + 100g tbc for the connectors; shorter distance to PSS would decrease mass	0,31	
LPX					0,00	2,48
	3 Boom Units	1,440	10%	each incl. Probes, Deployment Mechanisms and internal harness	1,58	
	1 Double-Eurocard PCB	0,375	20%		0,45	
	harness to BEE	0,375	20%	3 cables with lengths 2m, 1.5m and 1m (70g/m); 6*10g for connectors; cable mass in boom included in Boom Unit mass	0,45	
PSS						3,54
	1 Double-Eurocard PCB Instrument Control	0,375	20%	L-DEPP Main Processor Board: CPU, Memory, Interfaces to all instruments and to Lander, thermanl control	0,45	
	1 Double-Eurocard PCB for DC-DC	0,400	20%	PCB not fully occupied, spare allocated for mechanisms drivers and control	0,48	
	PCB casing with PCB support and internal harness / small backplane	1,500	10%	E-box for 5 Double-Eurocard PCB's	1,65	
	Thermal hardware	0,800	20%	with 500g for one louver, 300g for MLI and heater	0,96	
	Sum Mass					10,80

6.2 Power

In order to fulfill the thermal requirements for the hot case the performed analyses show that a typical steady-state power consumption of 20 W will be sufficient, allowing an increased power of 30 W for about 5 hours or 40 W for about 1 hour.

These results were taken as target for generating a typical operations scenario for L-DEPP, comprising also a low power mode of LRX. As this low power mode is not enough for the necessary power reduction we propose some periods where L-DEPP is fully switched off. This is the most effective way (only in this case PSS can be switched off, too). If L-DEPP is switched off 4 times per day for 1 hour each the mean steady-state power of about 20W can be fulfilled. This can be tolerated from the science view.

When optimum scientific measurements are required, the secondary power consumption of LRX may rise to 20W (High Power Mode). In this case 5 one-hour interruptions of L-DEPP within 24 h are necessary.

6.3 Data

Assuming an operational scenario with 19 to 20 hours of operations time per day, a maximum of 360 MByte/day is generated (after compression; averaged over several days).

6.4 Options for Descoping

Even after significant engineering effort, the total mass of the developed L-DEPP concept is at 10.8 kg (see Table 6-1). This value is 3.1 kg above the mass required in [AD 05]. In order to further reduce the L-DEPP mass requirement, the following options are available:

- **Simplified PSS electronics box thermal design**

  Placing the PSS electronics box inside the Lunar lander and connecting it to a radiator on its outside would reduce the radiative heat input during sunlight and the radiative heat loss during night. While this has not been studied in detail, it is expected that this will lead to a simplification of the PSS electronics box's thermal control system and a consequent reduction in mass. A similar effect is expected if the operating temperature range of the electronics within the PSS electronics box can be increased. Both these options are recommended for future studies of L-DEPP.

- **Reduced instrument autonomy**

  Currently, the PSS's instrument control system is able to buffer recorded data during dawn/dusk and night time operations so that the lander's main computer can be switched off in the meantime. Also, the PSS includes the electronic circuits necessary for the actuation of L-DEPP's mechanisms. If both of these functions – night time and no-comms data storage and mechanism actuation – could be performed by the lander, it is expected that a full double Eurocard size electronics board of 375 g can be saved.

- **Scientific descoping**

  While this is not recommended by the study team, further mass reductions could be achieved by descoping of the package's scientific capabilities.

7 Conclusion and Outlook

After the completion of this L-DEPP study, the Lunar Dust Environment and Plasma Package is defined as a combination of three instruments. While each investigates very different physical phenomena, only their combination allows a complete and thorough understanding of the dynamics surrounding the Moon's dusty plasma environment. This is of crucial importance in order to prepare for future extended scientific or human exploration missions to the Moon, especially when taking the dust-related problems of the short-duration Apollo missions into account.

To analyze the levitated dust particles and ejecta themselves, the Lunar Dust Explorer (LDX) measures their physical characteristics such as speed, charge and trajectory. The electric field and surface potential, influencing the movements of charged dust and plasma, are analyzed by the Lunar Plasma Explorer (LPX), which also measures the density and temperature of the plasma. Complementary to this, the Lunar Radio Explorer's (LRX) low frequency radio receiver adds remote sensing capabilities to L-DEPP. The LRX will allow to link the local impacts of, for instance, micro-meteorites and the creation and transportation of dust to changes in the Lunar ionosphere. In addition the LRX will virtually open up the low frequency regime (<30 MHz) for radio astronomy which for many years has been considered a major science area identified to be performed on the Moon.

In order to minimize the resources required for L-DEPP, the Package Support System (PSS) serves the instruments' common infrastructure needs such as power conversion, instrument control, thermal control and interfaces to the lander.

As presented in [RD 05], the L-DEPP team is confident that the here presented Lunar Dust Environment and Plasma Package can be developed in time to meet the Lunar Lander mission's schedule.

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