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1 INTRODUCTION

This report provides a complete description of the PHILIP/HILPBS Project: the scope of the study, the performed activities and main results obtained during the corresponding work-packages. A possible mission scenario has been identified, together with a possible PHILIP/HILPBS conceptual design.

As a conclusion, a comparison among the PHILIP/HILPBS powering concept and conventional powering solutions has been carried out and a development plan has been traced in order to identify the future steps towards a space product, paying special attention to the definition of a Development Model.

2 REFERENCE DOCUMENTS

2.1 Applicable Documents

Ref.	Identifier	Title
A1.	SOW-PHILIP-MMA-20170118	PHILIP Statement of Work
A2.	ASSD/Space/17-209	PHILIP Detailed Proposal

2.2 Referenced Documents

Ref.	Number	Title
R1.	ENG-05, LPSR-LVP-AirbusDS-TN-001, issue 1, Airbus Defence & Space, (2015)	ESA Lunar Polar Sample Return – MSA Study, LVP Requirements Review
R2.	ENG-06, LPSR-LVP-AirbusDS-TN-002, issue 3, Airbus Defence & Space, (2016)	ESA Lunar Polar Sample Return – MSA Study, LVP System Concept and Operations Definition
R3.	ENG05, TASI-SD-LPSR-TNO-0108, Thales Alenia Space (2016)	Lunar Polar Sample Return Mission and System Assessment, LVP Requirements Review
R4.	ENG06, TASI-SD-LPSR-TNO-0124, Thales Alenia Space, (2016)	Lunar Polar Sample Return Mission and System Assessment, LVP System Concept and Operations Definition
R5.	SPIE_DSS11	"Laser power beaming for defense and security applications", T. J. Nugent, Jr., Dr. J.T. Kare (LaserMotive), 2011
R6.	USNA11-NUGENT	"12-hour hover: flight demonstration of a laser powered quadrocopter", T. Nugent Jr. et al., 2011
R7.	SPIE, Vol.4632, 2002, pp.199-223	"Laser power transmission for the energy supply to the rover exploring ice on the bottom of the crater in the lunar polar region" , K.Takeda et al., 2002
R8.	Chin. Opt. Lett. 5, S109-S110	"Application of the laser energy transmission technology to drive a small airplane", N. Kawashima et al., 2007
R9.	RAND – Project Air Force	"Feasibility of Laser Power Transmission to a High-Altitude Unmanned Aerial Vehicle", R. Mason, 2011
R10.	In proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation –ASTRA 2004- ESTEC	"Wireless power transmission experiment using an airship as relay system and a moveable rover as ground target for later planetary exploration missions", F. Steinsiek et al., 2004
R11.	Wikipedia, Shackleton crater	https://en.wikipedia.org/wiki/Shackleton_(crater)
R12.	NASA "Moon Trek" tool (Lunar Mapping and Modeling Portal (LMMP)	https://moontrek.jpl.nasa.gov

Ref.	Number	Title
R13.	Earth and Planetary Astrophysics (astro-ph.EP), arXiv:1208.5587	"Characterisation of Potential Landing Sites for the European Space Agency's Lunar Lander Project", De Rosa et al., (2012) https://arxiv.org/abs/1208.5587
R14.	EPSC Abstracts, Vol. 9, EPSC2014-136-1	"Connecting Ridge - A landing site at the lunar south pole with extended illumination", P. Gläser et al., (2014)
R15.	ASTRA 2015, 13th Symposium on Advanced Space Technologies in Robotics and Automation	"Dextrous Lightweight Arm for Exploration (DELIAN) Project" Presentation, A. Rusconi et al. (2015)
R16.	H2020-LEIT-SPACE – COMPET-03-2015 (2015)	"ElectRomAgnetic Energy Beam as a SoUrce of Energy for Space Probes (ERASTUS)", LEONARDO proposal to the European Commission call, HORIZON 2020 EU Research and Innovation Programme
R17.	US department of energy, Multi-Mission Radioisotope Thermoelectric Generator (MMRTG)"	https://www.nasa.gov/sites/default/files/files/4_Mars_2020_MMRTG.pdf
R18.	ECSS-E-HB-10-02A (2010)	"Space Engineering Verification guidelines", ECSS Secretariat ESA-ESTEC

3 ACRONYMS

Acronym	Description
APT	Acquisition, pointing and tracking
DC	Direct current
DELIAN	Dextrous Lightweight Arm For Exploration
E/E	Electrical to Electrical (efficiency)
E/O	Electro-Optical
ERASTUS	(ElectRomAgnetic Energy Beam as a SoUrce of Energy for Space Probes)
ERM	External Re-pointing Mechanism
HILPBS	High Intensity Laser Power Beaming System
LVP	Lunar Volatile Prospector
METIS	Multi Element Telescope for Imaging and Spectroscopy
MMRTG	Multi Mission Radioisotope Thermoelectric Generator
MRR	Modulating Retro-Reflector
O/E	Optical to Electrical (efficiency)
PHILIP	Powering Rovers by High Intensity Laser Induction on Planets
PSR	Permanently Shaded Regions
PV	Photo-Voltaic
SoW	Statement of Work
TRL	Technology Readiness Level

4 SCOPE OF THE STUDY

Scope of the study was to investigate the possibility to design a wireless power transfer system from the lander to the rover, based on laser technology, to:

- Avoid the use of nuclear powering systems, such as the plutonium Multi Mission Radioisotope Thermoelectric Generator (MMRTG) accommodated onboard the NASA/JPL MSL Curiosity Rover, due to the constraints imposed by the use of radioactive materials
- Extend the exploration capabilities towards areas in which solar collection is problematic, such as in the Moon PSRs (Permanently Shaded Regions): the exploration of PSRs implies that the batteries – charged via a solar photovoltaic panel- would need to be massive to allow the rover to penetrate deep in the PSR and to frequently get out of the PSR to recharge batteries

A laser-power-supplied rover, in fact, could penetrate easily up to 15 km in the PSR being constantly supplied with power by the lander. Such laser systems may have also the capability of pointing with centimeter accuracy over several kilometers, ensuring an uninterrupted power supply of the rover from the lander. It has to be remarked that several studies show that a HILPB system has the capability to deliver energy indefinitely to remote vehicles and crafts such as climbers, small demo rovers, kites, quadrocopters, unmanned aerial vehicles, thereby increasing their autonomy and endurance. [R5, R6, R7, R8, R9, R10].

5 PERFORMED ACTIVITIES AND MAIN RESULTS

5.1 Project WBS and work logic

The study has been articulated in five work packages, according to the following work breakdown structure:

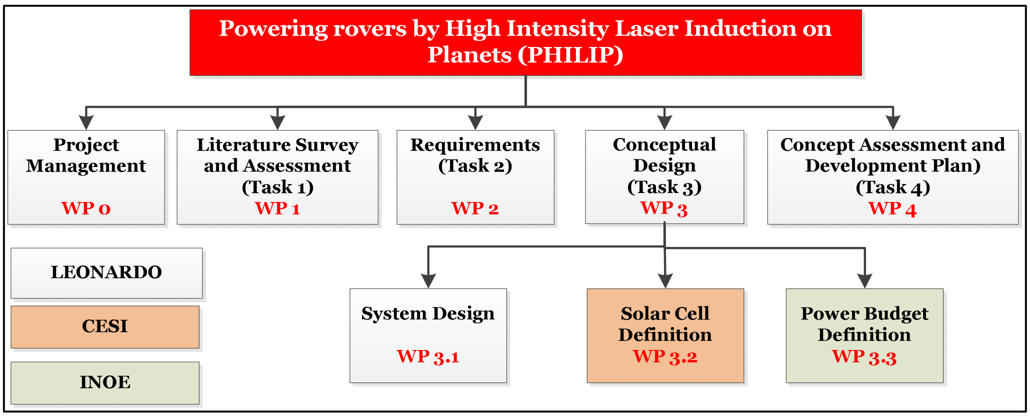


Figure 1: PHILIP Project Work Breakdown Structure

WP0 was aimed to manage the activity, traced via dedicated meetings and progress reports. 5 meetings have been held (including the SRR and the Final Review) and 7 progress reports have been issued during the whole project duration (10 months).

WP1 was aimed to report the literature survey on current PHILIP – HILPBS systems, such as small scale demonstrators and concept studies, and to provide assessments and recommendations on main technologies that can be used to build such a system.

WP2 was aimed to define the requirement for HILPB system and its subsystems, starting from Lunar Reference Mission requirements and from a deep analysis of reference documents listed in the SoW [A1].

WP3 was aimed to provide a conceptual design of the HILPB system, identifying the main subsystems, the resources needed for this system to operate and reachable efficiencies, assessing the impact on lander and rover system design. A detailed energy link budget and communication link budget have been provided, to study the option of dual functionality charging/communicating; the compliance matrix has been traced together with the single point failure identification and the investigation of potential hazards on the optical payloads onboard the rover, due to accidental high power laser beam illumination.

It has to be remarked that this activity has been performed in close collaboration with CESI and INOE 2000, responsible respectively of the definition of the best solar cells solution for this application and the power budget definition.

WP4 was aimed to assess the available technologies for implementing the concept and to outline the advantages and disadvantages of a HILPBS solution with respect to a more conventional PV/battery solution and microwave tethering technology, together with the preparation of a development plan including the definition of a test using a breadboard model for concept demonstration.

For each technical WP a dedicated TN was issued reporting the related activity; in addition to what above, system illustrations have been provided to synthetically and graphically resume the conceptual design for this application.

The activity performed under this contract can be classified as TRL 2, "*Technology concept and/ or application formulated*".

5.2 Main results achieved

This study defined a possible scenario for this mission (WP1), individuating a possible landing area and three PSRs exploration points within the range of 10 km defined in the SoW [A1].

According to this, a conceptual design (WP3) has been formulated, starting from:

- The definition of system requirements (WP2)
- Preliminary simulations, performed to derive the requirements at subsystem level (WP2)
- A survey of the technologies and components that are used in space or in other application fields for the same concept (i.e. demos or studies) (WP1)

The conceptual design included:

- a functional block diagram
- selected technologies to be adopted to sustain the power transfer
- the estimation of power consumption, heat to be dissipated, mass and volume related to lander and rover sections of HILPB system

The compliance matrix compiled by cross correlating the requirements defined in WP2 and the conceptual design reported in WP3 identified some non-compliances with respect to the identified requirements, deemed however not critical for the implementation of this technology.

In particular, most of the non-compliances were referred to the possibility to transmit payload/images data on the optical communication channel (> 0.8 Mb), not possible with the selected technology foreseen for the optical communication link, operating at 200 KHz but advantageous in terms of alignment and design complexity; a possible solution to overcome this issue could be to reduce the amount of data to be exchanged (e.g. by a suitable compression algorithm for images) and/or to increase the data transmission time from rover to the lander.

To define a roadmap for the PHILIP/HILPBS concept, following aspects have been considered in WP4:

- identification of critical areas and development effort to bring this technology to the requested TRL
- the definition of the components to be integrated in a future Development Model (laboratory testing)
- definition of a test campaign on the Development Model to check main functionalities and to provide a feedback for system design.

Finally, a comparison among this technology and other powering concepts (i.e. photovoltaic panel and batteries, microwaves, nuclear power generation) has been performed, taking into account:

- the exploration capabilities and heritage in space
- the related efficiencies
- mass and sizes
- handling issues

6 PHILIP/HILPBS CONCEPT

6.1 Mission scenario

The results of this study could be applied to explorative missions in areas where no sunlight is available: very close to the Lunar South Pole, in fact, there are locations where a HILPB System can potentially be used in order to explore Permanently Shaded Regions (PSRs). Among the proposed operation sites, the PHILIP/HILPBS mission was initially assumed to be performed near the Lunar South Pole, in the Shoemaker/Faustini region according to [A1], [R2], [R4].

However, a deeper analysis of illuminated areas surrounding the Lunar South Pole suggests to perform the PHILIP activity in the Connecting Ridge area, located between the de Gerlache and the Shackleton craters (Figure 2), around the CR1 landing site [R13], [R14]. In fact, a lander landing at CR1 will benefit from excellent illumination conditions with respect to Shoemaker Faustini region: more than 87.9% of accumulated illumination can be reached at heights of above 2 meters over 20 years. This in turn will help the powering of laser source located on the lander, which is supposed to be powered mainly via solar photovoltaic panels and either powered by nuclear power source in combination with lander batteries in dark periods. In the CR1 surrounding area there are three nearby PSRs (< 15 km), which are likely to be reachable via paths with a downhill inclination of at most 10 degrees, suitable for a typical rover locomotion system [R2], [R4]. Nevertheless, similar circumstances may exist at and near other potential landing sites in the same area; it may also be possible to consider the exploration of other PSRs near the CR1 landing site but, being the straight paths steeper with respect to the selected one, a non-straight-line path for the rover - i.e. not exceeding 10 deg of slope- has to be evaluated.

Concerning the exploration of Shackleton crater [A1], landing on its craters rims it is another exploration possibility, but the slopes of its inner walls (> 20 deg) are very demanding for a typical rover locomotion system. Other technologies for rover locomotion system -such as a rapelling rover-, or other landing schemes -e.g. rover landed separately onto Shackleton crater floor- can be assumed to permit the exploration of Shackleton crater. However, in order to cover also these scenarios, linked with the exploration of the bottom of Shackleton Crater, a goal of 15 km for the power beaming distance to be covered by the PHILIP system has been considered in this document.

Connecting Ridge as landing area and proposed PSR exploration points

Figure 2 below is the zoomed image of the Lunar South Pole (taken with Moon Trek NASA tool [R12]), identifying the Connecting Ridge and the surrounding craters:

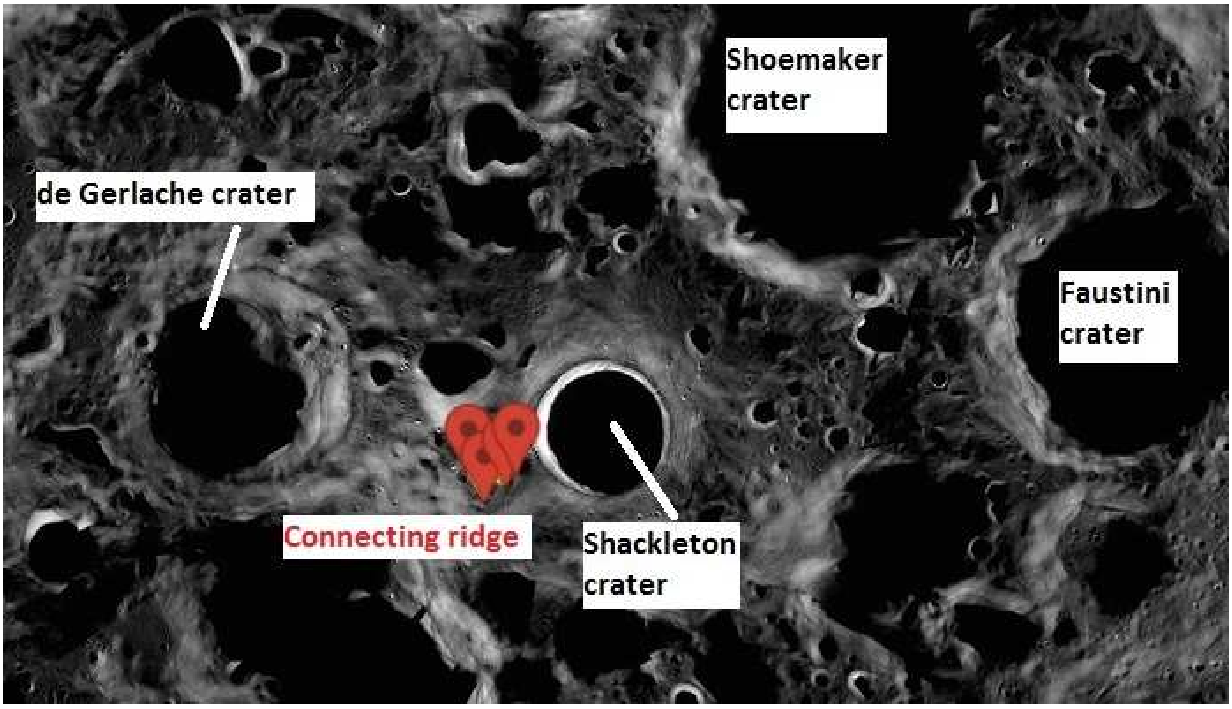


Figure 2: South Pole zoomed map, Moon Trek NASA tool [R12]

Some simulations around the Connecting Ridge CR1 landing site have been performed with Moon Trek tool [R12], resulting in three possible exploration points located near PSRs (Figure 3), compatible with the envisaged type of exploration scenario mentioned in [A1]:

- Exploration point PSR#1:
  distance landing site - PSR#1 edge ~ 7.1 km; distance landing site - PSR#1 ideal center ~ 7.9 km
- Exploration point PSR#2: distance landing site - PSR#2 edge ~ 5.7 km
- Exploration point PSR#3: distance landing site - PSR#3 edge ~ 4,6 km

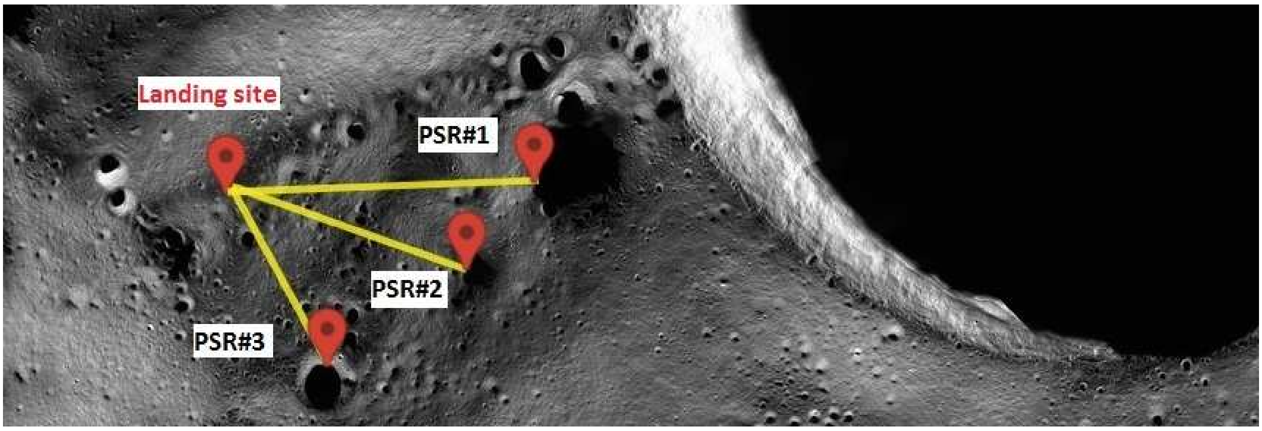


Figure 3: Proposed landing site and possible PSRs exploration points

Angular span among PSR#1 and PSR#3 is of about 65 deg; the positions of these exploration points impact on the requirements for the APT subsystem, in particular in terms of orientation capability of the steering system located on the lander. The rover is supposed to move with a 7 cm/s as the maximum speed, 8 hours driving (1/3 of an Earth day) corresponding to a typical daily driving distance on the order of 2 km.

6.2 PHLIP/HILPB System Overview

The HILPBS approach explored within the frame of PHILIP Project conceives a laser based system, made of two main sections -one located on the lander and the other on the exploration rover- in a wireless power continuous transfer modality from the lander to the rover. In details, the lander is equipped with a high power laser source and the rover is equipped with photovoltaic panel and batteries.

In fact, by remotely supplying power continuously to the rover through a high power laser beam out of the lander, the power transfer is assured even during driving mode, permitting both the exploration in the PSR without interruptions and to extend the duration of powering, reducing the needed laser output power with respect to a stationary powering method.

In support to the powering transfer modality, an APT (acquisition, pointing and tracking) subsystem has been defined to keep the correct line of sight among the lander and the rover, together with an optical communication channel (communication subsystem), aimed to efficiently exchange among the two HILPBS sections the data related to rover position and to the rover payload data.

The HILPB system can therefore be assumed to be made of three subsystems:

- The powering subsystem, to transfer wireless power from lander to the rover. This subsystem is made of:
  - High power fibre laser source, to generate laser optical power (on lander)
  - Optical system, to create the proper beam dimension at designed rover distance (on lander), interfaced via a fibre connector with the laser source
  - PV panel equipped with photovoltaic cells, to convert laser optical power to electrical power (on rover)
  - Batteries, to store electrical power for rover operations (on rover)

- The APT subsystem, to assure the reciprocal optical alignment among the lander and the rover. This subsystem is mainly made of:
    - o Photodiodes on the PV panel, to detect laser beam position on PV panel: their cross-correlated signals are used to detect the direction of the laser beam shift with respect to the optimal central position on the PV panel.
    - o a modulating retro-reflector (MRR) integrated in the central region of PV panel, to close the lander/rover alignment process. The photodiodes detection information is sent back to the lander via the superimposition of the modulated information on the MRR back-reflected laser beam
    - o Steering mechanisms (on lander and rover), to orient laser beam and photovoltaic panel towards the best charging direction

- The Communication subsystem, in support to the APT subsystem and in charge of transmitting payload data, based on an asymmetric link concept. This concept is preferable for this application because the supposed amount of data to be transmitted from the rover to the lander is higher (compressed images and videos, etc.) in comparison with the one from the lander to the rover (navigation information, telemetries interrogations, etc.).
  This subsystem is made of:
    - o Modulating retro-reflector, in common with the APT subsystem, to minimize the impact of this channel on the HILPBS recharging system design
    - o Receiving optics and optical receiver on lander to acquire position data

A visual sketch of the HILPB System is reported in the following figure, in which the optical communication beam is represented (in light red), in addition to the powering beam (dark red):

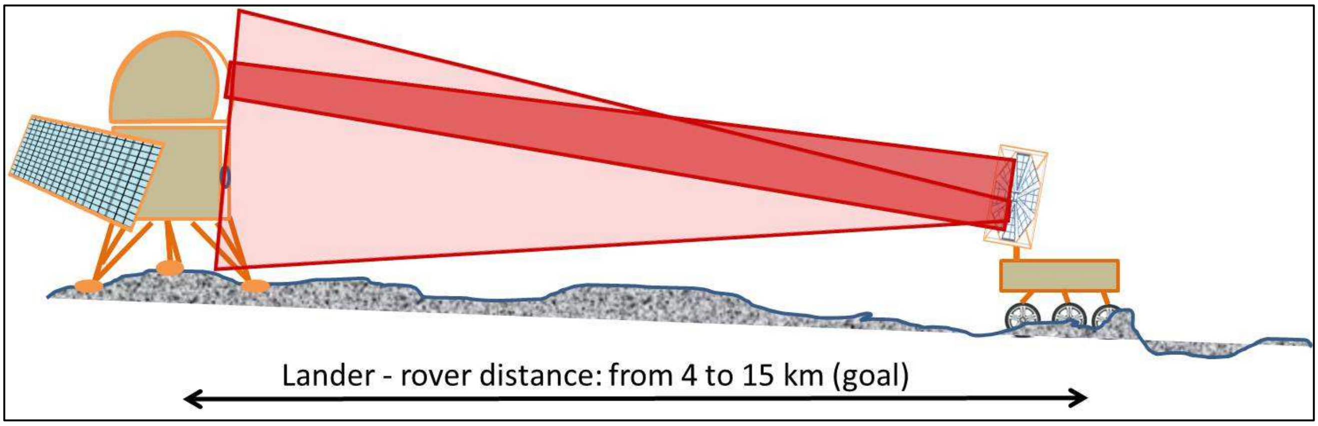


Figure 4: Visual sketch of the HILPB System

6.3 PHILIP/HILPBS operating modes

Two operative modes have been identified for the HILPB system, the nominal mode and the safe mode.

The PHILIP/HILPBS safe mode is foreseen in case of a detected reduced power transfer (i.e. received power being not sufficient to recharge the rover batteries), involving the:

- Rover navigation system, to eventually stop the rover or directing it in a previous defined position or exploration point; the batteries' power reserve can be used to drive towards a previous defined position or exploration point
- Lander/Rover APT subsystems in loop, to perform a complete scan along the uncertainty rover position range/to orient the panel and the laser beam accordingly

6.4 PHILIP/HILPBS Powering modes/rover batteries charging/discharging cycles

Considering modes power consumptions and foreseen duration times, the mean recharging power on batteries results to be 136.7 W; following table resumes also expected charging/discharging phases:

	Idle/survival mode	**Driving mode**	**Payload operations mode**
Total Power consumption [W]	40	255 (*)	115
Mode duration time (estimated)	1/3 (8 hours)	1/3 (8 hours)	1/3 (8 hours)
Batteries	ON, recharging: + 96.7 W	ON, discharging: - 118.3 W	ON, recharging: + 21.7 W

Table 1: Batteries charging/discharging phases

(*) the contribution of Rover APT subsystem components has been added with respect to [A1], accounting for 10 W;
Remark: the 35 W related to the communication link [A1] are intended to be available for the optical communication link (e.g. the communications link is supposed to be here optical instead of non-optical)

6.5 PHILIP/HILPBS interfaces with lander and rover

Preliminary estimations of power consumption, heat dissipation mass and volume are here recalled:

	HILPBS- Lander section	**HILPBS- Rover section**	**HILPBS- Lander and Rover sections**	**HILPBS + 20% contingency**
Power consumption [W]	2950	20 (*)	2970	3565
Heat dissipation [W]	2445 (**)	260 (**)	2705	3245
Mass [kg]	180	15	195	235
Volume [m3]	0.50	0.05	0.55	0.65

Table 2: HILPBS Interfaces with Lander and Rover

(*) this power consumption details only the HILPBS components to be integrated on rover (APT/communication subsystems)

(**) the generated heat can be efficiently reused to warm components, to withstand low temperatures

6.6 PHILIP/HILPBS Single Point Failures and potential hazards on rover optical payloads

The identified single point failures are:

1. High power laser source, based on fibre laser technology with diode pumped modules. In order to mitigate potential failures, a redundancy approach is here implemented: the diodes inside the laser work in a derated way, so to be able to increase output power if needed.

2. Optical communication system (optional). In order to mitigate potential failures, another communication channel has to be used (radiowaves, etc.) to track the rover position

In case of failure of APT system, the rover's batteries have been dimensioned to have a power reserve able to let the rover drive towards a known charging position; the exploration capability results to be degraded but the system can still be operative in the surroundings.

No potential hazards are envisaged for the optical payloads onboard the rover when the HILPB System is working in nominal operation, thanks to the vertical configuration of the panel and to the APT subsystem, in charge of continuously track the laser beam on photovoltaic panel.

In case of HILPB System working in safe mode, the laser beam is steered in order to recover the last useful recharging position, the rover is not anymore in driving mode and the payloads are not operating to save power; a shutter mechanism on payloads optical windows (if any) can be activated when in safe mode, in order to prevent from accidental laser beam radiation on the optical windows.

6.7 PHILIP/HILPBS – Lander/Rover section main components

The main elements for the Lander section are the:

- High power laser source
- Optical system
- Steering mechanisms (robotic joints for coarse steering and pistons for fine steering)

Following Figure 5 reports the system illustration for the lander section of the HILPB System:

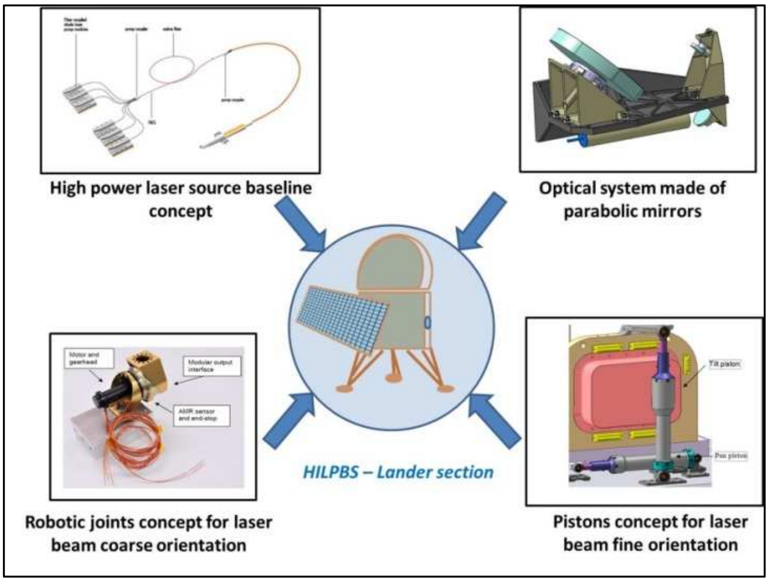


Figure 5: PHILIP/HILPBS illustrations, Lander section

The main elements for the Rover section are the:

- Photovoltaic panel, equipped with InGaNAs cells, photodiodes and the MRR
- Batteries
- Steering mechanism (robotic joints)

Following Figure 6 reports the system illustration for the rover sections of the HILPB System:

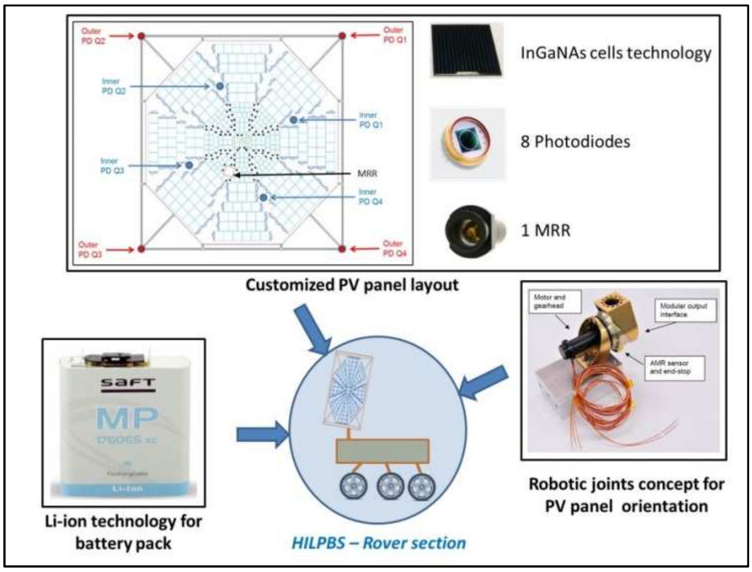
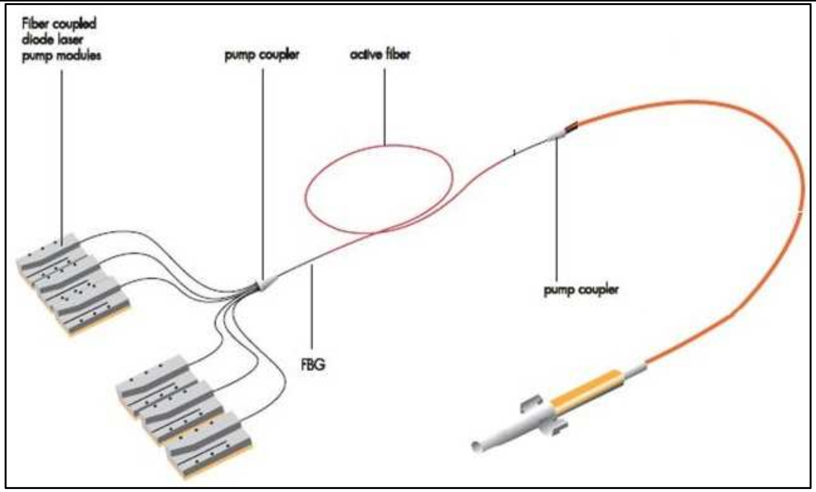
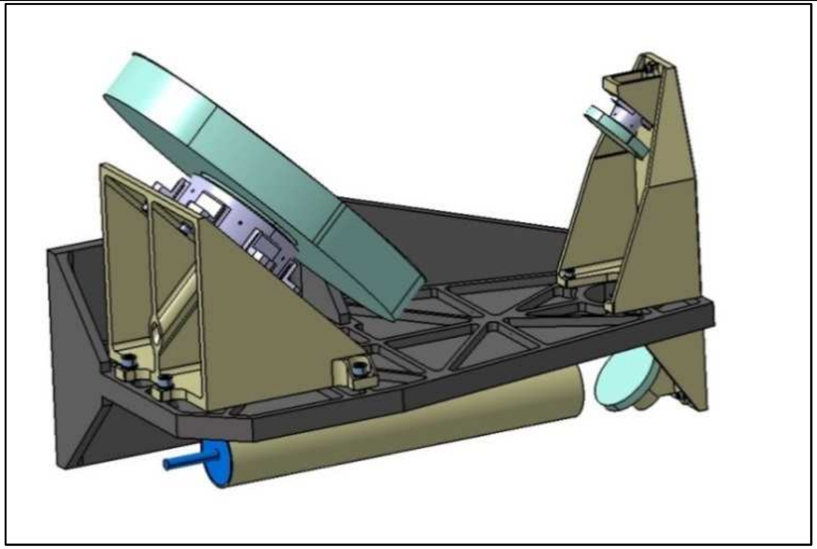


Figure 6: PHILIP/HILPBS illustrations, Rover section

Main Component (Lander section)	**Technical data**	**Conceptual sketch**
High power Laser source (Lander section)	Fibre-based laser technology, single source: • Output power: 500 W • Laser E/O efficiency: 17% • Mass (commercial device): 140 kg • Volume: < 0.751 x 0.953 x 0.584 m = 0.42 m3	
Optical system	Input: fibre connector Output: collimated beam, diameter 22 cm @ 1/e2 (Rayleigh range conditions) at optical system output; 22.6 at 8 km (see 6.1, PSR#1 exploration point) Components: • Collimator (output beam ~ 40 mm) • Flat folding mirror • Parabolic mirrors beam expander (magnification ~5.5x) Materials: • aluminum for optical bench • aluminum and invar for optical mounts (aluminum for supports and invar to host the optics) • fused silica for the optics, in order to withstand high power laser radiation	

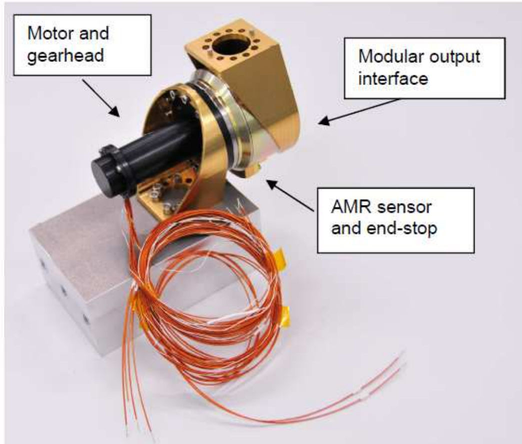
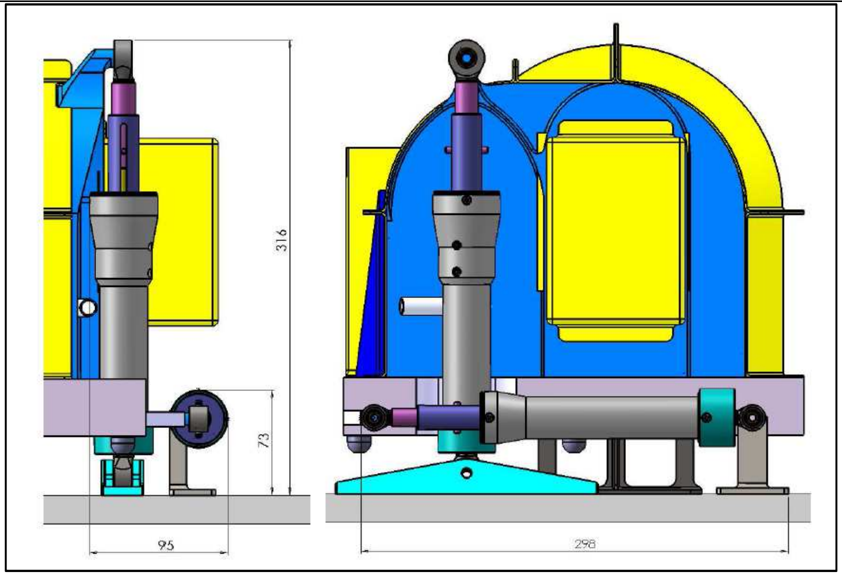
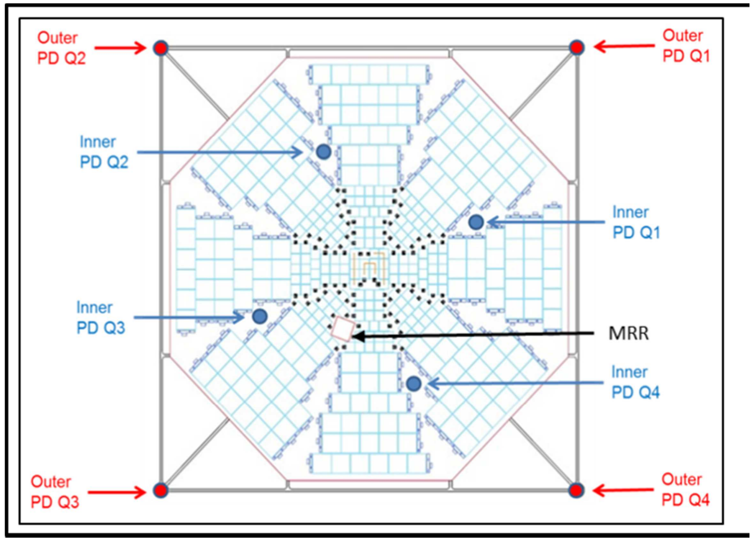
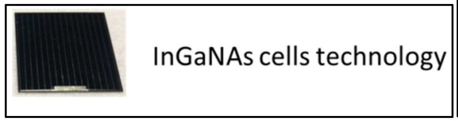
Main Component (Lander section)	**Technical data**	**Conceptual sketch**
Coarse Steering mechanism	Robotic joints technology: • Brushless DC motors studied for robotic arms, suitable for continuous rotations in vacuum in long life applications • Typical angular accuracy = 0.2 deg. • Typical speed of these systems is > 0.7 deg/s.	
Fine Steering mechanism	Funding elements: • Additional optical bench with respect to the optical system bench • a two actuators (pistons) system, to orient the optical bench by pushing on the additional optical bench • a flex spring acting as the fulcrum Technical data: • Typical pointing range: ±1.1° • Designed for a load to be oriented: < 24 kg; HILPBS optical bench ~ 21 kg • Typical speed ~ 0.03 deg/s	

Table 3: HILPBS – Lander section main components, technical data

Main Component (Rover section)	**Technical data**	**Conceptual sketch**

Photovoltaic panel	Cells and PV panel layout:
	• Octagonal panel geometry, with lateral dimension of 93 cm
	• InGaNAs cells technology, in an annular layout on photovoltaic panel to match the Gaussian beam symmetry over the whole lander/rover distance span
	• Filling factor = 67.4% (216 cells 40x40 mm and 169 cells 20x20 mm)
	• Smaller cells for the central zone to limit the circulating photocurrents (the laser beam is more intense in the central zone of the PV panel); cells are in strings, according to their expected generated current, connected in series or parallel to efficiently manage the currents and tensions over the whole photovoltaic panel
	APT elements on PV panel:
	• 4 inner and 4 outer photodiodes, providing the information on beam displacement on PV panel and on power collected
	  o active area diameter: 10 mm, case diameter: 20 mm.
	  o Photodiode responsivity: ~ 0.3 A/W
	• the MRR
	  o Clear aperture: 14 mm; larger device is under study (22 mm)
	  o Thickness: 24 mm
	  o Datarate currently limited to ~ 200 kHz
		  

Batteries	• ~ 174.6 Wh/kg • ~ 385 Wh/l • Long cycle-life (600 to 1000+ cycles), depending on conditions	
Coarse Steering mechanism	Robotic joints technology, same as the one foreseen for the lander section	

Table 4: HILPBS – Rover section main components, technical data

6.8 PHILIP/HILPBS concept against conventional solutions

The table below compares the HILPBS powering concepts against conventional powering solutions.

	PHILIP/HILPBS	Microwaves	Conventional PV / Battery	Nuclear power generation
Tethering with lander / Rover exploration capability	Tethered: the Lander is both a deployer and a power source generator Exploration is limited to the area covered by laser-illumination; powering distance limited	Tethered: the Lander is both a deployer and a power source generator Exploration is limited to the area covered by microwaves-illumination; powering distance limited	Not tethered: the Lander is a deployer Exploration limited by the solar-illumination incidence angles and to the batteries' capacity	Not tethered: the Lander is a deployer Exploration is not limited; Curiosity rover (2012) is still operating
Power sizing	• E/E: 4.6% High beam efficiency, low E/O and O/E efficiencies • System efficiency is > 13% if the heat generated by PV panel is used to warm rover components	• E/E: < 1.8%, High DC/RF and RF/DC efficiencies, low beam efficiency Note: figures calculated on 15 km range; for increased distances the efficiency decreases	PV panel efficiency: 30-33%	• Radioisotope Thermo-electric Generator (RTGs) system efficiency: ~ 5% • with Stirling Radioisotope Generator (SRGs) system efficiency: ~ 25-30%
Size	• High power laser source size (to be optimized): 0.75 m x 0.95 m x 0.58 m • PV panel size: maximum lateral dimension): 0.9 m octagonal area: 0.6 m2	• Transmitter antenna size: > 7 m • Receiver antenna size: > 10 m Note: The required antennas are larger with respect to HILPB concept due to the diffraction limit, which is depending on considered wavelength	Spirit/Opportunity PV panel area:1.3 m2	MMRTG Length/Diameter: 0.67 m/0.64 m [R17] .
Mass	The lander mass is higher but rover mass is reduced (i.e. batteries have less capacity with respect to conventional systems: one battery, 7.5 kg)	Lander is higher but rover mass is reduced (i.e. batteries have less capacity with respect to conventional systems).	Rover shall host batteries with high capacity, to store power for exploration in PSRs, where solar power is absent by definition (estimated mass > 48 kg)	Rover shall host radioactive materials: Curiosity rover was equipped with ~4 kg of plutonium, generating ~110 W; MMRTG mass: 43.6 kg.

	PHILIP/HILPBS	Microwaves	Conventional PV / Battery	Nuclear power generation
Possible issues	Possible discontinuous production of electrical power due to beam displacement during rover exploration path: orientation mechanisms to be integrated to support the powering (i.e. APT subsystem in loop between lander and rover)	Possible discontinuous production of electrical power, due to beam displacement during rover exploration path: orientation mechanisms to be integrated to support the powering (i.e. APT subsystem in loop between lander and rover)	Possible discontinuous production of electrical power due to solar cycle and site surroundings morphology. No power generation in PSRs areas Orientation mechanisms needed to optimize solar energy collection -where available	Continuous provision of electrical powering independently from environmental conditions (suitable for extended missions in darkness areas and with low/variable illumination levels); exceeding power could be difficult to be managed Heat power could affect the PSRs sampling areas
Heritage for space applications	New concept for a space application	Dedicated studies for space applications, heritage for other applications (e.g. communications)	High heritage in space	Europe has no heritage on the implementation of radioactive power sources for powering space systems, just collaboration with US and Russian Agencies in spacecraft and launchers that use nuclear generators; no heritage in ESA member states. US has limited heritage in space for nuclear powering rovers (i.e. Curiosity)
Manufacturing complexity	High power laser source and PV panel to be developed on purpose; specific tools to be developed for cells deposition on PV panel according to the identified layout	The transmitter and receiver antennas to be developed on purpose	Manufacturing, integration and assembly processes are well known	Manufacturing, integration and assembly processes are known (US rovers missions); no heritage in ESA member states.
Human handling issues	Potential injury caused by handling of high power laser source (i.e. potential eyes and/or skin injuries)	Potential injury caused by intense electromagnetic fields	No major issues	Potential injury caused by handling of radioactive materials

Table 5: Comparison among PHILIP/HILPBS and other powering technologies

As a conclusion, the most promising solution in terms of exploration capability seems to be the nuclear power generation, despite the heavier mass requested to host the powering system but, due to constraints imposed by the use of radioactive materials, other technologies have to be considered; on the other hand, the conventional PV panel/battery technology seems to be disadvantageous in PSRs, because batteries should have a higher capacity to sustain the permanence inside a region in which no sunlight is available or the exploration could be limited only to the rims of considered craters.
Among the two tethering concepts, PHILIP/HILPBS seems to be the most promising, both in terms of E/E system efficiency and mass, volumes and human handling issues; the implementation of this technology is demanding for the distances considered (accuracy of APT system and stability of optical line of sight under rover solicitations) and for the space qualification of optical components to be used for this application.

7 DEVELOPMENT PLAN

This chapter is aimed to identify the key components development effort and to propose the first steps of the roadmap for future PHILIP/HILPBS activities.

7.1 Key components development effort analysis

The following Table 6 reports the identification of HILPBS critical areas and the related development effort analysis, traced in order to identify the critical elements that need further investigation/tests.

HILPBS subsystems	**Identified critical areas**	**Development effort (Low, Medium, High)**
High power Laser Source	The high power laser source has to be space qualified.	High
	The laser is water cooled, a proper heat dissipation system has to be designed	Low (e.g. loop heat pipes already developed)
	The optical fibre shall be tested under space environmental conditions (especially under radiations)	High, the performance can be degraded under radiations
Optical system	Wavefront distortions impact on divergence to be evaluated	Low
	Laser damage issue to be deeply investigated for CW operation	High
Photovoltaic system	InGANAs cells to be developed on purpose	Medium (dedicated performance tests to be done to assess the efficiency, even under temperature variations)
	Manufacturing of central cells, which require a special miniaturized design (i.e. optical radiation concentrating systems) and special tools for their deposition on photovoltaic panel to be realized	Medium
	High current/voltage operations under high laser power illumination	Medium
	Losses due to strings connections to be assessed in case of beam displacement: set of strings are not anymore under uniform illumination. The resulting conversion efficiency loss has to be estimated with a dedicated BB activity	High (BB required)
	Thermal dissipation system to be developed for PV panel, related to unconverted energy	Low
Acquisition, pointing and tracking system	The alignment among lander/rover is demanding considering temperature and vibration effects	Medium
	Active systems (robotic joints and electronic actuators) have been already used in space environment but are considered critical here for the demanding requirements of the HILPBS application	Medium
Comms. system (optional)	Selected devices do not exactly match with the full set of requirements: it works at 200 KHz	Low
	Devices (e.g. MRR) to be space qualified	High

Table 6: Development effort analysis

7.2 Proposed roadmap for future PHILIP/HILPBS activities

As the first step of the roadmap proposed for future PHILIP/HILPBS activities, the realization of a dedicated breadboarding of critical components is highly recommended, to experimentally assess the photovoltaic cells (customized wavelength), the integration of cells inside a scaled photovoltaic panel and testing of the cells efficiency and optoelectronic performances (I,V curves) under low power laser illumination.

Subsequently, a Development Model can be conceived - together with the related test campaign - to assess on a scaled distance the PHILIP/HILPBS main system functionalities, following the guidelines traced in [R18].

In particular, the Development Model will be aimed to:

- Confirm or provide indications on adequacy of implemented technologies
- Highlight and trace critical aspects raised under conceptual design study or to identify other potential risks, together with the identification of critical and long lead items
- Evaluate system efficiencies, in particular InGaNAs cells efficiency under laser illumination
- Provide feedback on system modelling tools and to refine the requirements for system and subsystems’ components
- Define preliminary testing tools and preliminary test procedures (to be finalized during following models activity); a dedicated supporting tool is useful to control the beam spatial qualities, in order to help integration and testing phases
- Identify system monitoring and protections of key components (e.g. thermistors, encoders) that will be necessary in a space environment, e.g.:
    - dedicated thermistors placed near active optical components such as the active materials, the optical bench and the interface area with the lander heat dissipator system, in order to provide information on the correct system operation by measuring the deviation from a tested reference value
    - dedicated internal photodiode(s) along optical path help provide information on the generated output power
    - a series of protections are suggested to be implemented on laser sources, in charge of taking actions when some critical parameter goes out of a predefined “hazard threshold limit”, forcing the laser source in a safe operation mode. This should prevent failures or damage of components, improving the system safety.

- Provide feedback in terms of:
    - optical layout design
    - thermo-mechanical design
    - electronics design
    - algorithm formulas to be implemented

8 CONCLUSIONS

In support to the conceptual study reported here, a system power budget was calculated by considering the laser output power, the photovoltaic panel efficiency, together with an estimation of expected losses due to mission in space (gravity, launch vibrations, lifetime degradation, etc.). The outcomes of the power budget calculations assessed the feasibility of such system, showing a calculation margin compatible with the ESA new development concepts (20% margin).

The study showed that some requested system performances are very demanding (e.g. the requested accuracy for the APT subsystem) and that some technological concepts need to be tested carefully, such as the InGaNAs cells performances under laser illumination at foreseen operating temperatures.

To conclude, the results of this study could be applied for example to the Lunar Volatile Prospector, a mission studied for characterizing the geographical distribution of volatiles over areas of the lunar south pole, an area where the rover is tasked to explore Permanently Shaded Regions (PSRs) where no sunlight is available; this principle could also be applied to small planetary mission scenarios, similar to the past NASA/JPL Mars Pathfinder mission, operating rovers in the proximity of a lander, i.e. within line of sight.