THE ROSETTA LANDER ("PHILAE") INVESTIGATIONS

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Abstract. The paper describes the Rosetta Lander named Philae and introduces its complement of scientific instruments. Philae was launched aboard the European Space Agency Rosetta spacecraft on 02 March 2004 and is expected to land and operate on the nucleus of 67P/Churyumov-Gerasimenko at a distance of about 3 AU from the Sun. Its overall mass is ~98 kg (plus the support systems remaining on the Orbiter), including its scientific payload of ~27 kg. It will operate autonomously, using the Rosetta Orbiter as a communication relay to Earth. The scientific goals of its experiments focus on elemental, isotopic, molecular and mineralogical composition of the cometary material, the characterization of physical properties of the surface and subsurface material, the large-scale structure and the magnetic and plasma environment of the nucleus. In particular, surface and sub-surface samples will be acquired and sequentially analyzed by a suite of instruments. Measurements will be performed primarily during descent and along the first five days following touch-down. Philae is designed to also operate on a long time-scale, to monitor the evolution of the nucleus properties. Philae is a very integrated project at system, science and management levels, provided by an international consortium. The Philae experiments have the potential of providing unique scientific outcomes, complementing by in situ ground truth the Rosetta Orbiter investigations.

Keywords: *in situ* measurements, cometary nucleus, Lander

1. Introduction

As part of the Rosetta mission, the "Philae" Lander will be released from the Orbiter and soft-land on the nucleus of Comet 67P/Churyumov-Gerasimenko at a heliocentric distance of about 3 AU. Philae results from the merging of the two "Surface Science Packages" proposed in response to the Rosetta Announcement of Opportunity, namely "Champollion", proposed by NASA and CNES (Champollion,

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1995) and RoLand, proposed by an international consortium under German responsibility (RoLand, 1995). Prior to launch the name "Philae" has been chosen for the Lander: an inscription on an obelisk from Philae (an island near Aswan/Egypt) confirmed the decipherment of the Rosetta stone (Andrews, 1981).

The Rosetta Lander is a contribution to the European Space Agency (ESA) mission by a consortium of scientific institutes and agencies from Germany, France, Italy, Hungary, Ireland, Great Britain, Finland and Austria. ESA contributed to the Project with substantial technical and financial support.

2. Philae Mission Overview

Within the Rosetta Project, Philae is regarded as a single scientific unit, commissioned and checked out during cruise together with the Orbiter Investigations. Up to the separation, power is supplied from the Orbiter through an umbilical connection.

The delivery of the Lander to the surface of the comet is foreseen in November 2014 at a distance of about 3 Astronomical Units (AU) to the Sun (Sánchez Pérez and Rodríguez Canabal, 2003). Rosetta's original mission design target was comet 46/P Wirtanen. For launch opportunity reasons, the Rosetta mission had to be retargeted in early 2003 to comet 67P/Churyumov-Gerasimenko. The change of the target comet has a major impact on the Philae landing safety, since the expected touchdown velocity is higher than in the case of 46P/Wirtanen, due to the much larger size of P/Churyumov-Gerasimenko (Lamy *et al.*, 2003). Some hardware changes have been implemented, to increase robustness at touch-down (Ulamec *et al.*, 2006). However, the safe landing remains highly sensitive to actual nucleus properties, largely unknown at this time. A dedicated mapping phase will take place several months prior to separation, acquiring data from Orbiter instruments to update environmental and surface cometary models, towards an optimized selection of the landing site and of the release strategy. Following touch-down, Philae will have mission priority over Orbiter investigations for one week (see below, Section 5). After this phase, Philae will share resources with the Orbiter investigations.

The Rosetta Lander will separate from the Orbiter with an adjustable velocity of 0,05 to 0,52 m/s and will descend to the comet surface stabilised by an internal flywheel and (if necessary) supported by a cold gas system (Figure 2).

3. Lander Design

The overall Lander system has a mass of 97.9 kg including 26.7 kg for the scientific payload, plus 13.1 kg for parts which support the Lander on the Orbiter and will stay there after separation: the Mechanical Support System (MSS) including the push-off device and the Electrical Support System (ESS) including part of the telecommunications system (Table I).

Figure 1. The temple of Philae.

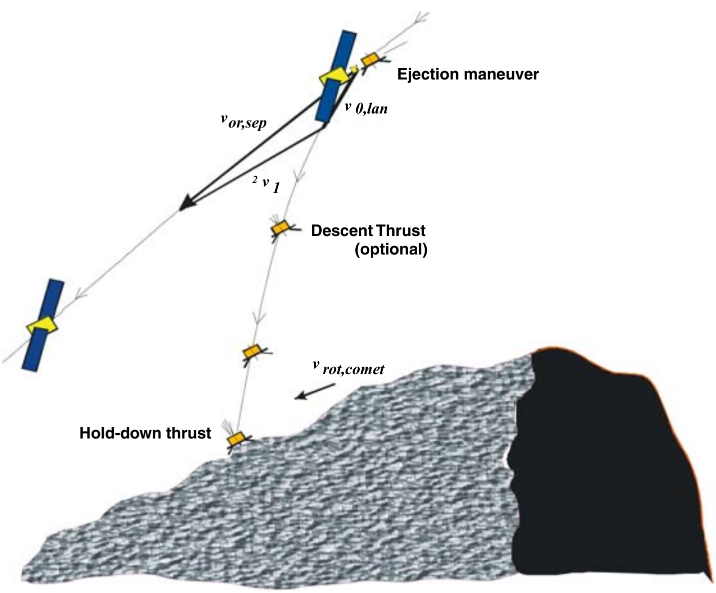

Figure 2. Philae landing scenario.

TABLE I

Mass breakdown of Rosetta Lander, including sub-units on the Orbiter.

Unit	Mass (kg)
Structure	18.0
Thermal Control System (MLI)	3.9 (2.7)
Power System (Electronics/Batteries/Solar Generator)	12.2 (2.0/8.5/1.7)
Active Descent System	4.1
Flywheel	2.9
Landing Gear	10.0
Anchoring System	1.4
CDMS	2.9
TxRx	2.4
Common Electronics Box	9.8
MSS (on Lander), Harness, balancing mass	3.6
Payload	26.7
Sum [Lander]	97.9
ESS, TxRx (on Orbiter)	4.4
MSS, harness	8.7
Sum [incl. Orbiter units]	111.0

3.1. Structure

The Lander structure is manufactured mainly in carbon fibre and carbon fibre with aluminium honeycomb (Obst *et al.*, 1998). It consists of a baseplate including the "balcony", an experiment carrier underneath a polygonal sandwich construction; the hood, covering the warm area and carrying the solar generator; and the truss, supporting a stiff connection to the Orbiter during launch and cruise. Figure 3 shows the Lander accommodation as seen from balcony side; Figure 4 shows the instrument carrier in the warm compartment (without thermal insulation foils (MLI) and harness), as it can be seen when the hood is removed, and Figure 5 shows the EQM.

3.2. Thermal Control System

One of the major challenges of the Rosetta Lander mission is the thermal control of the Lander, which has to operate on a comet nucleus with uncertain rotation period, in a wide range of heliocentric distances, from 3 to ≤ 2 AU. All sub-systems and payload elements requiring warm environment have been mounted on the thermally insulated experiment platform underneath the hood (Schmidt and Maibaum, 2000). Since no radioactive heaters are used and with very limited available electrical power, an efficient thermal insulation is required to keep the temperature inside the Lander between -55 °C and $+70$ °C throughout the mission. This is achieved by

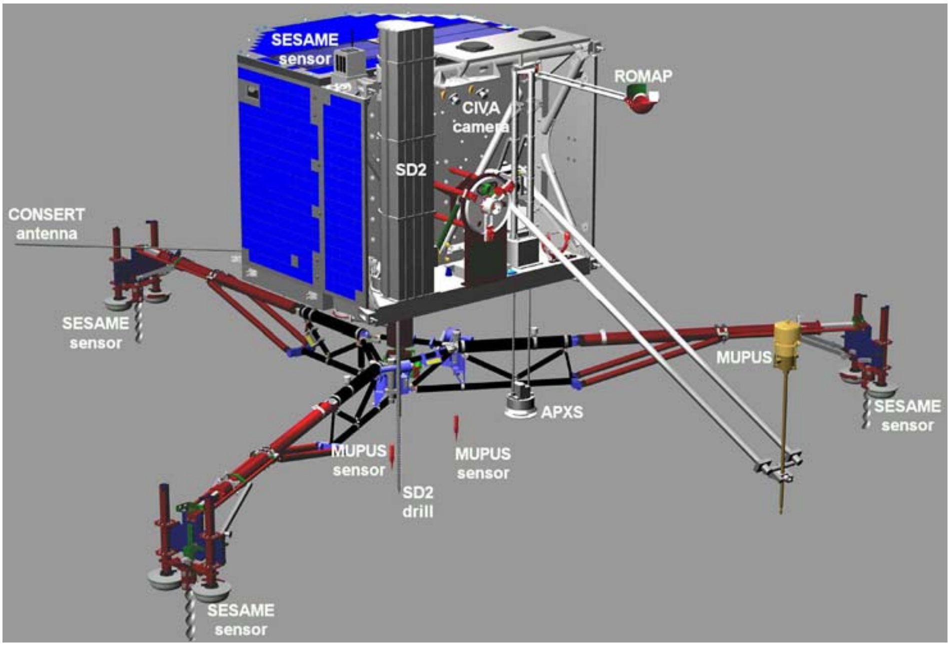

Figure 3. Schematic view of the Philae spacecraft. The figure shows the overall structure, the subsystems and the experiment compartment of the Lander. The location of some scientific instruments and their sensors are indicated; some are not visible in the drawing: specifically, the instruments in charge of analyzing the samples distributed by the SD2 (CIVA, COSAC, PTOLEMY), and the down-looking camera (ROLIS).

thermally decoupling the structural elements in the warm compartment (with low conductive stand-offs) and a combination of two multi layer insulation (MLI) tents. On top of the hood two absorber foils with a TINOX® surface of about 0.06 m^2 each (very high α/ε ratio) will collect energy during insolation periods. At 3 AU, up to 17.5 W thermal power can be collected, depending on the actual attitude upon landing.

During cruise the Lander is mounted on the side of Rosetta pointing away from the Sun, and thus remains in permanent shadow to minimize battery discharge. It is heated by either the so-called hibernation heaters from the Orbiter (12W), or the internal Philae thermal control system when the Lander is activated.

3.3. Power System

The power system of the Lander is based on a solar generator (Figure 3, blue), primary and secondary batteries (Gave, 1997). A central electronics provides standardized voltages to the various subsystems and instruments, manages the various power sources (batteries, solar generator and umbilical to the Orbiter) and controls the wake-up sequence during the long term operations on the comet.

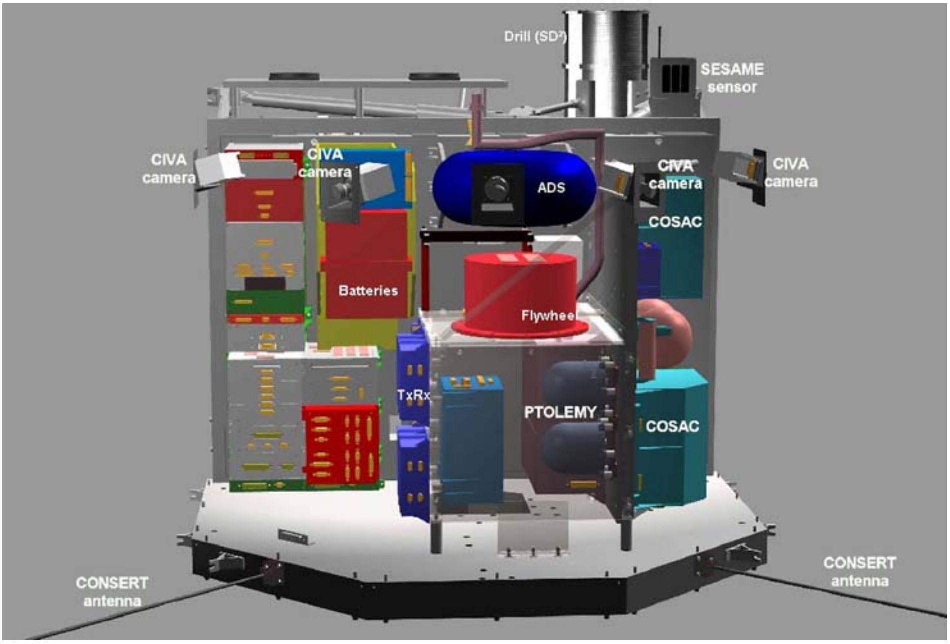

Figure 4. Side view schematics of the inner structure of the lander compartment showing the location of COSAC and PTOLEMY systems, the CONSERT antennas, the SESAME dust sensor and various CIVA cameras.

The primary batteries, which are not rechargeable, will be used to support operations following release until ∼5 days on the comet, to secure a first scientific sequence, during which all instruments can be operated at least once. The primary batteries consist of four strings with eight $Li/SOCl_2$ cells each and have a capacity (beginning of life, depending on discharge current and temperature) of about 1200 Wh. Degradation up to the end of the cruise is expected to be ∼10%: 1000 Wh is considered as the energy available upon release (Table IV).

The secondary batteries with a total capacity of about 150 Wh (beginning of life; for planning 130 Wh is the expected value) consist of two blocks with 14 Li-Ion cells each and will be the prime energy source during the long term operations on the comet. They are rechargeable via the solar generator or, during cruise, via current lines from the Orbiter. The secondary batteries are monitored in the checkout phases during cruise to keep the charge status at a level which leads to minimum degradation (Debus *et al*., 2003).

The solar generator is based on low intensity-low temperature (LILT) silicon solar cells (Strobl *et al*., 1993). Depending on the Lander attitude with respect to illumination, it will provide up to ∼10 W on a daily average at 3 AU distance to the Sun and allow, in part through the recharge of the secondary batteries, long terms operations during which experiments will be operated mainly sequentially.

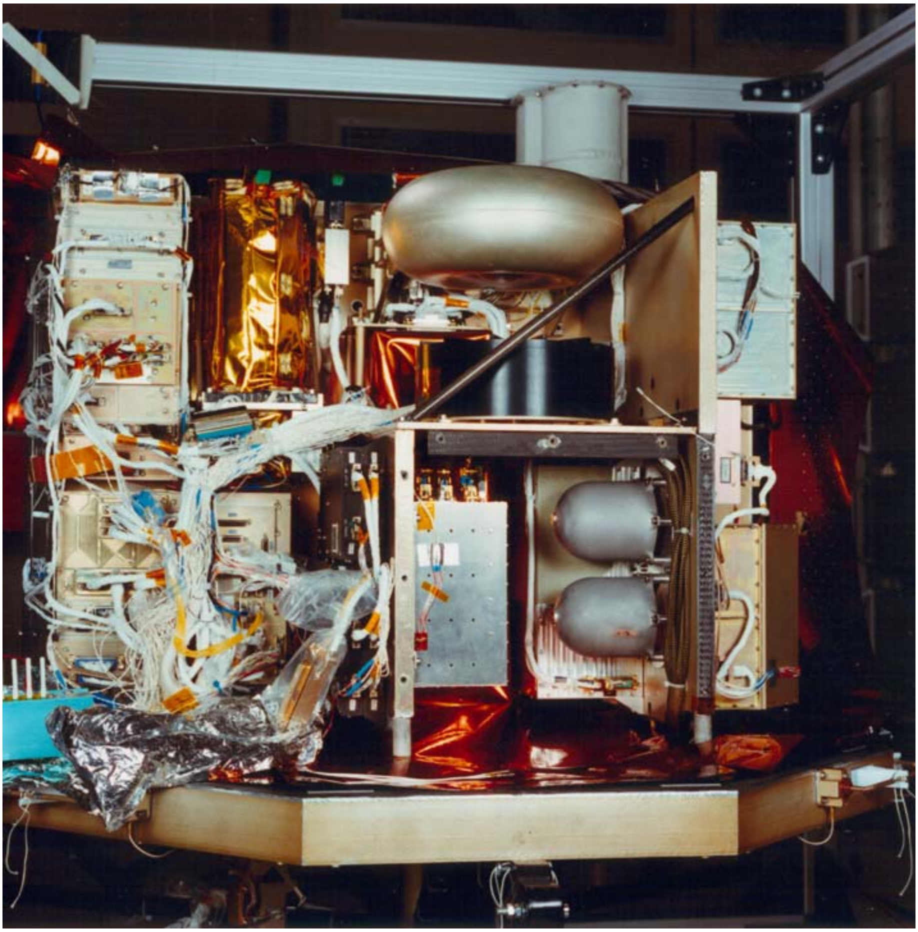

Figure 5. Internal compartment of the Lander Electrical Qualification Model (EQM), during integration.

3.4. Central Data Management System (CDMS)

Philae is controlled via the Central Data Management System (CDMS), which is in charge of the autonomous execution of on board sequences, including the control of subsystems (e.g. power system, anchoring), the activation of subsystems and instruments, the execution of commands and the storage of telemetry data as well as the interacting with the telecommunications system (TxRx) (Baksa *et al.*, 2003). The CDMS is a fault tolerant, hot redundant system, and it has a real-time, multitasking kernel. The processor resources are allocating to different tasks sequentially by the round robin method, running different program processes in turn to optimize computer efficiency.

3.5. Communication System

Communication of Philae uses the Orbiter as a relay for data and command transfer. Short range communications between the Orbiter and Philae are realized by means of a specific and fully redundant RF subsystem working in S band (Sarthou, 1998). The RF subsystem is organized around a high performance and low cost transceiver. The equipment has an overall consumption of only 6.5 W (1.5 W for the receiver and 5 W for the transmitter with 1 W RF output) and a total mass of 1 kg (transceiver + filter). Communications between the Orbiter and Philae can be established in full duplex at a 16 kbits/s bit rate, in a distance range from a few hundred meters up to 150 km; given the system overheads, actual rate for scientific data uplink to the Orbiter have been measured during cruise checkouts at ~10 kbits/s. Lander data transmission will be scheduled according to the visibility of the Orbiter from the landing site. The RF subsystems are interfaced with the CDMS (Lander side) and the ESS (Orbiter side), which manages the protocol and its redundancy (Cluzel *et al.*, 1998).

3.6. Landing Gear and Descent and Anchoring System

The MSS (Mechanical Support System) serves for the fastening of the Lander to the Orbiter during launch and cruise and for the separation and eject for landing. The four launch locks were opened eight hours after separation of the Orbiter/Lander complex from the Ariane launcher. The MSS includes a release device, consisting of three lead screws that will separate the Lander from the Orbiter with high accuracy at a velocity pre-adjustable between 0,05 and 0,52 m/s. The Lander will rest on a landing gear forming a tripod (Figure 6). This tripod is connected to the structure by a mechanism that allows rotation of the complete Lander above its legs and adjustment to surface slope by a cardanic joint. It will dissipate most of the kinetic impact energy upon landing by a dumping mechanism based of a motor that acts as a generator and converts the impact energy into electric energy.

In each of the “feet” a device is implemented which will rotate a screw into the surface material. This provides anchoring in materials with a medium surface strength and prevents the Lander from gliding on the surface during the landing process, on a slope or with some lateral landing velocity.

The Active Descent System (ADS) was originally implemented to be used during descent, to reduce the time between separation and touch down. It consists in a cold gas system with one thruster, pointing in the Lander $+z$ axis (“upwards”), using nitrogen as the propellant. Since the new target comet is expected to be much larger in mass than Wirtanen, this maneuver will most probably not be performed. However, the ADS will still be activated at touch-down for a few seconds to avoid rebound.

For attitude control during descent a flywheel providing a momentum of 6,2 Nms at a speed of 9600 rpm will be used. By changing the speed of the wheel the

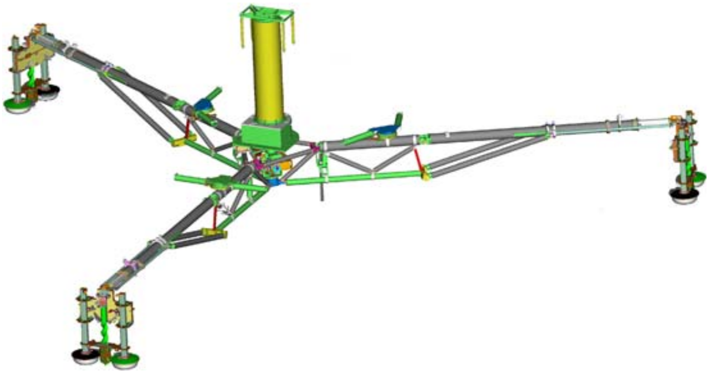

Figure 6. Landing gear.

Lander may be brought into slow rotation during descent, minimizing nutation due to gas drag.

Upon landing, an anchoring harpoon will be fired into ground. This anchoring harpoon device consists of a (redundant) harpoon projectile, a firing device and a cable re-tensioning mechanism (Thiel *et al.*, 1999). After firing the projectile into the ground, a motor will tension the cable (with a coil) and the Lander will be firmly tethered to the surface for the rest of the mission.

4. The PHILAE Experiment Package

The scientific investigations will be carried out through ten instruments, each under the responsibility of a principal investigator (Table II). They will cover a very broad variety of investigations and are presented thoroughly in dedicated companion papers. Figures 3 and 4 provide a schematic view of the location of the various experiments within Philae.

The Philae science objectives will complement those of the Orbiter investigations, in:

(i) characterizing, by in-situ measurements and observations, the composition of the cometary material down to its microscopic scale, the physical properties of the nucleus, its environment, its large scale structure and its interior;
(ii) contributing to the monitoring of the long-term evolution (activity) of the comet.

With respect to the *composition of the cometary material*, the Lander will constitute a sophisticated and miniaturized laboratory operating in-situ, along a protocol as close as possible to the one used on the Earth when analysing extraterrestrial materials. Using the SD2 (Sample Drill and Distribution) system, surface and sub-

TABLE II

The 10 scientific experiments on board Philae.

Instrument	PI: Principal investigator[a]	Science investigation	Mass (kg)
APXS	R. Rieder/G. Klingelhöfer	Elemental composition of surface material	1.3
CIVA	J-P. Bibring	Panoramic imaging. Microscopic imaging and analysis of the sample composition	3.4 (sharing parts with ROLIS)
CONSERT (lander unit)	W. Kofman	Internal structure of the nucleus by radio-wave sounding	1.8
COSAC	H. Rosenbauer/F. Goesmann	Molecular composition and chirality of samples	4.9
MUPUS	T. Spohn	Physical properties of the subsurface (density, porosity, thermal properties)	2.2
PTOLEMY	C. Pillinger/I. Wright	Isotopic composition of light stable elements in samples	4.5
ROLIS	S. Mottola	Descent and down-looking imaging	1.4
ROMAP	U. Auster	Magnetic and plasma monitoring	0.7
SESAME	D. Mölhmann/K. Seidensticker	Electric and acoustic sounding, dust impact monitoring	1.8
SD2	A. Finzi	Sample acquisition (drill) and transfer	4.7
Total			26.7

[a]In case the PI changed over the development, both names are indicated.

surface (up to 30 cm in depth) samples, a few mm^3 in volume, will be acquired and distributed to dedicated ovens, mounted on a carousel. Some ovens are closed by a transparent window: CIVA-M will obtain microscopic three-colour images (7 μm spatial sampling) and a complete near-IR (1 to 4 μm) high resolution spectrum (40 μm spatial sampling) of the samples, to assess the scale of their heterogeneity, and to determine non destructively the mineralogical and molecular composition of all cometary phases (ices, minerals, refractories). Then each sample will be step-wise heated, and the output gas piped to the PTOLEMY and COSAC instruments in order to identify its elemental, molecular and isotopic composition. More specifically, PTOLEMY will measure by chemistry and mass analysis, the H, C, N, O and S stable isotopes, while COSAC will identify, by gas chromatography and high-resolution time-of-flight (TOF) mass spectrometry, the molecular composition of the material, in particular of the complex organics. COSAC has also the possibility to measure chirality of the gas, with the aim of addressing the pre-biotic relevance of cometary material. Elemental abundances of the surface material will also be measured by the APXS instrument in a small (few cm^2) area below the Lander.

Physical properties of the surface and subsurface material will be derived from optical images (CIVA-P and ROLIS) and will be accurately determined by direct measurements (MUPUS and SESAME). More specifically, MUPUS will deploy several sets of sensors to measure the cohesion of the top surface materials, its density and potential layering, the heat flow, the thermal conductivity and the thermal profile at different locations around the lander down to several tens of centimetres. SESAME will focus on measuring the mechanical and electrical properties of the surface, typically down to two meters depth, and the dust environment along with its diurnal and long-term variations.

The *large-scale structure of the nucleus* will be studied by the CONSERT experiment, analysing the propagation of electromagnetic waves transmitted between a unit onboard the Philae Lander and one onboard the Rosetta Orbiter and travelling through the interior of the comet. The large-scale topography and properties of the nucleus will also be studied through panoramic stereoscopic images of the landing site after touch down (CIVA-P), and through images acquired during descent (ROLIS).

The *magnetic and plasma environment of the nucleus* will be measured by the magnetic, electron and ion detectors of the ROMAP experiment onboard Philae.

The goals of the scientific investigations onboard Philae are closely coupled to that of the Orbiter experiments and are summarized in Table III.

5. The Philae Science Operations

The science operations of Philae are divided into various phases:

(1) check-ups, calibration, software and command up-loads, thermal preparation and battery charging, before the release from the Orbiter;
(2) scientific measurements during the decent to the comet, to monitor the cometary environment between the Orbiter and the surface of the nucleus, to observe the nucleus while approaching, to characterize remotely the landing site and to document the touch-down event of the Lander at the surface;
(3) the "first science sequence" of approximately 5 days, operated mainly on primary batteries, thus minimizing sensitivity to landing geometry (solar irradiance of the cells). During the first 60 hours following the touch-down, all instruments

TABLE III
Coupled science goals of Lander and Orbiter experiments.

	Lander	Orbiter
Composition of cometary material		
APXS	Elemental composition	ALICE
CIVA-M	Mineralogical & molecular composition	VIRTIS
COSAC	Isotopic & elemental composition, chirality	ROSINA
PTOLEMY	CHON chemistry, stable isotopes	COSIMA
Physical properties of cometary material		
MUPUS	Temperature, density, porosity	MIDAS
SESAME	Electrical & acoustic surface properties	
CIVA-M	Microscopic structure	
Large scale structure of the comet		
ROMAP	Exosphere plasma & magnetic fields	RPC
SESAME	Dust environment	GIADA
ROLIS/CIVA-P	Surface structure	OSIRIS
CONSERT	Nucleus interior	CONSERT
Cometary activity		
ALL	All	ALL

will work in their baseline mode at least once at full completion of their relevant science goals. In particular a full panorama of the landing site will be taken and cometary samples will be acquired, both from the surface and from the maximum depth reachable with SD2 drill (i.e. about 0.3 m); these samples will then be processed by the relevant instruments (COSAC, PTOLEMY, CIVA-M). MUPUS and APXS will be deployed. CONSERT will sound the nucleus over at least one full Orbiter orbit relative to the Lander. The Lander resources should enable at least a partial redo of this sequence over the following 60 hours, if partial failure (for example in data transmission) happened. If performed successfully, the first sequence will secure a ”minimum science success” of the Lander mission;

(4) the “long-term science mission” with all instruments operating mostly sequentially, powered by the solar cells and the secondary (rechargeable) batteries. The Lander has enough flexibility to allow – by rotation around its body axis – the optimized orientation of the solar cells with respect to the local time, to drill several boreholes, and to measure physical properties all around the landing site.

The Philae operations will be cooperatively conducted at the LCC (Lander Control Centre) at DLR, Cologne, and at the SONC (Science Operations and Navigation Centre) at CNES in Toulouse. These Centres are responsible for all Lander operations, including:

– Philae mission planning, data monitoring and control of the subsystems and instruments;
– science coordination of the Philae instruments;
– distribution & archiving of all received Philae data.

Both Centres are directly connected via the Ground Segment to the Mission Operation Center RMOC (Rosetta Mission Operations Center) at ESA's Space Operation Center ESOC in Darmstadt. The Lander Operation Centres include a Lander Telemetry and Command System to support all data-processing and distribution tasks for system and experiment control, software for Lander Operations planning purposes and Data Archive hardware and software. At the LCC a Lander Software Simulator is available for test and troubleshooting tasks, as well as a Ground Reference Model for Lander system reference tests.

6. Operational Constraints for the PHILAE Science Experiments

In the baseline mission scenario, Philae will land on the comet at a 3 AU heliocentric distance. This distance has been chosen as a trade-off between conflicting constraints: one is to land far enough from the Sun to analyze as pristine as possible cometary material with respect to solar processing; the other is to land close enough to the Sun to minimize the related operational constraints (thermal, solar energy). On top of these, other major constraints make the Philae operations very challenging:

(1) the change of mission target, from the small size 46P/Wirtanen for which the Lander had been designed, significantly increases the risks associated to safe-landing given the likely higher nucleus mass of the new comet and the derived increase in impact velocity;
(2) a number of unknowns, such as surface texture and strength of the landing site (for a safe landing), the rotation of the nucleus (for solar energy resource), the thermal environment, the outgassing and re-condensation rate of volatiles species encountered by the spacecraft at the comet;
(3) mission-related resources, mainly the energy availability and the data volume that can be downloaded: transmission is made via the Rosetta Orbiter, the visibility periods of which, as seen from the Lander, are still to be worked out and optimized.

Table IV provides a summary of the energy available to the Lander (systems + payload) for its science mission after release from the Orbiter, with expected degradation during cruise (see above 3.3. for description).

With the presently agreed uplink sessions to the Orbiter (Table V), given the available telemetry rate of ~10 kbits/s for scientific data, only ~9 Mbits of system and scientific data can be downloaded in the 15 minutes following the touch-down: this is highly critical since all further operations will depend on the assessment

TABLE IV

Expected energy resources for the Philae science mission (i.e. after release from the Orbiter).

Primary batteries (at release)	1000 Wh
Rechargeable batteries (at release)	130 Wh
Solar generator (over 60 hours; 50% daytime)	300 Wh
Total (descent + 60 hours)	1430 Wh
Total (descent + 5 days)	1730 Wh
Any following 60 hours period	300 Wh

TABLE V

Downlink (Philae to Orbiter) resources, in the "nominal" visibility scenario.

Downlink period	Duration (mn)	Transferred data volume (Mbits)
Just before landing	15	9
Just after landing	15	9
Next 24 hours	180	110
Each following 16 hours	30	18
Total (descent + 5 days)	390	235
Each following 60 hours	110	65

of the landing status derived from the quick-look reduction of the data acquired during and just after landing, presently capped to 9 Mbits by this uplink to the Orbiter constraint. For the 5 days of the "first science sequence", a total of ∼225 Mbits of data would be transmitted via the Orbiter. After this phase and during the period of long-term science, the rate for the data download will be 35 Mbits/day on the average. Although all instruments have implemented sophisticated means of compressing their data, this uplink constraint is very severe. There is, however, potential for improvement of these figures, in case the landing geometry and the choice of Orbiter trajectory allow extension of the visibility periods of the Orbiter as seen from the Lander. By sending more complete data sets, the science return of the Philae investigations will be greatly enhanced.

The mass ratio of the payload experiments to the Lander spacecraft amounts to an unprecedented 25 percent (Table I). As a consequence, the mass challenge and the required miniaturization are also unprecedented for each of the Lander instruments. Most instruments weigh up to one order of magnitude less than those developed previously with similar performance.

7. Conclusion

The combination of scientific and technological challenges makes the Philae Rosetta Lander a unique project, certainly amongst the most ambitious and exciting ones ever flown. For the first time, a robotic system will land on a cometary nucleus, with the goal of deciphering, by direct *in-situ* measurements and observations, so far unrevealed key properties of a body conceived as having preserved pristine materials and conditions that drove the evolution of the Solar System.

Forming a highly integrated instrument complement, the package of Philae experiments has been developed and is operated in very close cooperation between ten scientific teams in charge of the investigations, and a technical, operational and managing team, responsible for the Lander as an autonomous vehicle. In the Philae mission success, the Rosetta Orbiter plays a major role: as the carrier and host during the 10 years cruise phase, for the release and the descent phase, and as a relay for all Lander commands and data transmission during on comet operations. In addition, it will contribute to the CONSERT investigation, as it is mounted on and operated from both the Lander and the Orbiter.

The Philae Lander Project is the result of a very broad, efficient and coordinated international cooperation, involving more than 20 institutes in more than 10 countries. Philae has the ambition to provide a major contribution to the global success of the Rosetta mission.

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