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Rosetta Lander – Landing and operations on comet 67P/Churyumov–Gerasimenko

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A B S T R A C T

The Rosetta Lander Philae is part of the ESA Rosetta Mission which reached comet 67P/Churyumov–Gerasimenko after a 10 year cruise in August 2014. Since then, Rosetta has been studying both its nucleus and coma with instruments aboard the Orbiter. On November 12th, 2014 the Lander, Philae, was successfully delivered to the surface of the comet and operated for approximately 64 h after separation from the mother spacecraft. Since the active cold gas system aboard the Lander as well as the anchoring harpoons did not work, Philae bounced after the first touch-down at the planned landing site “Agilkia”. At the final landing site, “Abydos”, a modified First Scientific Sequence was performed. Due to the unexpectedly low illumination conditions and a lack of anchoring the sequence had to be adapted in order to minimize risk and maximize the scientific output. All ten instruments could be activated at least once, before Philae went into hibernation. In June 2015, the Lander contacted Rosetta again having survived successfully a long hibernation phase.

This paper describes the Lander operations around separation, during descent and on the surface of the comet. We also address the partly successful attempts to re-establish contact with the Lander in June/July, when the internal temperature & power received were sufficient for Philae to become active again.

1. Introduction

Rosetta is a Cornerstone Mission of the ESA Horizon 2000 programme [1]. Launched in March 2004, it arrived at its final destination, comet 67P/Churyumov–Gerasimenko (CG), in August 2014 following a 10 year cruise. Since then, both its nucleus and coma have been studied in detail. This mission is dramatically improving our understanding of the formation and evolution of the Solar System as well as the origin of life due to investigations of a comet both from orbit with the Rosetta spacecraft as well as in-situ with the Lander, Philae, positioned on the surface of the nucleus.

Observations with the instruments aboard the Rosetta spacecraft allowed the selection of a landing site for Philae and the preparation of the actual landing sequence [2]. Philae was separated from the Rosetta main spacecraft on November 12th, 2014 and reached the comet surface after seven hours of descent. However, the lander bounced and only came to rest after a leap of about 2 h, in a location approximately one kilometre from the originally targeted site [3]. Philae was operational for almost 64 h after separation and provided

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unique information from the surface of the comet. All ten instruments aboard could be operated at least once. First scientific results have since been published e.g. in [4].

Philae is operated by the Lander Control Centre (LCC) at the German Aerospace Center, DLR, in Cologne and the Science Operations and Navigation Centre (SONC) at the Centre national d'études spatiales, CNES, in Toulouse. Commanding is sent via the Rosetta Orbiter which is controlled by the Rosetta Mission Operations Center, RMOC at the European Spacecraft Operations Centre (ESOC) in Darmstadt. The scientific lead is at the Max Planck Institute for Solar System Science, MPS, in Göttingen, Germany, and the Institut d'Astrophysique Spatiale, IAS, in Paris, France.

The Lander system has been provided by an international consortium (with partners in Germany (lead), France, Italy, Hungary, Finland, UK, Ireland and Austria) and supports a scientific payload of ten instruments with an even larger number of sensor elements [5].

Fig. 1 shows a drawing of the Rosetta Lander (Philae), Fig. 2 an image of the Flight Model during integration at ESTEC [6].

2. Scientific and technological background

Comets are believed to be the primitive leftover of the Solar System formation process. Thus, they contain

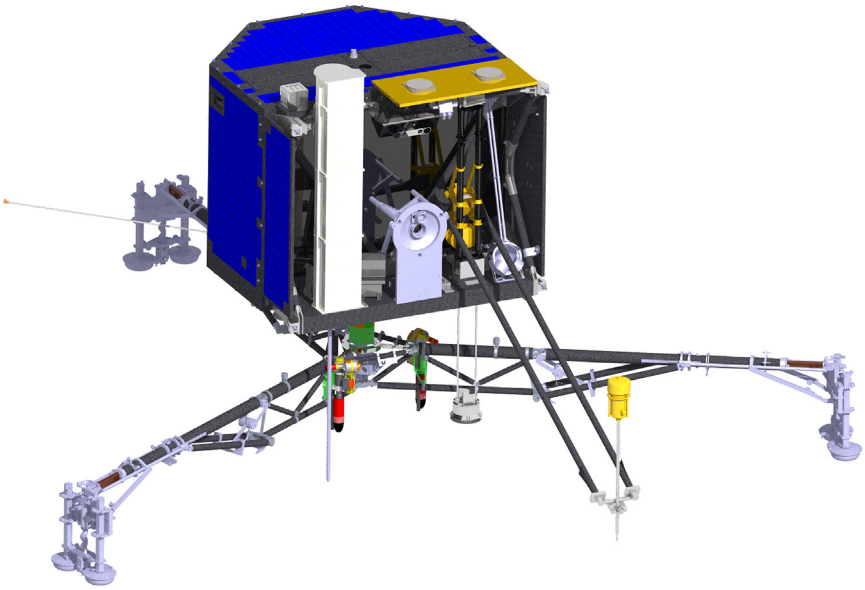

Fig. 1. Rosetta Lander, Philae, in landed configuration.

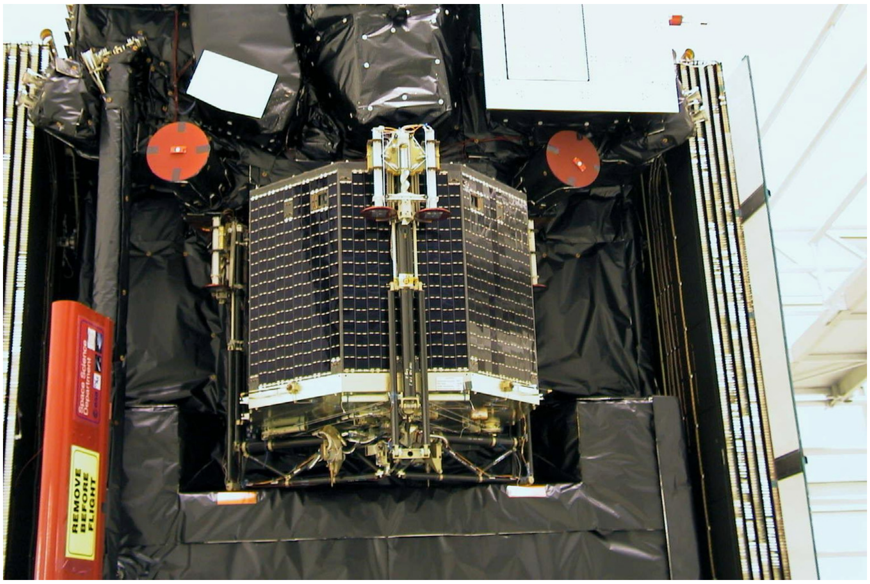

Fig. 2. Rosetta Lander as attached to the Orbiter [6].

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information on the compositional mixture from which the planets formed about 4.6 billion years ago. They carry records of the Solar System's very early phase and are, thus, a key for our understanding of its origin and development (e.g. [7]).

In addition, comets may have played an important role for the origin of life, since they transported organic matter to the early Earth [8].

In addition to being of important scientific interest, the first landing on a comet was also a technological challenge, with 67P being an almost unknown object, spinning, ejecting gas and welcoming Philae on a surface covered with boulders, cracks, scarps, dust and hard ice.

2.1. Scientific payload

The payload of the Rosetta Lander is composed of 10 individual instruments (some of which include several sub-elements), as listed in Table 1.

Two evolved gas analysers (Ptolemy and COSAC) are aboard to investigate the volatile components of the material of the comet's surface and sub-surface. It was planned to deliver surface and sub-surface samples by the Sampling and Drilling Device (SD^2), to both instruments. However, sampling was not successful, due to the unfavourable final orientation of the Lander relative to the local surface. An alpha-x-ray fluorescence spectrometer (APXS) also suffered from the large distances of comet material relative to the Lander baseplate. Philae also accommodates a combined magnetometer and simple plasma monitor (ROMAP), instrumentation to investigate the physical properties of the surface material i.e. dielectric-, acoustic-, mechanical- and thermal parameters (SESAME, MUPUS and SD^2) and a radiowave experiment (CONSERT) which has also been used for ranging, and thus determining the final landing area of Philae. Camera systems include sensors for panoramic imaging (ÇIVA-P), downward viewing (ROLIS) and microscope devices (ÇIVA-M).

For first scientific results, which are clearly beyond the scope of this paper, refer e.g. to the special issue of *Science*, July 31, 2015 [4]. For more detailed descriptions on the instrument designs see the special issue of *Space Science Rev*, Vol. 128, 2007 or Schulz et al. (Eds.) [9].

2.2. Technological challenge

The Lander had to be designed in a way that it could cope with a wide variety of possible comet thermal environments and surface properties. Indeed, one of the main challenges of the first landing on a comet was the fact that very little was known about the target prior to Rosetta's arrival, which was only in August 2014, about 3 months before landing [10]. 67P/Churyumov–Gerasimenko turned out to have an unexpected shape and rough surface [11], which limited the possible areas for landing. Criteria for the Rosetta Orbiter regarding the selection of the landing site included the identification of a safe pre- and post-delivery orbit as well as ensuring a stable communication profile with Philae and with the Earth during the whole phase. For the case of Philae, important factors were the feasibility of both nominal and backup descent trajectories, the possibility of periodic communications with Rosetta during on comet operations, feasibility for CONSERT sounding experiments and the physical properties of the site including illumination condition.

A very stringent plan to coordinate the reception of data obtained from the Orbiter since arrival at the comet, analysis and interpretation of these data, led to a landing site selection process carried out in three steps leading to the required preparations for the actual Separation–Landing–Descent (SDL) sequence [2,12].

The site selected and later named “Agilkia”, was judged to be of valuable scientific interest, having good illumination conditions for further operations after FSS (First Science Sequence) as well as minimizing risks for landing. Agilkia was selected accepting the fact that the surface roughness, as revealed by the OSIRIS camera, showed that no landing area completely satisfied the predefined constraints for Philae in terms of low risk to capsize due to a slope or boulder.

Other surface properties like compressive strength could not be determined before the actual landing. For the design of the Lander, an engineering model was used, based on a best estimate of such properties [13].

The suitability of the potential landing site for the science experiments was also taken into account. One requirement was e.g. to have a clear day–night cycle for

Table 1
Rosetta Lander scientific instruments.

Instrument	Type	Principal investigator	Responsible (PI-)institute
APXS	Alpha/x-ray - spectrometer	G. Klingelhöfer	University of Mainz (D)
COSAC	Evolved gas analyzer	F. Goesmann	MPS, Max Planck Inst. f. Solar System Research (D)
Ptolemy	Evolved gas analyzer	I. Wright	Open University (UK)
ÇIVA	Imaging system	J.-P. Bibring	IAS (F)
ROLIS	Imaging system	S. Mottola	DLR (D)
ROMAP	Magnetometer/ plasma monitor	U. Auster	TU Braunschweig (D)
SESAME (incl. CASSE, PP and DIM)	Acoustic properties analyzer, dust impact monitor, permittivity probe	K. Seidensticker	DLR (D)
MUPUS	Temperature, physical properties	T. Spohn	DLR (D)
CONSERT	Radio wave experiment	W. Kofman	IPAG (F)
SD2	Drill and sampler	A. Ercoli-Finzi	Politecnico Milano (I)

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determining the thermal properties of the surface material.

2.3. Lander design

Philae was designed to cope with a wide variety of possible scenarios for reasons addressed in Section 2.2. Consequently, also the SDL (Separation Descent Landing) sequence was prepared to cope with the wide range of uncertainties and included a high level of redundancy and automation some of which are described below.

The prime ejection mechanism, a part of the MSS (Mechanical Support System), which provided firm attachment of the Lander to the Orbiter during cruise, is based on three lead screws allowing adjustment of the separation velocity from the Orbiter with high accuracy in a range between 5 and 50 cm/s. A redundant spring driven device however was fixed pre-launch to a separations velocity of 18.7 cm/s. In the end, the prime was also set to this value in such a way that the selected landing site would be reached with both, the nominal as well as with the non-nominal spring-driven separation. The actual separation successfully took place using the nominal mechanism.

After separation from Rosetta, a radio link with the Lander was established using the Orbiter as a relay station.

At touch-down the Active Descent System ADS (a cold gas system) was supposed to fire "upwards" and give thrust to hold the Lander to the surface. Two anchoring harpoons were also planned to be fired to fix Philae to the comet with tethers that would be wound up to pull the Lander to the surface. The Landing gear contains a sophisticated damping device to dissipate most of the (vertical) kinetic energy and avoid re-bounce. Although ADS and harpoons failed, this damping system helped limit the bounce so that Philae eventually came to rest some 1100 m from the target area, remaining operational and oriented in a way that allowed regular communications during the First Scientific Sequence (FSS).

The thermal and power control systems of Philae have been designed in a way that operations on the comet surface at a heliocentric distance of 3 AU would have been possible, assuming solar coverage for $>50\%$ of a comet rotation, which in November 2014 was approximately 12.4 h. The power system of Philae is based on a primary battery ($Li/SOCl_2$) with an estimated capacity of approximately 1300 W h at comet arrival, which could support most of the FSS, a secondary rechargeable battery with a capacity of 151.2 W h and a solar generator. In November 2014, at 3AU, Philae landed in Abydos which had highly unfavourable illumination conditions due to it being a mostly shadowed location.

For the power system, only about 2.9 W h could be provided by the solar generator during one comet rotation; not sufficient to even partially recharge the secondary battery to allow Long Term Science (LTS) operations to begin.

Abydos turned out to be a mostly shadowed location. The solar generator was illuminated for only about 1:30 h per comet day. In that respect, a gradual reduction of internal temperature could be tracked during the FSS and it is believed that the temperatures of the internal compartment of Philae dropped to very low values, far below qualification levels, after the FSS finished. However, the design turned out to be very robust and after a hibernation period of about seven months, in June 2015, when the comet and Philae reached closer heliocentric distances, the Lander became active again and contact with Rosetta could be re-established.

For more details on the Lander design see e.g. [5,14,15]; more information on landing tests is given by Witte et al. in [16].

3. Operations activities

3.1. Operations concept

The Rosetta Lander operations centres are the LCC (Lander Control Centre) at DLR, Cologne, and the SONC (Science Operations and Navigation Centre) at CNES, Toulouse. These centres are responsible for all Lander operations during cruise and on the comet, including:

- Lander operations planning and verification
- Data monitoring and control of the subsystems and instruments
- Distribution & archiving of all received Lander data
- Science coordination of the Lander instruments

Both centres are directly connected via the ground segment to the Rosetta Mission Operations Centre (RMOC) at ESOC, Darmstadt. Rosetta science operations planning is performed at the RSGS (Rosetta Science Ground Segment) at ESAC, near Madrid. Fig. 3 shows the overall operations concept. The Lander operations 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 archiving hardware and software. At the LCC, a Lander Ground Reference Model (GRM), as well as a software simulator, are available for reference tests, validation of procedures and trouble-shooting tasks [6].

On-comet operations were planned in two distinct phases: A First Scientific Sequence (FSS) of about 60 h (based mainly on batteries), and a long-term operations phase (Long Term Science – LTS) where power from the solar generator is required. Initially, LTS was planned to directly follow FSS, but due to the poor illumination conditions it took until end of April 2015 (heliocentric distance of about 1.75 AU), when Philae's electronics got warm enough (minimum temperature -45 °C) and the generated power was sufficient to re-boot the system (minimum 5.5 W). First radio contact after hibernation was established on June 13th, 2015.

3.2. Landing preparation

In preparation for the comet landing on November 12th, Philae was switched ON, two days earlier, on November 10th at 18:05 UTC. This was necessary to allow for a 24 h heating phase to warm up the Lander batteries

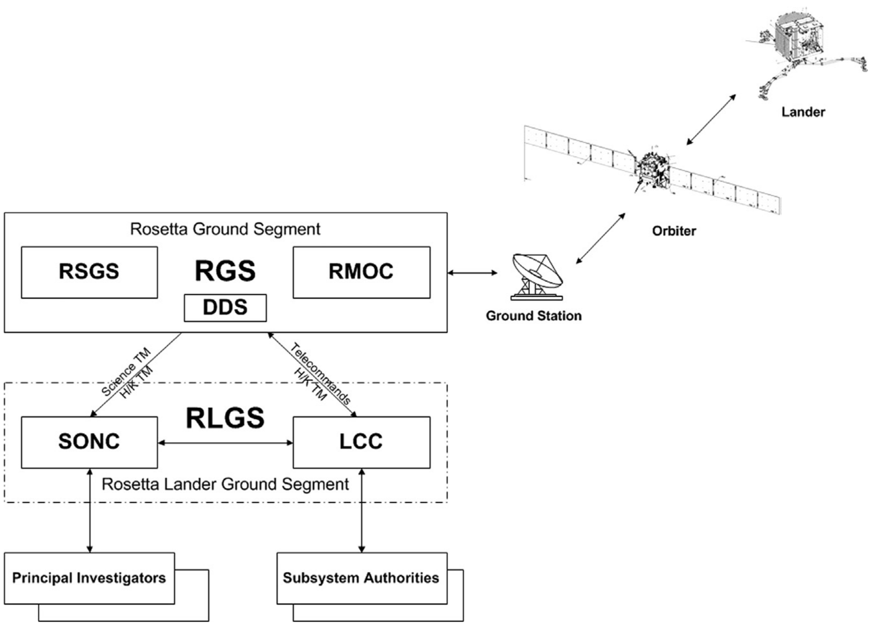

Fig. 3. Rosetta/Philae operations scheme.

to the required temperatures for operations followed by other preparatory separation steps.

At switch-ON, the Philae on-board computer experienced a problem, which left the system in an unresponsive state a few minutes after boot. To recover the situation, the system was power cycled, which resulted in it being switched OFF at around 19:52 UTC and ON again, nominally at 20:33 UTC. The issue which was never observed before, neither on-ground nor in space, could not be reproduced and only a few TM packets were available for analysis, therefore an unambiguous root-cause was not identified.

Then the heating phase was resumed and once completed, the conduction of all critical activities in preparation for the separation and landing phases started.

On November 11th at 18:05 UTC, the ADS (Active Descent System) tank opening failed. Also a second attempt failed few hours later. During the first try ADS was commanded to perform the tank opening using internal routines, while during the retry the unit was commanded manually to activate its tank openers. A diaphragm was supposed to be perforated with a pin, activated by a wax motor. Although the temperature of the wax motor increased, indicating nominal behaviour, the pressure in the pipe behind the tank opener did not show significant increase. It was not clear if this was due to a malfunction of the opener or the (non redundant) pressure sensor.

Shortly after the failure of ADS, at 19:07 UTC, the primary battery conditioning stopped unexpectedly after only 50 s instead of the nominal 9 min.

Fortunately, during a second attempt of the primary battery conditioning activity, the reason for the anomaly was fully understood and did not jeopardize the planned separation.

A GO decision was given at 02:30 UTC to continue the sequence to deliver the Lander to the comet, as confidence existed that the software would work correctly for the SDL and FSS phases, the ADS failure was not classified as a separation abort criterion and the primary battery conditioning requirement was waived by the battery team as conditioning had already been performed a few days before.

As expected, all the following planned activities in the landing timeline were performed flawlessly. On the Philae side this included the activation of instruments like ROMAP, MUPUS, CIVA, SESAME and CONSERT and subsystems' operations like Fly Wheel switch-ON and battery heating, while for the Orbiter, the manoeuvre to place Rosetta and Philae on the right trajectory for separation was carried out [17].

3.3. *SDL (Separation, Descent, Landing)*

The final Rosetta pre-delivery manoeuvre was performed on November 12th at 06:06 UTC.

At 08:18 UTC the MSS (Mechanical Support System) which provided firm attachment of the Lander to the Orbiter during cruise via the so called Cruise Latch mechanism, started operating. The actual Lander separation occurred, exactly as planned, at 08:35 UTC.

At this point, the umbilical connection between Philae and Rosetta showed a disconnect as planned.

In line with the planned operations, Rosetta performed an escape manoeuvre 40 min after separation and an additional manoeuvre one hour later to re-establish communication with Philae.

During the communication outage of approximately 2 h following separation, the Lander correctly deployed its landing gear, the ROMAP boom and CONSERT antennas at 08:43 UTC, just after having taken a "farewell image" of the Orbiter with CIVA at 08:37 UTC.

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Descent to the comet surface continued for another 5 h, with a good communication link, during which Philae continued its science programme: determination of the chemical composition of the neutral coma gas by Ptolemy, gravimetric measurements by CONSERT, characterization of the near-nucleus atmospheric composition of neutral volatiles by COSAC, far/near field descent imaging to characterize the landing site on global/local scale by ROLIS, characterization of the magnetic properties of the nucleus by ROMAP, study of the fluxes and dynamics of the orbital cometary particle flow by SESAME, as well as MUPUS calibration of the TM sensor head.

Finally, the Touch-Down signal was generated at 15:34 UTC [3].

Within Philae itself, two touch-down signals were generated; a first touch-down signal generated inside the Landing Gear by a Damping Generator and a second touch-down signal calculated by CDMS from the readings of the potentiometer, which measured the Landing Gear bubble movements during landing.

The outputs were forwarded hardwired to several units to trigger their related landing functionalities:

- to CDMS to start the execution of the harpoon firing, changing the SW mode from “descent” to “on-surface”;
- to ROLIS to stop taking descent images;
- to the Landing Gear initially planned to set the Landing Gear brake at the Cardanic Joint for 2 s to full closure of the brake preventing any re-tilting of the Lander during this period. Finally this was not needed as the brake was already commanded to full closure.
- to ADS to (attempt to) operate the thruster valves and thus provide a hold down thrust to push the Lander toward the surface as long as the harpoons are operating;
- to the anchoring mechanism to initiate the firing of the harpoons by powering the bridge-wires.

While CDMS, landing gear and ROLIS performed the planned post-TD operations smoothly, this was not the case for ADS and the anchor, as the cold gas system failed to thrust and the harpoons did not fire.

3.4. Failure analysis for ADS and harpoons

Already before separation, there was an indication that ADS would not provide any thrust due to the problems regarding the opening of the nitrogen gas tank (see chapter III.II). However, there was some hope the failure was due to a malfunction in the pressure sensor rather than the tank opener. The procedure for SDL was not modified. ADS was commanded ON at 14:33 UTC in preparation for touchdown. The housekeeping TM received from the unit showed that ADS did not boot correctly; HK values remained set to “0”, except for ‘sync patterns’, indicating the unit malfunction. As had to be expected, after touchdown, the ADS did not provide any hold down thrust.

For the anchor, despite the fact that the touch-down signal was received, both anchoring harpoons did not fire at touch down. Thus, Philae was not fixed to the surface.

In preparation for the Philae Landing, an on-ground spare of the Philae harpoon pyro (i.e. gas generator) which was stored in a thermal vacuum chamber between 2004 and 2013 was tested and was found to be unsuccessful in igniting. The pyro bridge-wires burned through prior to igniting the nitrocellulose of the gas generator. This behaviour was different from what was observed before launch, and may be linked to storage conditions under vacuum inside the harpoon housing. Due to these results, it was obvious that the pyros could not be initiated sequentially, as originally planned. As a work-around a new firing sequence was defined, operating one bridge-wire of each harpoon on one pyro converter in parallel to half the individual current. This new sequence was successfully tested at MPS with spare pyros and at the GRM with pyro simulators. So the teams were confident that the new sequence would also work with the flight model. Unfortunately, on Philae, the harpoons did not fire, although the command was sent successfully to the devices, after the touch down signal was detected. It remains unclear whether the failure was due to the pyro converters at the FM not providing power or the bridge-wires burning through too fast. Note that ROMAP magnetometer data show no signal corresponding to an ignition current.

3.5. Touch-down and bouncing

Philae touched the surface of 67P on November 12th at 15:34:03.98 (± 0.10 s) UTC [3]. The touchdown signal was received and the Lander switched into the on-comet mode, starting the pre-programmed timeline. As neither ADS nor the anchoring harpoons were working, the Lander bounced off the surface and only came to rest after about 2 h and three more contacts of the cometary surface. The landings as well as the re-construction of the trajectory (see Fig. 4) are described in detail by Biele et al. in [3].

A number of instruments were switched ON during the bounce trajectory, as it was planned to operate them immediately after landing, e.g. an image taken by CIVA-P that was blurred, due to the movement [18]. ROMAP obtained particularly valuable data, while Philae was hopping in low altitude above ground [19]. CONSERT measured the internal properties of the nucleus [20] and COSAC and Ptolemy received excellent mass spectra in “sniffing mode”, apparently analysing material excavated during the (first) touchdown [21,22].

Besides the real-time Lander HK data (following the first touchdown) indicating that the harpoons had not been fired it also indicated that the movement and rotation of the Lander (periodic illumination of the solar panels) was continuing; a situation further supported by ROMAP data. Upon touch-down at the final location, this movement could be seen to stop in the HK.

For the analysis of the hopping and the determination of the final location of the Lander data from OSIRIS, NAV-CAM, ROMAP, ROLIS, CONSERT, MUPUS -TM and Lander HK have been used [3].

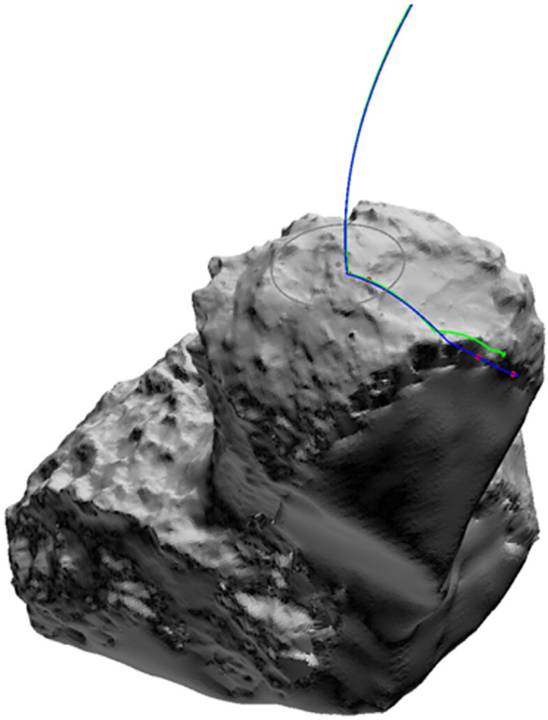

Fig. 4. Descent and bouncing trajectory of Philae [3].

3.6. Local terrain

After Philae came to rest at the final landing site “Abydos”, the panoramic cameras CIVA-P were activated on November 13th at 06:13:46 UTC on-board time [18] and acquired an error-free set of 7 images revealing the local terrain. In addition, the ROLIS camera, situated in the baseplate of the Lander, could successfully record pictures of the region under Philae from perspectives before and after the Lander rotation during two imaging sessions on November 13th at 00:09:20 and November 14th 23:20:10 UTC on-board time, respectively. Despite the fact that the environment was poorly illuminated for most of the terrain, it was possible to use the imaging data as a basis for the reconstruction of the local terrain. From the images it could be clearly identified that Philae was resting on its side in a cavity with dimensions similar to its own size surrounded by boulders, cliffs and ledges. In addition to the portions of the local topography shown in the pictures, the lighting and shadowing conditions on the solar hood of Philae-as can be deduced from the solar generator maximum power point tracker (MPPT) telemetry-strongly suggested the additional presence of a structure above Philae, in order to explain the shadowing pattern especially as observed during FSS.

Fig. 5 represents the terrain reconstruction inferred from the images of the local environment that could be photographically captured by the CIVA and ROLIS camera systems. The bottom part (2) stems from ROLIS camera based information, the surrounding part (1) from the CIVA imaging campaign. Except for some parts in the CIVA pictures that could be stereographically analysed in order to extract depth information implemented in the terrain model (i.e. the feature (4)), it was built such that also shadowing information as observed in the images and the MPPT telemetry can be reproduced. Furthermore, some parts of the Lander visible in the CIVA pictures could be used to estimate their attitude as well as their distances with respect to the direct vicinity. The CONSERT antenna appears to be in contact with the terrain (3) as indicated in the CIVA-P 4 image. The tip and thus the terrain at this place is approximately 0.9–1 m away from the camera [18].

Fig. 6 shows another illustration of Philae positioned in the local terrain, embedded into the global shape model of the comet. It explains the actual orientation of the Lander with respect to the local normal that is virtually in line with the Lander's $+Y$ axis.

Defining the local normal to be parallel to the local gravity vector, Philae is, thus, supported at its –Y side rather than its feet as Fig. 5 may suggest.

3.7. Improvised FSS

For the months leading up to the landing, significant work was placed in putting together and validating at the SONC and at the LCC the First Science Sequence set of activities. Although the unexpected bounce at touch down led to a major adaptation of these planned activities, this adaptation nevertheless resulted in a self-standing suite of in-situ measurements being successfully executed for the first time on the surface of a comet.

This success was possible thanks to the combined effort of the engineering teams at DLR, ESA and CNES, together with all the science teams of Philae and Rosetta. For more information on the activities at SONC see [12,23].

The entire FSS phase was designed as a sequence of several blocks of activities, pre-stored on-board of Philae (note that the numbering of blocks is not chronological):

- Block 1: CONSERT sounding, ROMAP and MUPUS operations and ROLIS CUC (close up camera) imaging
- Interblock 1: CIVA Panorama and Lander rotation for power optimization
- Block 8: SD2 sampling and Ptolemy and COSAC measurements; SESAME DIM and PP measurements
- Block 6: Landing gear rotation and MUPUS and APXS deployment and measurements; SESAME (CASSE/DIM/PP) measurements; Ptolemy and COSAC sniffing
- Block 7: SD2 sampling and CIVA-MV measurements; COSAC medium-temperature oven measurements

While the first block (Block 1) was executed autonomously following the reception of the touchdown signal, all other blocks had to be initiated through explicit commanding from ground, due to the need to evaluate the Lander status after landing prior to any mechanical movement (e.g. rotation and drilling). The evaluation of the Lander status was expected to be performed during the execution of the respective previous block of activities.

The order of execution of these blocks was interchangeable and the blocks themselves allowed some level of adaptation through parameter adjustment.

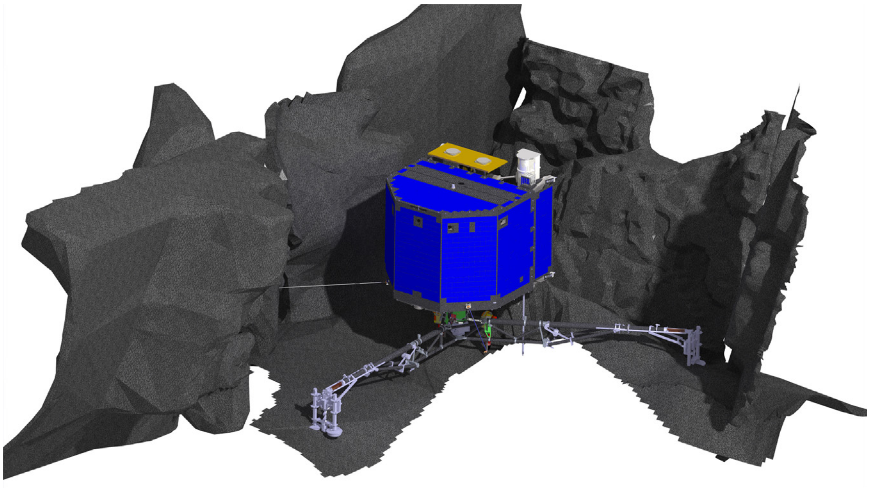

Fig. 5. Philae positioned in the re-constructed surface terrain.

Fig. 6. Philae embedded into local shape model of the comet.

In addition, the CDMS was programmed for autonomous handling of non-nominal situations and recovery branching to a safe configuration by either continuing the nominal timeline, albeit in a degraded manner, or waiting for ground commands (GO/NOGO commanding).

Being well aware of the risks associated with the landing, an exhaustive failure modes and effect analysis was conducted in the months before, to be prepared to react as quickly as possible, also to a higher level of possible non-nominal situations. In this context a short block – Safe Block-was designed including only "safe" science activities to ensure science results even in a failure case, when mechanisms cannot be activated.

This was indeed the case after the actual landing, with Philae not anchored and in an unknown attitude and location.

Following a nominal landing, Philae would have started with the drilling activities, but as this activity was considered too risky without the knowledge of Philae's status, the planned Block 8 was replaced by the execution of a CIVA image and the so-called "Safe Block", executed on November 13th at 06:13 UTC and 06:30 UTC, respectively, during the second RF link.

This block included only static science activities (MUPUS-TM measurement, ROMAP Slow Mode measurement, Ptolemy and COSAC MS sniffing and SESAME DIM and PP measurement) and it was executed four times while the scientific and telemetry data already collected were analysed and the status and location of Philae was better understood.

As it turned out, it was determined that there was not enough sunlight falling on Philae to charge its secondary battery and thus allow the LTS (long-term science) phase to follow the FSS. This meant that after the depletion of the batteries, Philae was expected to transition to hibernation mode.

It was, thus, decided to take higher risks and give all instruments the possibility to operate in order to accomplish a maximum of the Landers scientific objectives.

During the third RF communication slot with Philae which started on November 13th around 19:27 UTC, a modified Block 6 was commanded: MUPUS PEN and APXS deployment and measurements (both without any previous Lander rotation), SESAME CASSE and DIM measurements and CONSERT at the beginning of the block for ranging (to support Lander localization).

These activities were followed by a modified Block 8, commanded for execution during the fourth RF link, established on November 14th around 09:00 UTC.

Originally, during Block 8, SD2 was supposed to sample the comet surface twice and distribute the samples to both COSAC and Ptolemy. As the estimation of energy still available for operations excluded the possibility of operating both evolved gas analysers, only COSAC was selected and its sequence had to be reduced.

In parallel, COSAC and Ptolemy MS sniffing during drilling were included in Block 8, while a second CONSERT ranging was added to the beginning of the block.

The fifth and last communication slot with the Lander started again approximately 12 h later, on November 14th around 22:20 UTC and the last Philae FSS operations were designed in advance of that time and uplinked during the link. They included Ptolemy CASE oven analysis, landing gear rotation to illuminate the larger solar panel 1 in order to increase the chances of being able to exit hibernation, an image by ROLIS CUC after rotation and finally CONSERT for additional ranging and sounding, as long as power would be available.

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The battery depleted during this last communication link and Philae switched off on November 15th at 00:08 UTC, entering a hibernation phase which would last several months.

Table 2 lists the activities performed during FSS in the various AOS (Acquisition of Signal) phases. Fig. 7 graphically illustrates payload operations. For more details regarding the sequence of science operations see Moussi et al. [23].

3.8. Preparing Philae for Hibernation on the comet

At the end of FSS the Philae on-board software was configured to switch on both of its redundant receivers in case the rechargeable battery reached a minimum cell voltage of 3.4 V or sufficient surplus solar power became available. This was done in order to maximise the possibility for Philae to receive any incoming signal. Otherwise the receivers would only have been switched on periodically, which could have led to missing the Rosetta signals in case of short visibility windows (<30 min).

Table 2
Philae activities during SDL and FSS.

RF link	Time (UTC)	Duration of AOS	Comments
Descent	12.11.14, 08:35–15:34	~7 h	CIVA: Farewell imaging of the Rosetta S/C Landing Gear: Unfolded CONSERT: Gravimetry measurement and surface and sub-surface (global) dielectric constant and reflectivity measurements ROLIS: Far/near field descent imaging to characterize landing site on global/local scale. MUPUS: Deep space calibration measurement ROMAP: Characterization of the magnetic properties of the nucleus SESAME: Study the fluxes and dynamics of the orbital cometary particle flow
TD, hopping, final landing (LOS1)	12.11.14, 15:34-17:59	~2,5 h	CIVA: First image, while bouncing back (blurred) COSAC: Characterization of the gas composition of neutral volatiles at the surface in “sniffing mode” PTOLEMY: Chemical analysis at the surface in “sniffing mode” ROLIS: Characterization of the surface and grain material at the landing site ROMAP: Characterization of the magnetic properties of the nucleus CONSERT: Surface and sub-surface dielectric constant and reflectivity measurements SESAME: Determination of the elastic properties of the cometary surface layer
AOS-LOS 2nd **RF link**	13.11.14, 05:33-09:30	3 h 57	CIVA: Analysis of the landing site through 360deg stereo imaging MUPUS: Measurement of the thermal properties of cometary soil on the surface ROMAP: Characterization of the magnetic properties of the nucleus PTOLEMY: Chemical analysis at the surface in “sniffing mode” COSAC: Characterisation of the gas composition of neutral volatiles at the surface in “sniffing mode” SESAME: Study the fluxes and dynamics of near-surface cometary particle flow and determination of the elastic properties of the cometary surface layer
AOS-LOS 3rd **RF link**	13.11.14, 19:27–23h09	3 h 42	MUPUS: Measurement of strength of cometary soil, through PEN deployment and hammering activity CIVA: imaging attempt (insufficient illumination) SESAME: Determination of the macro-structure of the surface layer on a metre scale COSAC: Characterisation of the gas composition of neutral volatiles at the surface in “sniffing mode” PTOLEMY: Chemical analysis at the surface in “sniffing mode” APXS: Attempted measurement of the elemental composition of the surface and near-surface material after sensor head deployment CONSERT: Support the search for the Lander on the surface (ranging).
AOS-LOS 4th **RF link**	14.11.14, 09:01–11:49	2 h 48	SD2: Attempted sampling at 560 mm and sample delivery for COSAC COSAC: Attempted measurement of the composition of the volatile fraction of nuclear matter close to the surface, by heating oven (GCMS) PTOLEMY: Chemical analysis at the surface in “sniffing mode” CONSERT: Support the search for the Lander on the surface (ranging).
AOS-LOS 5th **RF link**	14.11.14, 21:47-15.11.14, 0:09	2 h 22	Landing Gear: Lander rotation in order to place largest solar panel into position with highest sun illumination. PTOLEMY: Attempted analysis of the chemical and isotopic composition of soil material, assumed to be gathered in oven after TD (CASE mode) ROLIS: Characterization of surface and grain material at the landing site, after rotation. CONSERT: Support the search for the Lander on the surface and initiation of measurement of global dielectric properties.

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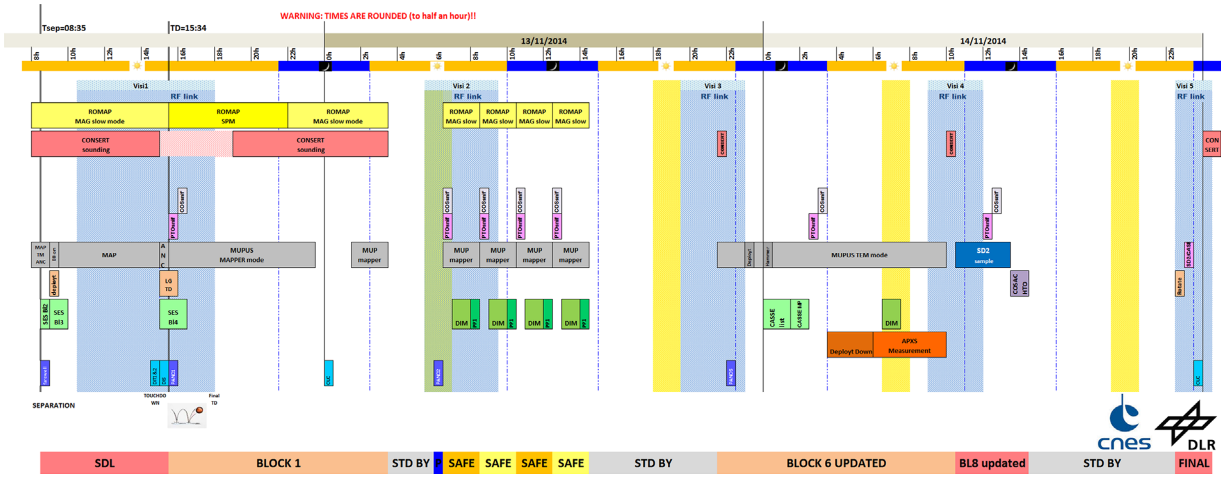

Fig. 7. On-comet performed FSS sequence (RF links are coloured in blue and periods with Philae illuminated in yellow). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In order to enter a two-way link, when the receivers detect a signal, the on-board software performs an energy check to evaluate if one of the two redundant transmitters can be switched on, without causing a power collapse. The transmitter then returns a signal with a specific pattern, signalling the ESS (Electrical Supports system, including communications units aboard the Orbiter) that a two-way link can be established. After that, Philae immediately begins to send science or housekeeping data stored in the mass memory. With the two-way link established, Rosetta can also send commands to Philae.

3.9. Lander wake up and attempted LTS

When Philae entered hibernation after FSS, it was not clear, when (and if) it would be possible to get into contact with the Lander again. Although the position of Philae on the comet was constrained rather well, using images taken with the cameras aboard the Orbiter as well as CONSERT ranging data [3,20,24] and its orientation was determined using ROMAP measurements [25], the uncertainties regarding the surrounding terrain, illumination during seasonal changes and thermal input from the comet environment were rather high. Consequently, it was impossible to give exact predictions on when the Lander would have sufficient power to boot and when radio contact could be possible again. A most probable wake-up time between May and June 2015 was predicted.

And indeed, the first contact with Philae after hibernation was established on June 13th, 20:28:11 UTC. The contact was established when Rosetta was flying at a latitude of 39°. The housekeeping data indicated that Philae had already been booting since end of April but was not able to establish radio link with Rosetta. This first link only lasted for 78 s, a total of 343 housekeeping packets containing information on the thermal-, power- and on-board computer subsystems were transmitted.

Since initially the secondary battery was empty, Philae booted every time the solar array was able to provide at least 5.5 W (each comet day). At each new boot, Philae's on-board clock starts from zero. Time synchronization occurs as soon as a link with Rosetta is established. So, in order to keep track of the moment telemetry (TM) is generated, the on-board software computes a "comet day counter", which increments at every new day. Housekeeping data as obtained on June 13th included packets from days 2, 19 and 20, in addition to six real-time TM packets with a counter of 95. Iterating backwards, it is possible to conclude that Philae was already active on April 26th (day2). The other counts refer to May 5th and 6th. It is currently not understood, why radio contact could not be established before the middle of June.

The second contact with Philae occurred a day (i.e. 2 comet days) later on June 14th at 21:22:47 UTC. This time the duration between the first and final link was 04:04 min, although in this timeframe frequent link interruptions occurred. A total of only 26 TM packets could be received, all real-time, with comet day count 97.

With these contacts established, significant work was made by the ESA RMOC and RSGS teams to redesign the trajectory being flown by the Orbiter to allow the same communication conditions (latitude of comet – Table 3) to be repeated in the weeks after. For the weeks that followed, the trajectory flown was designed to oscillate between 0° and 50° latitude as shown in Fig. 8 with the distance being reduced accordingly.

The third contact did not occur until June 19th at 13:20:33 UTC, although this time for a significantly longer duration of 18:53 min but again frequently interrupted. A total of 180 packets were received with day count 107, i.e. real-time data and data with day count 96, which was generated during the previous contact. For the first time, the real-time data allowed determination of the configuration of the communication hardware: transmitter Tx1 and receiver Rx2.

The next contact, on June 20th at 13:55:25 UTC, had a total duration of 31:01 min with many interruptions. A total of 744 packets were transferred containing stored TM of comet days 21 to 25 and 97 as well as real-time data of the current comet day 109. For the first time, it was

Table 3
Philae activities after hibernation. Duration of the link as indicated in this table does not consider intermediate link breaks. One data packet consists of 141 16-bit words i.e. 2256 bits.

Contact	Date & Time (UTC)	Duration (first 2 last)	Packets	Distance (km)	Latitude
1	13.06 @ 20:28	00:01:18	343	200	39°N
2	14.06 @ 21:22	00:04:04	26	206	48°N
3	19.06 @ 13:20	00:18:53	180	178	25°N
4	20.06 @ 13:55	00:31:01	744	181	19°N
5	21.06 @ 02:32	00:11:25	294	178	25°N
6	23.06 @ 04:08	n.a.	0	186	47°N
7	24.06 @ 17:32	00:17:11	83	180	45°N
8	09.07 @ 17:45	00:22:00	246	155	11°N

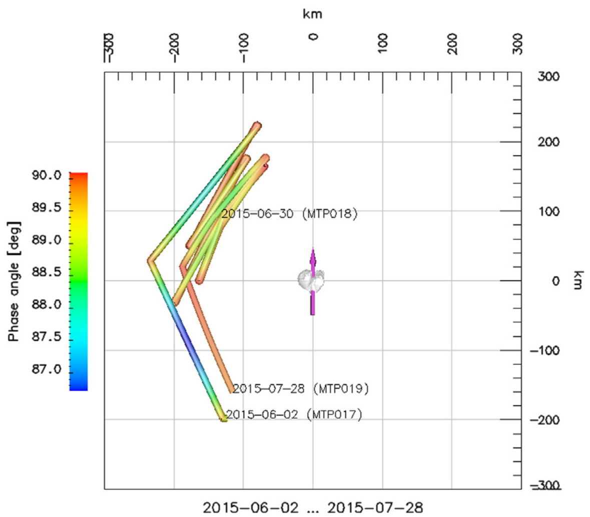

Fig. 8. Rosetta Orbiter trajectory flown around the comet during period 2nd June to 28th July 2015. Significant time period was spent in latitudes between 0 and 50° to maximise contacts with Philae. The distance can also be seen to reduce during that time, as Rosetta moved closer to the comet.

possible to reconstruct several sequential comet days. Again, the link was established with Tx1 and Rx2.

The fifth contact occurred on June 21st at 02:32:50 UTC and lasted 11:25 min, with a 10:37 min interruption. 294 TM packets were transferred with comet day count 25 to 27; no real-time TM was received. Another short reception of signals from Philae, June 23rd, did not lead to the transmission of any data packets.

The next contact occurred on June 24th at 17:23:48 and lasted 17:11 min with continuous link interruptions. A total of 83 real-time TM packets were received with comet day count 118.

The sparse stored and real-time data obtained showed that the temperatures were steadily increasing, the battery was being charged and the comet days were getting longer. The data also showed that Rx1 had suffered a short circuit resulting in it being switched off by the on board overcurrent protection. As in the following days no link with the Lander could be established, there was a fear that also Rx2 could be damaged.

However, other possibilities for the lack of contact between Philae and Rosetta were also analysed e.g. that the reply signal from Philae to Rosetta would have been too weak (due to disturbance by the comet environment) to be detected by the Lander dedicated Electrical Support System (ESS) unit on board Rosetta.

During nominal link establishment the ESS's transmitter sends signals with a specific pattern that are recognised by Philae; when the receivers aboard Philae receive a signal, the on-board software would activate the transmitter, which then returns a signal, signalling the ESS that a two-way link can be established and the communication begins.

However, in order to exclude also an Rx2 failure it was attempted to send "blind commands" in the so called TeleCommand Backup Mode (TCBM) where (limited) commanding of the Lander is possible without a two way communications link. CONSERT was commanded ON, since its activation could be detected without the Philae communications system establishing a two-way link through the unit on board Rosetta. CONSERT sends radar waves between the respective Lander and Orbiter units, hence the Orbiter unit can detect a signal from the Lander unit via its independent antenna system, thus confirming the functioning of RX2.

During the second attempt of CONSERT operations via TCBM, a full two-way communications link was established on July 9th at 17:45 UTC for a total duration of 22:00 min with an uninterrupted period of approximately 12 min (the longest till then). A total of 246 packets were received, all from that comet day both stored in the mass memory (MM) as well as real-time (once the MM dump was completed).

Although, the CONSERT unit on the Orbiter did not detect a signal from Philae, the telemetry obtained through the two-way link (TCBM is interrupted in case a reply from Philae is received by the ESS) showed that TCs were received and CONSERT was in fact switched on.

After CONSERT was switched on and started its boot sequence; first "science packets" were received indicating nominal behaviour; however after approximately 6 min (while preparing its internal science mode) the sequence suddenly stopped. The unit remained switched ON, reporting off-nominal currents. This explains why no CONSERT signal was detected by the CONSERT Orbiter unit, while the general behaviour of the CONSERT Lander unit is currently not understood. Damage of the instrument, possibly due to the cold temperatures during hibernation, cannot be excluded.

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Further analysis of the HK data received on July 9th seemed to indicate also a possible failure of the Tx2 unit. A detailed analysis of the radio links between Lander and Orbiter is given by Dudal and Loisel [26].

As the current status of the TxRx unit on board Philae cannot be assessed, the attempts to contact Philae since the end of July are both in nominal “Research Mode” and in TCBM, forcing CDMS to use only Tx1 or only Tx2 to establish the link.

Table 3 gives an overview of the contacts with Philae, after hibernation, up to July 9th.

4. Conclusions

Philae performed the first ever landing on a comet on November 12th, 2014. Despite its unplanned bouncing a modified First Scientific Sequence could be performed and data were received until about 64 h after separation from the Rosetta Orbiter. The situation, Philae was in (not anchored, uncertain final location, limited illumination) required a high degree of flexibility to modify the planned operational timeline.

Fascinating scientific results could be received not only from one part of the surface of the comet but, due to the bounce, was also received from a second location; an unexpected science bonus welcomed by the Philae experiment teams. Philae gave ground truth for orbiter measurements and obtained results which can only be gained by in-situ measurements.

The current situation does not allow reliable predictions on further opportunities to contact the Lander during LTS. In the light of future missions to small bodies (e.g. Hayabusa 2, OSIRIS-REx or AIDA or possible comet sample return missions) experience and lessons-learned during Philae's operations will be particularly helpful, whenever Landers or Surface Packages are considered [27].

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