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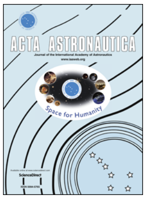

Invited Paper

The Philae Lander: Science planning and operations

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ABSTRACT

Rosetta is an ambitious mission launched in March 2004 to study comet 67P/Churyumov–Gerasimenko. It is composed of a space probe (Rosetta) and the Philae Lander. The mission is a series of premieres: among others, first probe to escort a comet, first time a landing site is selected with short turnaround time, first time a lander has landed on a comet nucleus. In November 2014, once stabilized on the comet, Philae has performed its "First Science Sequence". Philae's aim was to perform detailed and innovative in-situ experiments on the comet's surface to characterize the nucleus by performing mechanical, chemical and physical investigations on the comet surface. The main contribution to the Rosetta lander by the French space agency (CNES) is the Science Operation and Navigation Center (SONC) located in Toulouse. Among its tasks is the scheduling of the scientific activities of the 10 lander experiments and then to provide it to the Lander Control Center (LCC) located in DLR Cologne. The teams in charge of the Philae activity scheduling had to cope with considerable constraints in term of energy, data management, asynchronous processes and co-activities or exclusions between instruments. Moreover the comet itself, its environment and the landing conditions remained unknown until separation time. The landing site was selected once the operational sequence was already designed. This paper will explain the specific context of the Rosetta lander mission and all the constraints that the lander activity scheduling had to face to fulfill the scientific objectives specified for Philae. A specific tool was developed by CNES and used to design the complete sequence of activities on the comet with respect to all constraints. The baseline scenario for the lander operation will also be detailed as well as the sequence performed on the comet to highlight the difficulties and challenges that the operational team faced.

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1. Introduction

1.1. Rosetta mission

Rosetta is a Cornerstone Mission of the ESA science program. In 2014 the probe reached its target: comet 67P/Churyumov–Gerasimenko. Both its nucleus and coma are studied in detail. An exceptional payload was also on board Rosetta until its delivery in November 2014: the Philae Lander. It was the first spacecraft to land on a comet and to perform in-situ analysis of the nucleus. Philae is a contribution to the mission by a European consortium (DLR, CNES, MPS, MPE, ASI, KFKI, UK SA, FMI, STIL and IWF)

(“Rosetta Lander – Landing and Operations on Comet 67P/Churyumov–Gerasimenko” Ulamec et al., 2016)

1.2. Lander ground segment

The Rosetta Lander Ground Segment (RLGS, Fig. 1) is composed of two entities

The Lander Control Center (LCC), located at DLR in Köln (Germany), is in charge of Rosetta Lander operations (Ulamec et al., 2016).

The Science Operation and Navigation Center (SONC) is located at CNES in Toulouse (France).

The SONC is more specifically in charge of data management (retrieval, distribution and archiving), Lander Science Activities scheduling and flight dynamics for the Lander. (Jurado et al. 2016)

The Science Activity Management (SAM) team at SONC is responsible for the science planning on board Philae and this paper will focus on this task. The main tool developed for the scheduling task is called MOST for Mission Operations Scheduling Tool. [1].

1.3. Philae

PHILAE Lander (Fig. 2) weighs roughly 100 kg and includes ten instruments (each one with specific constraints) to measure chemical and physical properties of the comet

2. Scheduling constraints

2.1. Science objectives and ranking

The lander aimed to monitor the daily and secular activity of the comet as well as to determine the composition of the comet surface material, the physical properties of the soil (thermal, electrical and mechanical) and the structure of the nucleus (internal heterogeneity, magnetic field…). The scientific objectives were defined by the experimenters responsible for the instruments on Philae.

The planning of the science sequence required as a guideline an overall ranking of all the Philae objectives to design a sequence which aim is to maximize the possible science return of the lander experiments.

2.2. Operations constraints

In November 2014, Rosetta was at 3 AU heliocentric distance; the time to receive or transmit data to/from Earth was consequently roughly half an hour. Moreover due to Rosetta's orbiting, the visibility between Lander and Orbiter was not permanent and prevented close loops with Philae.

The day/night cycle depending on the landing site had also to be considered to prepare the science activities. Indeed some activities scheduled depend on day/night positioning; some should be scheduled several times a day whereas others had to be performed exclusively during night or day.

2.3. Parallel activities and interferences

Some experiments shall operate alone to avoid interferences or corrupted measurements or because co-activities are not mechanically feasible at the same time. Avoidance of parallel activities is a constraint for the scheduling, for example it is impossible to drill while the Lander body is rotating. On the other side, some parallel activities were explicitly requested such as SESAME CASSE listening to the hammering of MUPUS experiment.

Other experiments also required direct visibility between Orbiter and Lander or should be performed close to a radio link because of the large amount of data expected to be generated (imaging for example). Moreover a soil sampling shall be performed for obvious reason before any sample analysis.

2.4. Mechanical activities

Philae's orientation had to be determined (based on the housekeeping telemetry from the landing gear) before any mechanical activity would be commanded. Indeed all experiments requiring a deployment had to rely on data of the landing gear position versus the main body to be sure legs won't interfere. It was also critical to provide a slot before any drill to block the landing gear and ensure that no obstacle would be under the drill.

Moreover it was mandatory for Long Term Science (LTS) operations to increase the energy potentially produced by solar panels before the end of First Science Sequence (FSS) by placing the balcony (Philae side with no solar panel) in the shadow. That is the reason why the attitude (position of the main body regarding the Sun) had to be determined from Lander telemetry and images after touchdown.

2.5. Power

For the Separation, Descent and Landing (SDL) and FSS phases the Lander got power mainly from the primary and secondary batteries. The level of charge of the primary battery could not be monitored but the expected amount of energy was around 1350 Wh. Due to the severe constraints in terms of energy and in order to avoid operating the system without science measurements, the FSS sequence had to avoid any pause.

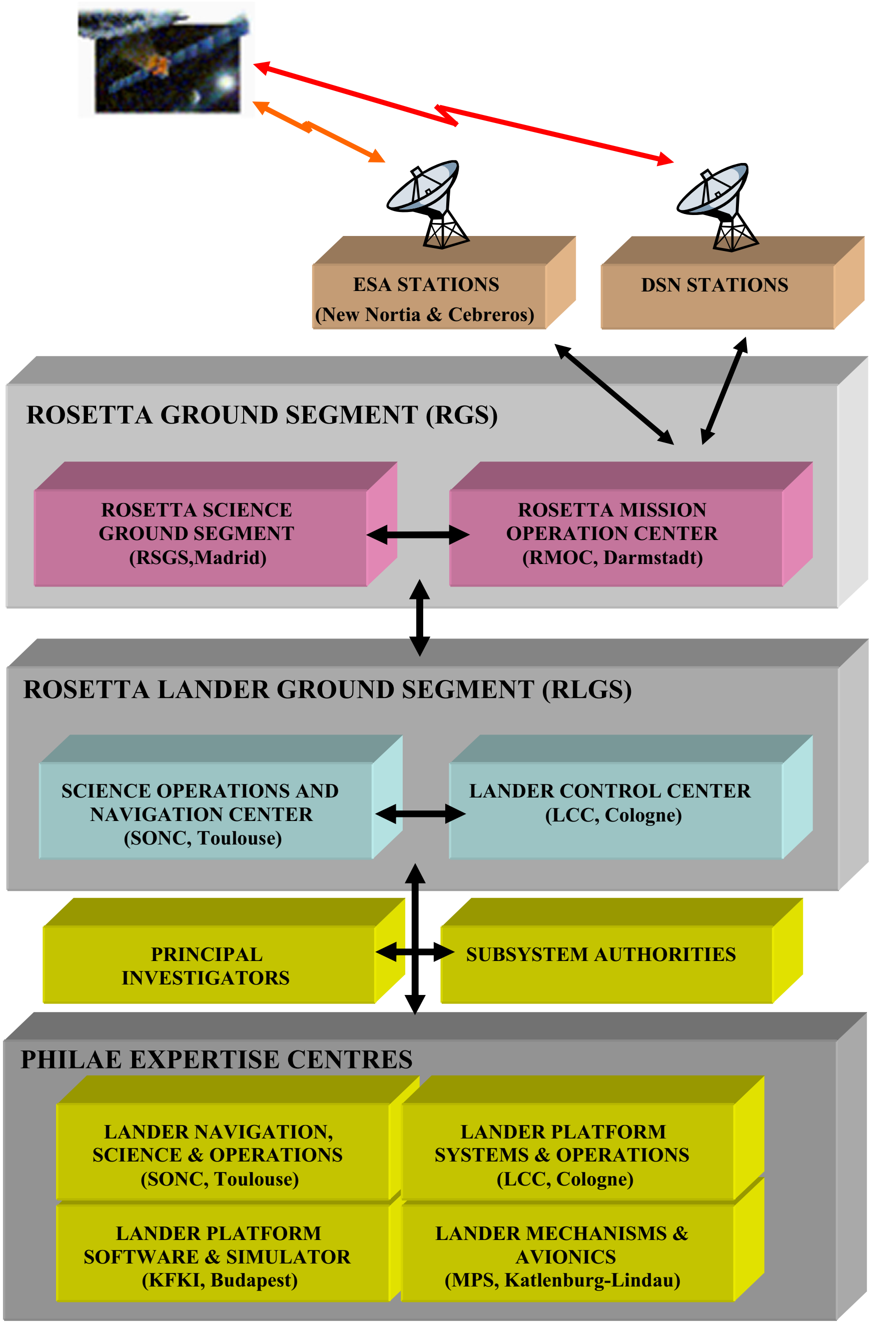


Fig. 1. Rosetta Lander Ground Segment (RLGS) schematic view.

In order to optimize the energy cost of the platform versus the science operations it was decided to parallelize as much as possible the instruments use.

2.6. *Data/mass memory and RF link*

As it was soon established that it was not possible for Rosetta to ensure permanent Lander/Orbiter visibilities and because of the small size of Philae the on-board mass memory (MM), data management was considered as the main constraint for the scheduling itself. Indeed the MM capacity (4 Mb) was insufficient regarding the amounts of data generated by experiments and also the instruments memories (IM) themselves were too small to cope with the dataload. Moreover the Lander data rate from instrument to MM depends on the number and type of instruments ON simultaneously and defined priorities.

It was also critical to empty the memory at the beginning of the FSS so a visibility was mandatory after the touchdown to transfer most of the data collected during descent (7 h duration!). Some of these first data were necessary for subsequent Lander operations (status needed for the Lander rotation in the FSS for example). The experiments scheduling and the data uploads to the Orbiter had to be scheduled at the best moments to optimize the full first science sequence data management.

3. The science scheduling tool

The scheduling of scientific measurements for the different phases of Philae mission had to maximize the science return with taking into account the different resources and constraints relative to the Lander and its experiments. The outcome of the scientific measurements planning performed at SONC is called a science sequence. At least one sequence had to be prepared per mission phase.

3.1. *Mission Operations Scheduling Tool (MOST)*

MOST is (C++) software using ILOG libraries and specifically designed for planning the Philae science mission under constraints. A feasible plan generated by MOST shall satisfy a number of constraints for energy, data management and precedence relations on activities, or incompatibility between instruments.

3.2. *Data management and power models*

The synthetic models for experiments implemented in the tool are representative for the real Lander behavior. A lot of parameters at Lander and Orbiter levels had to be described and modeled precisely: energy consumption profiles of each unit (instruments including sub-instruments in all modes, subsystems in all modes), power peaks and breaker limits, data management priorities, data storage in mass memory and dedicated instruments memories.

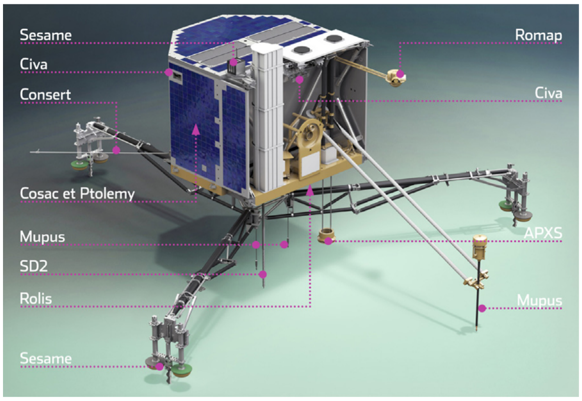


Fig. 2. View of Philae and instruments on board.

A very important use of MOST is to simulate the onboard data management process to compute the necessary transfers (to the orbiter and then to Earth) of the science data produced. These data are transferred from instrument memories to a central mass memory and then transmitted to the Orbiter when it is in visibility. Each instrument was previously assigned an allocation in mass memory and a dedicated priority for the duration of the activities. One goal of the scheduling using MOST is to ensure that data-producing activities are planned in such a way that no data would be lost.

3.3. *Science scheduling: Inputs*

A set of specific input was expected before any scheduling task. Among them were the descent duration, the orbital context with day/night cycle and visibilities between Orbiter and Lander, Lander instruments inputs (activities, power consumption and data production expected) as well as the available power and the priorities used for data management.

3.4. *Science scheduling: Outputs*

Once an operation plan has been generated, the scheduled tasks are stored including: a Gantt diagram presenting the list of activities, a data management synthesis (data transmitted for each orbiter/lander visibility), a mass memory management synthesis, the residual energy at the end of the sequence scheduled and finally a timeline of events. These products had to be delivered to LCC team for testing any possible implementation on the spacecraft.

4. The prepared science plan

The baseline scenario defined for FSS was a sequence of 4 activity blocks described here below (Fig. 3). Each block (numbered 1, 8, 6 or 7) combined in an optimized way a few instrument activities and is described in the following

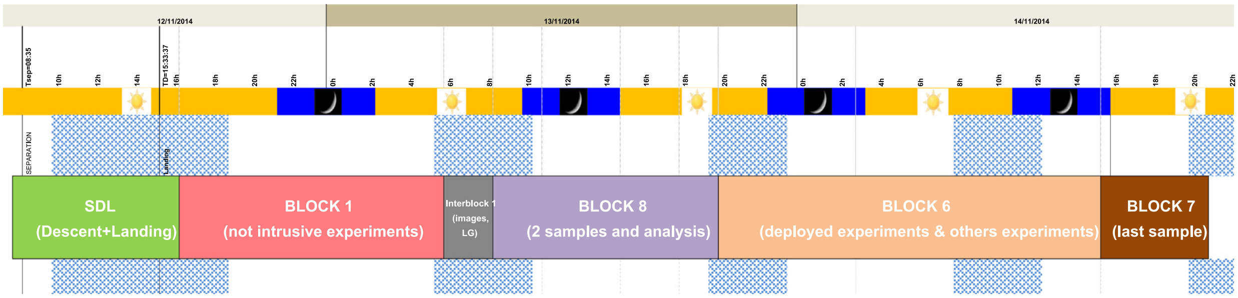


Fig. 3. Prepared sequence for FSS on Philae lander: general blocks vs day/night (yellow and dark blue) and RF links (light blue bars). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

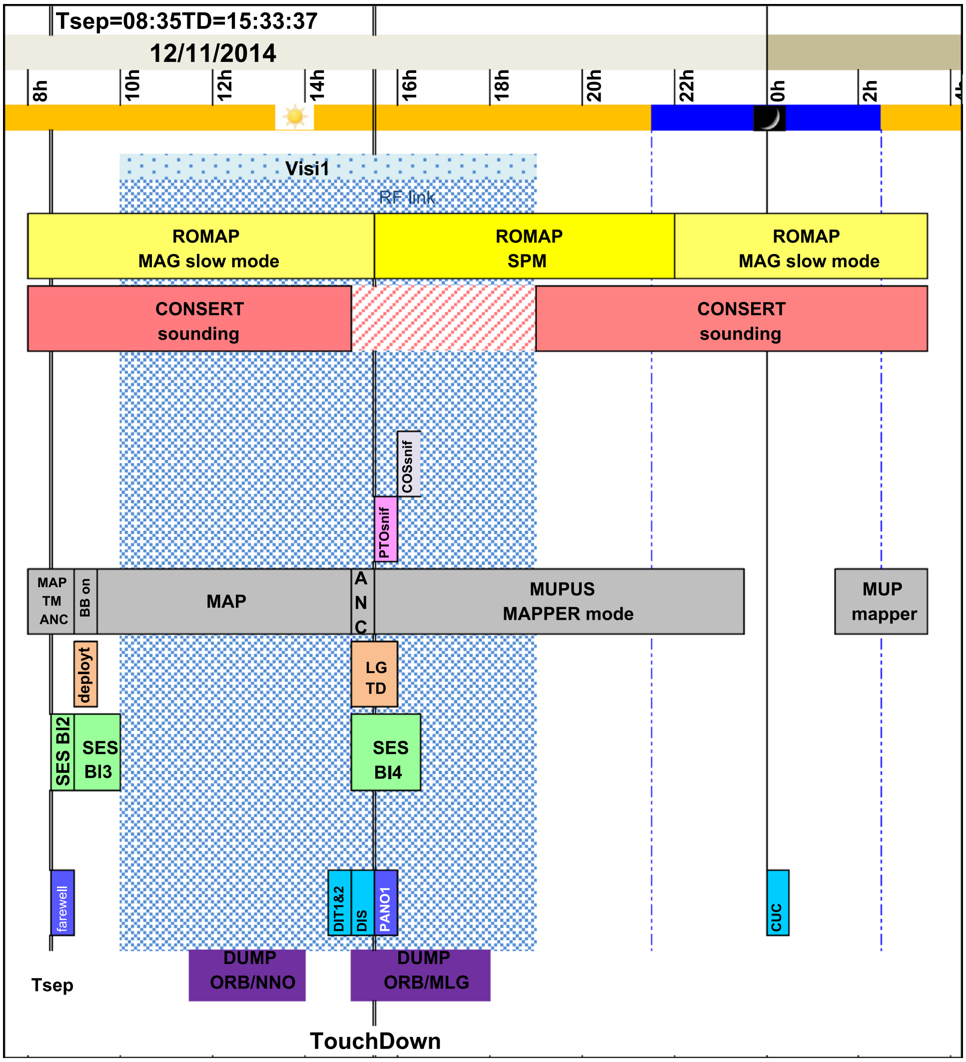


Fig. 4. Schematic view of the first FSS block.

sections. Note that the block numbering is not sequential for traceability reasons.

A block is made of several sub-sequences which can be used to reshuffle new blocks if needed in order to gain in flexibility in the planning.

The previous SDL phase was closely linked to the FSS but was under the responsibility of the system engineer at LCC due to the specific platform activities to be performed. (Ulamec et al. 2016)

4.1. *First science block (Block 1)*

The first block (Fig. 4) was designed to be the continuation of the separation, descent and landing (SDL) sequence and to run autonomously. It includes CONSERT (radio sounding and nucleus tomography), ROMAP (magnetometer and plasma monitor), MUPUS (thermal properties), CIVA (imaging system), ROLIS (imaging) activities as well as sniffing modes for PTOLEMY and COSAC (evolved gas analyzers). Most of the experiments are already switched ON before the separation or during the descent. [2–6].

The aim of the first block was to get results without any prerequisites on the landing status to save energy. As a consequence block 1 activities could have been performed whatever the descent duration and whatever the status of Philae after its landing without compromising the safety. Nevertheless this block's structure had to be adapted to the final comet context and was therefore constructed to allow updates of activities durations before descent without impacting the block structure itself.

ROMAP is switched on before the separation and begins during descent with the magnetometer activity. The plasma monitor activity is scheduled around noon and covers the day/night transition with at least 2 measurement cycles. Another magnetometer measurement completes the instrument activity to cover a full comet rotation.

CONSERT, a dual instrument with a part on the lander and a part on board the probe Rosetta, was also switched on before separation. Both parts were synchronized when still attached to the orbiter. The soundings are performed until the end of the first FSS block except during a standby period around the touch down to ensure SESAME to perform its touchdown listening without any perturbation.

MUPUS activity (duration and scheduling) was relative to touchdown and to the context. The experiment was also switched off during CONSERT operation

The first imaging activities after the landing (CIVA and ROLIS) were linked to the day/night cycle. So the scheduling was not frozen until the landing site, the landing time and trajectory were determined. Note that a first set of CIVA images was always scheduled right after the Landing at the beginning of the day to provide as soon as possible a complete view of the landing site.

Sniffing activities by COSAC and PTOLEMY (passive spectral analysis of the environment) were scheduled as soon as possible after the touch down to take advantage of the dust lifted due to the contact.

Accordingly to LCC operations request, all science activities in this first block except for ROLIS had to be stopped at the same time in visibility and with an impact on the next block's start. So activities' duration had to be updated 15 days before separation. Anyway a maximum duration for the block (time out) was considered in case of a late visibility to save energy necessary for the following blocks.

4.2. Inter-block between block1 and block 8

The first visibility after the landing one was critical to retrieve images of the landing area and to prepare for the following mechanical activity (need/possibility to rotate or not). In order to be more flexible it was soon decided to create an inter-block (Fig. 5) with Landing gear (LG) activities and panoramas combined as independent items or modules to be performed or not.

The philosophy was to schedule a number of CIVA panoramas in case the first attempt did not work or unexpected events might have corrupted the data. If one panorama was considered as not necessary after the first one, it could be deleted from the queue. The only remaining issue was the data volume in case of shortened visibilities. Indeed the landing status and location were unknown but CIVA-Panoramas had to be scheduled during visibilities and the link at the beginning of the second block should be long enough to transfer all images.

LG activities were composed of: lifting movement, rotation, lowering and blocking items. The first LG slot was scheduled before the second FSS block (so before SD2 drilling activities). The aim was to rotate Philae's body to optimize the solar power while primary battery was still enough charged to ensure the movement. It was important to ensure LTS phase before doing any mechanical- so risky-activity including drill.

If the landing gear position would have been an obstacle for drilling activities or if MUPUS was already able to determine its deployment zone, this LG rotation could have taken these constraints into account.

Consequently the Lander attitude and orientation had to be determined before the following block 8.

4.3. Second science block (Block 8)

The second block (Fig. 5) of FSS is mainly composed of the SD2 drilling and sample retrievals dedicated to PTOLEMY and COSAC for analysis (with high temperature ovens) [7–10]. This activity was one of the main objective of the mission but also one of the most expensive (power use) so it was decided to schedule it as soon as possible to

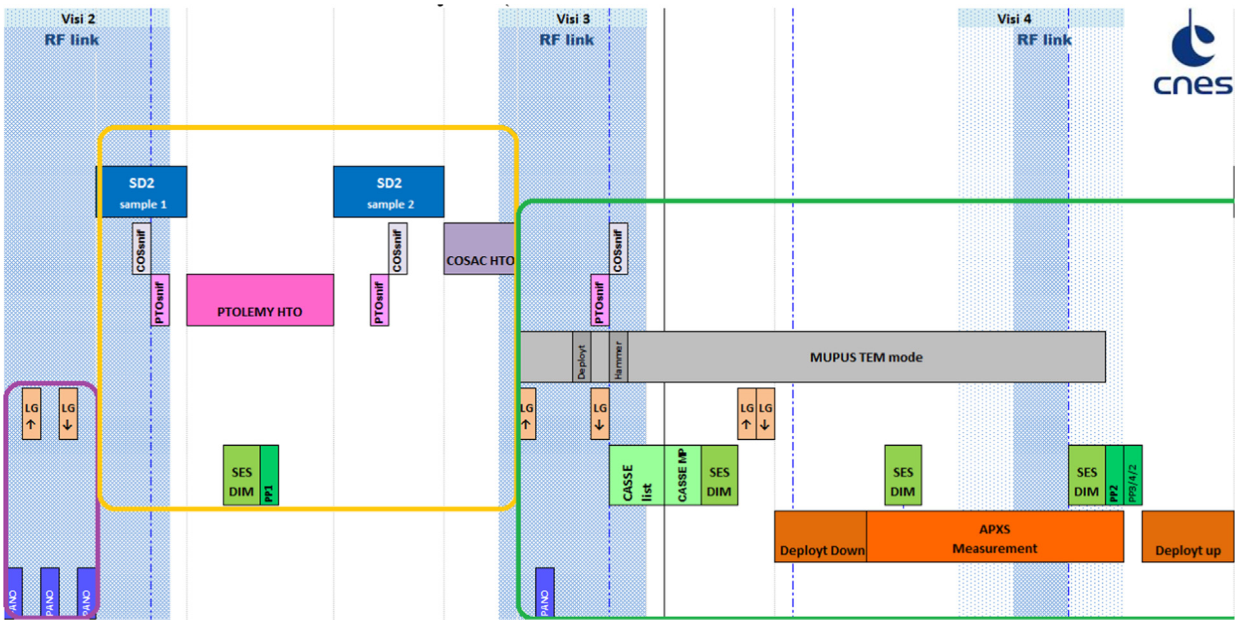


Fig. 5. Inter-block (purple frame), Second block (8, yellow frame) and third block (6, green frame) blocks prepared for FSS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

ensure its feasibility from a power point of view but long enough after the landing to be sure of the context.

Some atmospheric analyses by COSAC and PTOLEMY sniffing were also scheduled in parallel in case the drill would lift dust from the comet soil.

Some SESAME DIM and PP activities to measure the dust environment and mechanical properties of the soil had also to be scheduled in this block. Indeed DIM measurements should be repeated 4 times consequently the positioning had to be updated once the actual day/night cycle was known. As it was difficult to find 4 times a day suitable positions for DIM without any disturbance, the scheduling had to be revised frequently with the scientists.

The difficulty was to adapt the scheduling for the COSAC sample analysis once the orbital context was known in order to perform it during a visibility to secure the data management.

4.4. Third science block (Block 6)

The third block (Fig. 5) was mainly dedicated to experiments to be deployed (MUPUS [3], APXS [11]). These are more risky activities with a critical need of preliminary analysis) so scheduled later in the FSS.

A second Landing gear slot is scheduled at the beginning of the third block (after SD2 but before MUPUS deployment). The aim is to allow MUPUS deployment with LG in up position. It may also include an optional rotation to select a suitable deployment zone for MUPUS in agreement with the LTS solar illumination and APXS deployment needs.

Moreover if the targeted body orientation is not compatible with APXS deployment a third optional rotation was provided before APXS activity.

The MUPUS penetrator deployment is directly followed by the hammering into the soil and then a long measurement is performed by the thermal probe (at least during one comet period).

The APXS experiment was scheduled as soon as possible in parallel to MUPUS, to save energy and to optimize the sequence. However deployment and retracting movements of APXS are quite long (almost 3 h for maximum extension) and the measurement had to be reworked to fit in the assessed duration. Due to the length of this block APXS data could not be fully retrieved during the fourth visibility, but FSS was prepared to get the data at least partially to the orbiter in case the Lander battery were empty sooner than expected.

It is important to note that each time a rotation could be performed a CIVA panorama was associated.

SESAME experiments were also scheduled several times in the third block to fulfill instruments science objectives. CASSE had to listen to MUPUS hammering and was followed by DIM (while no mechanical disturbance was expected) whereas PP activities were dispatched along the block.

4.5. Last science block (Block 7)

The last FSS block baseline prepared had only a low chance to be executed based upon the predicted power. It was prepared not to lose a unique opportunity to complete all the FSS science objectives defined. This last block includes a last drilling to retrieve a soil sample to be analysed by COSAC (in medium temperature oven) and imaged by the CIVA MV experiment.

5. Planning for contingencies

Considering all the constraints previously mentioned it was difficult to find a suitable sequence to optimize the science return and taking care of all the constraints and resources. The proposed sequence detailed in the previous section was the optimized one. It was extensively tested by LCC operations team before its implementation. Once the landing scenario was better known only a few adjustments were possible i.e. adjustments of the timeline (and experiments slots) to the most likely visibilities and day/night cycle. Moreover to ensure flexibility, we had to determine key parameters and possible adaptation ranges as well as back-up plans to cope with any potential situation at the end of the landing. Despite the blocks were designed to face the expected modifications on the timeline, soon the mission was judged risky and very constrained.

It was mandatory to be prepared to contingencies and be able to “rescue” as much science as possible.

This objective was reached through the design of an extra block of activities called ‘safe’ block.

All activities scheduled in this block (MUPUS, ROMAP Magnetometer, PTOLEMY and COSAC sniffing, SESAME DIM and PP) are “safe” i.e. they can be performed without any mechanical activity and with a low consumption and data volume. No specific conditions were requested before commanding this block. Consequently this block could have been performed at any time during FSS (or LTS) phase upon request (either in case of a contingency in a pre-scheduled block or to complete a sequence). The 2 h duration of the block allows this block to be repeated several times if needed.

6. Assessment of the plan during landing site selection process

Once a baseline plan was prepared a lot of work was still to be done. Indeed the landing site was not yet selected so the SAM team was involved in the landing site selection process (LSSP). At each milestone (detailed in Table 1) it was important to evaluate the impacts of the potential sites on the science sequence, assess the robustness of the plan and eventually tune it to optimize the science as well as the power and data management.

6.1. Initial pre-selection of 10 sites

During summer 2014 SONC flight dynamics used the available shape model and associated gravity fields to determine areas where the landing would be feasible (Fig. 6). An exhaustive search was initially performed for points with satisfying illumination to find acceptable landing trajectories (comparable with Orbiter delivery orbit and lander descent trajectory constraints). [12].

Then a restrained LSSP meeting was organized on the 20th of August 2014 to define 10 candidates named A to J inside the reachable area. This selection was based only on technical criteria, without considering the scientific interest in the potential landing site.

At this point SAM's task was simply to check that the large variety of day/night pattern was in agreement with Philae's power and scheduling constraints.

FSS and LTS operations on the comet required to land in zones where the illumination conditions were acceptable (more than 6.2 h daylight duration and more than 30 min of night). It represented only a rather small part of the comet surface. [13].

6.2. Assessment of the 5 selected sites

A two-days meeting including the lander team, ESA and orbiter PIs was held in CNES Toulouse on 23rd and 24th August to review the different technical criteria (flight dynamics, Lander ops and science sequence). The scientific interest of the 10 landing sites were also considered to finally choose 5 candidate landing sites for further evaluation (called A, B, C, I and J; Fig. 7).

Two weeks later RMOC provided the operational feasibility analysis and the corresponding trajectory for two pre-defined sites and SONC FD provided as inputs for a further analysis by SAM team the associated patterns (day/night dispersion, visibilities and variability).

Table 1
LSSP milestones.

Objectives	Days to landing	Date
Selection of 5 candidate landing sites.	L-79	24/08/14
Selection of the nominal and backup landing.	L-58	14/09/14
Confirmation of the nominal landing site.	L-30	12/10/14

6.3. Context variability: Impacts on the plan

The 5 selected sites and particularly their potential impacts on the sequence once landed were analysed and compared to help the Lander Science team to pick the 2 preferred landing sites. A large set of dimensioning orbital event files (day, night, visibilities and descent durations…) were used as inputs for MOST runs. The resulting assessment (Table 2) is based one several criteria. The main criterion was to have the exhaustion of primary battery latest possible in the science sequence. Secondly: data retrieved the soonest at the end of FSS, low risk of ending FSS during mechanical activities (to end FSS in a safe state).

This study demonstrated that descent duration was not the only driver for SDL/FSS feasibility. Indeed, the visibility pattern has an impact on the instruments scheduling and on power consumption. For example, a permanent RF link during the whole descent visibility as requested by ESA (roughly 6 h) could be very useful but would increase the power consumption for site J: 66 Wh more so 3 h less for FSS.

Nevertheless none of the reachable/selected sites provided a context ensuring a complete feasibility of the third block on battery only. The estimated ends of the baseline sequence for the different sites if not supported by solar power are marked on Fig. 8. Solar power would be critical for the FSS completion whatever the final landing site.

The opportunity of communication windows between Orbiter and Lander during the Long Term Science phase, (expected for December 2014–March 2015) was also studied taking into account the LTS orbit for Rosetta to be considered for the final ranking of the landing sites.

6.4. Nominal and back-up sites

For each site the variability of the visibilities pattern was studied with MOST in order to select the more homogeneous site and the more suitable. Data management associated to the site RF visibilities (including dispersions) was studied to ensure that the mass memory could never be full and loose science data (Fig. 9).

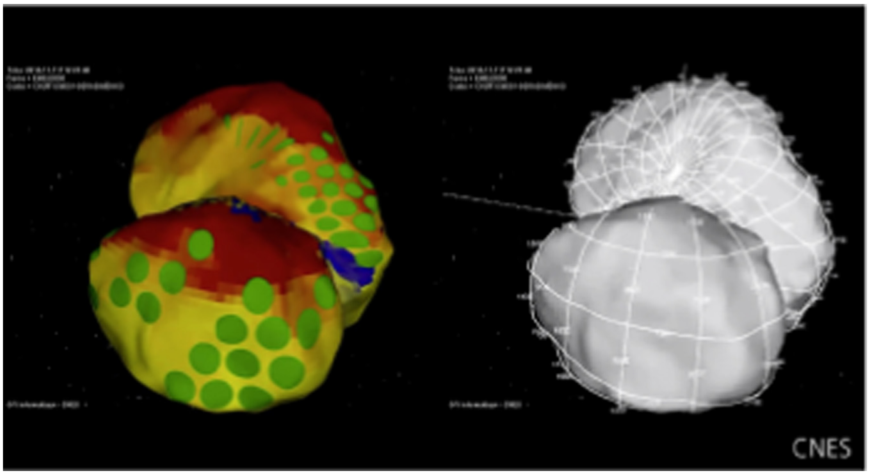


Fig. 6. Comet 67-P model and locations (green dots) of the pre-selected candidate sites (mid-august 2014).(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

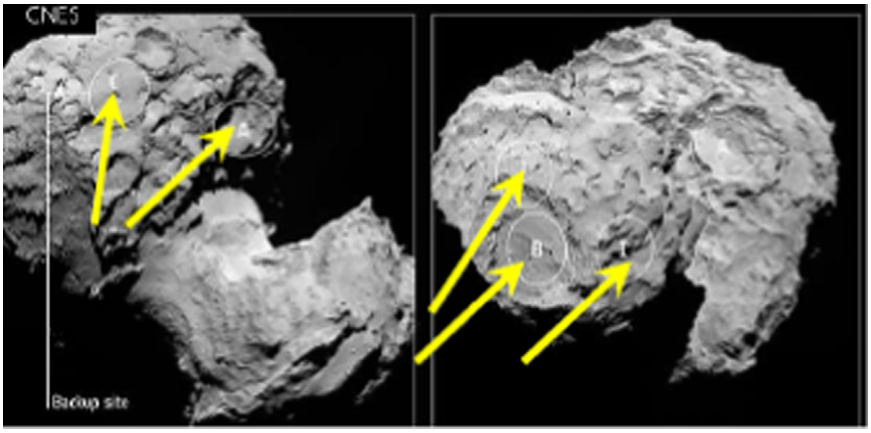
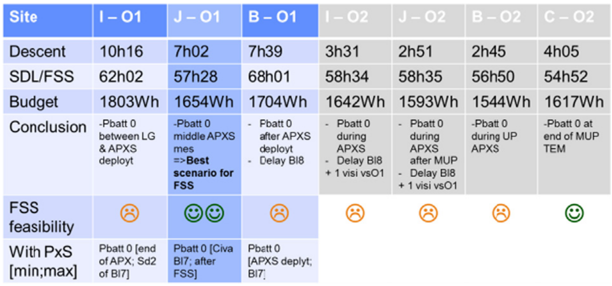


Fig. 7. Comet 67-P pictures and locations (white circles and yellow arrows) of the 5 sites selected during LSSP process. (ESA/Rosetta/MPS for OSIRIS Team). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

Table 2
Assessment of the 5 sites from the science planning point of view (no safe trajectory for site A, only 4 sites left). O1 and O2 strategies (with separation ΔV equal to emergency ΔV (0.18 m/s) or 0.3–0.5 m/).



Site	I – O1	J – O1	B – O1	I – O2	J – O2	B – O2	C – O2
Descent	10h16	7h02	7h39	3h31	2h51	2h45	4h05
SDL/FSS	62h02	57h28	68h01	58h34	58h35	56h50	54h52
Budget	1803Wh	1654Wh	1704Wh	1642Wh	1593Wh	1544Wh	1617Wh
Conclusion	-Pbatt 0 between LG & APXS deployt	-Pbatt 0 middle APXS mes =>**Best scenario for FSS**	- Pbatt 0 after APXS deployt - Delay BI8	- Pbatt 0 during APXS - Delay BI8 + 1 visi vsO1	- Pbatt 0 during APXS after MUP - Delay BI8 + 1 visi vsO1	-Pbatt 0 during UP APXS	-Pbatt 0 at end of MUP TEM
FSS feasibility	☹	☺☺	☹	☹	☹	☹	☺
With PxS [min;max]	Pbatt 0 [end of APX; Sd2 of BI7]	Pbatt 0 [Civa BI7; after FSS]	Pbatt 0 [APXS deplyt; BI7]				

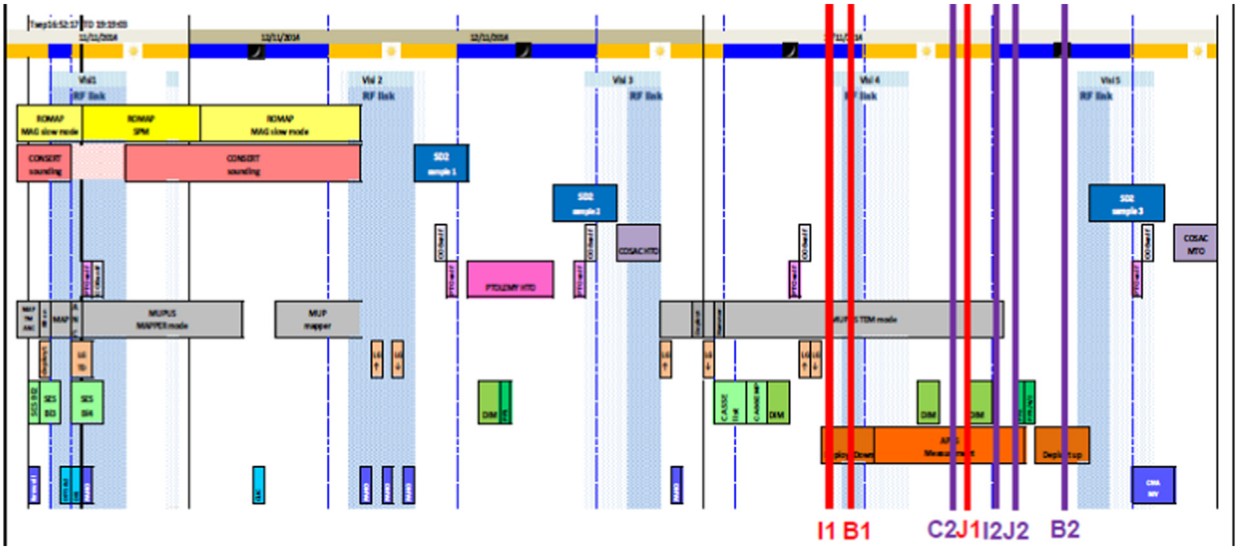


Fig. 8. Assessment of the sites in LSSP, impacts on SDL/FSS sequence. (Expected battery depletion: red, with solar power added: purple lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

As previously done for the 5 sites, the visibility patterns for the nominal and back-up sites were analyzed to assess the impacts on the science sequence scheduling and duration. The synthesis plot in Fig. 10 shows that the main criterion was the time frame between touchdown and the second visibility: the favorable case for science is when the delay is shorter.

Finally on 13th and 14th September a two-day LSSP meeting was held in CNES Toulouse to decide for the final ranking of the landing sites. Technical results for each site were presented, and the different sites were compared. Scientific interest of the different landing sites was also discussed. Site J (Fig. 11) was finally chosen as the preferred landing site and site C as the backup.

6.5. Delivery date

It was decided by ESA and PHILAE management to postpone the Lander delivery on 12th November 2014 afternoon instead of 11th November morning for public relations purpose. As a consequence, the complete analysis had to be redone by SONC and the science sequence had to be adapted.

This frozen calendar was less favorable due to a different visibility pattern between Orbiter and Lander. The resulting sequence would be 4 h duration less if based on primary battery (PBatt) only.

In conclusion solar power was more and more mandatory to allow full execution of the 3rd block (in some cases not achievable even with solar power).

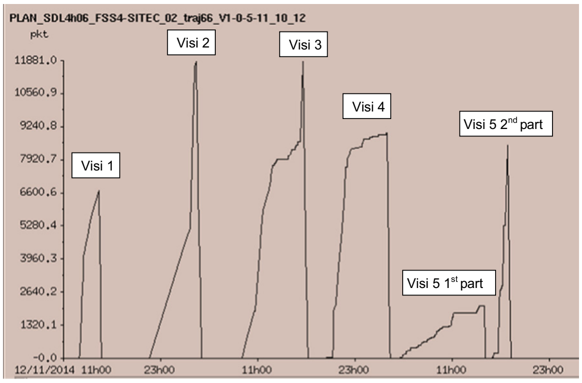


Fig. 9. Data management analysis during LSSP assessment of site J.

However updated orbital event file (OEF) did not show a huge impact on day/night cycles thus limited impact on the scheduling.

Site J remained the site with the most homogeneous parameters inside the dispersion ellipse from a science sequence point of view.

7. Operations

7.1. Once the landing site was selected

Many activities in block1 depended on orbital events so a different landing location inside the landing ellipse would impact the synchronization of these activities. (CONSERT, MUPUS, ROLIS)

Moreover SESAME activities might be re-scheduled during operations once we know where we have landed.

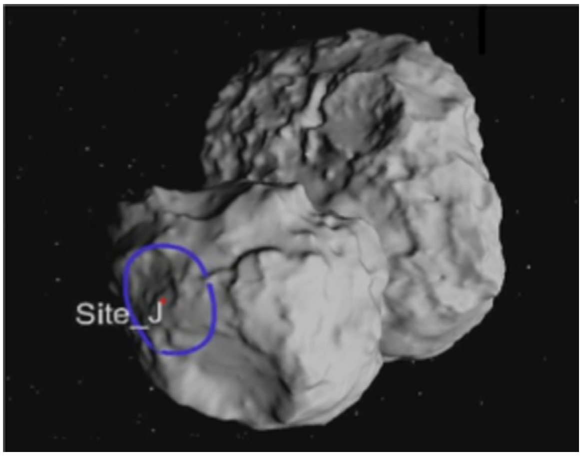
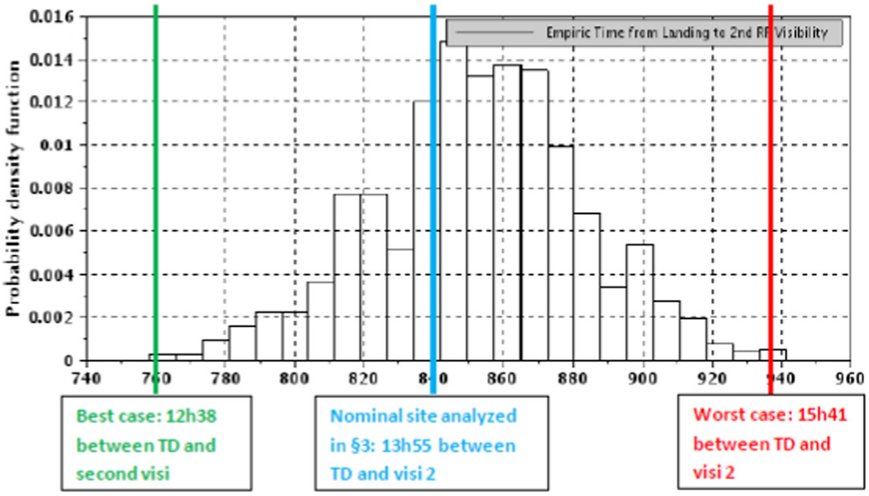


Fig. 11. Comet 67-P model and location of the selected primary landing site: AGILKIA (site J).



Best case: 12h38 between TD and second visi

Nominal site analyzed in §3: 13h55 between TD and visi 2

Worst case: 15h41 between TD and visi 2

Fig. 10. Visibility pattern analysis (and impacts on SDL/FSS sequence) during LSSP assessment of landing area J.

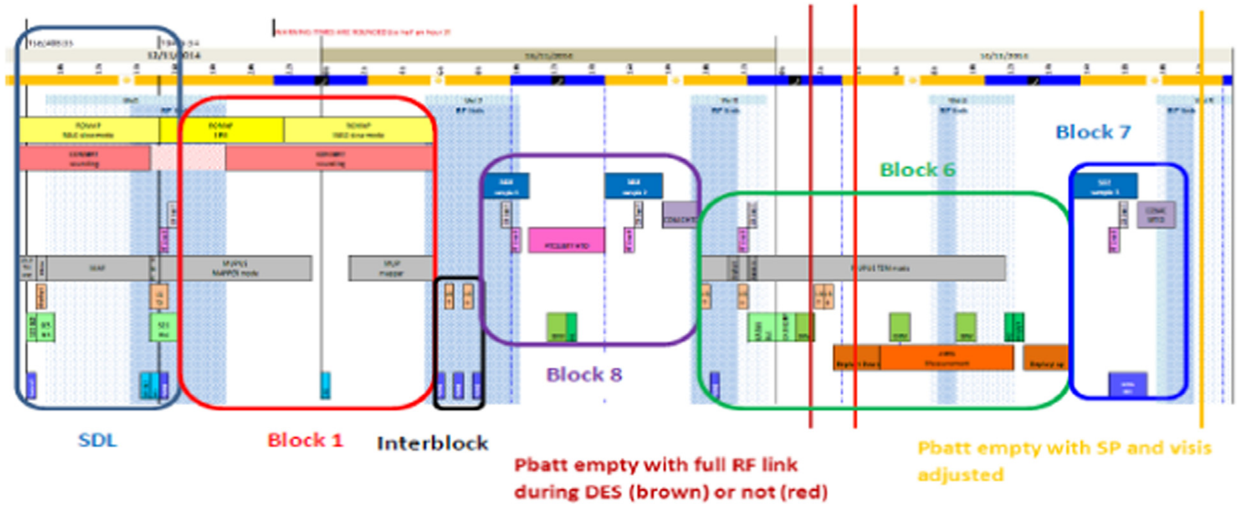


Fig. 12. Schematic sequence designed for SDL/FSS and adapted to the nominal landing site selected after LSSP. (1st vertical red line is the expected end of power with Pbatt only and the 2nd is the one including solar power). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The specific cases of CIVA (inter-block) and COSAC (2nd block) producing a large amount of data had also to be carefully analyzed to secure data management.

The final baseline updated once the landing site was selected is schematically shown in Fig. 12 and the expected end of power (red lines) was recomputed.

Activities durations were adjusted, fine tuning of the science sequence was then performed and the resulting science timeline was sent to LCC testing and inclusion in the execution sequences of the lander.

7.2. *On comet phase: Team organization*

For on comet operations 2 members of the science planning team (SAM) were at LCC in Cologne together with the PIs, the experts for subsystems on board Philae and the operations team in charge of the Lander commanding. Decisional meetings were held at LCC but in close loop with the rest of the SAM team located at SONC (Toulouse). To ease SONC engineers to follow operations a CNES tool customized to monitor instruments on Philae was also used.

7.3. *Executed science plan*

On the 12th of November 2014, the “GO” for the landing was given by the Lander authority and ESA. The Philae lander separated from the orbiter at 08h35 for its long descent toward the comet as planned. The link was correctly established during the descent and all instruments scheduled during its 7 h duration. The SDL sequence produced the wonderful and now famous images taken by CIVA of the orbiter and by ROLIS of the approaching surface. [15].

7.3.1. *First visibility*

The Lander was healthy and followed perfectly the expected descent trajectory. The touchdown was confirmed at 15h34. However Philae was not anchored to the soil and the first CIVA panorama was commanded when Philae was just bouncing.

At the end of the first visibility the strange behavior of Philae and the first corrupted images received could not be explained. It was then unconceivable to follow blindly the prepared FSS. The whole science team involved in the first block (including ROMAP [14]) analysed their preliminary data to understand the situation while the ops team had to decide the science activities to be commanded on-board.

7.3.2. *Second visibility*

The only choice after this non-nominal landing was the already prepared branching in interblock commanding a second CIVA panorama which was mandatory at this time. In order to increase the reactivity it was decided to keep the same parameters used for the first one, even if no information on the day/night cycle was available at this time. The most efficient block to get science data without endangering the lander was the ‘safe block’. This extra-block designed by SONC and already tested at LCC, was ready and was meant to be repeated 4 times to cover the estimated but unconfirmed inter-visibility period.

During the second visibility these activities were uploaded and data from the 1st block were received. The set of data included CIVA panorama of the surrounding “boulders” and “cliffs” and the beautiful images of the ground under Philae taken by ROLIS.

In the place where Philae had finally landed the sun light could rarely illuminated Philae (much less than expected for Agilkia). Nevertheless, fortunately the CIVA panorama scheduled during the inter-block was taken during the short daytime [16].

The second visibility was so long that the first safe block and even the beginning of the second one were observed in “real-time” (with 30 min of delay due to comet/earth distance).

7.3.3. *Third visibility*

Once the second visibility was over it was important to decide as soon as possible which science activities would come after the third one. As Philae was not anchored to the soil, drilling was considered as too risky by the lander authority so block 8 with SD2 activity combined with COSAC and PTOLEMY high temperature analysis was postponed.

A customized block was then designed from the former block 6 in order to take advantage of the available power (including MUPUS [17], APXS and SESAME). Based on the estimated duration between the visibilities some activities were adapted: SESAME DIM had to be deleted to shorten MUPUS, landing gear rotations and activities were deleted and the first LG slot was used to insert a CONSERT ranging to help finding the Philae location. And because the block had to be completed before the visibility used to retrieve data, APXS measurements were also shortened.

At each visibility a power assessment was done using the MOST tool and prepared models for on-going activities (with real durations). This activity was done by SAM team in close loop with battery experts from CNES. Indeed the temperature profile of the battery had a huge impact on its performances. This step by step assessment of the used power was used at each operational meeting to base the upcoming activities on the resulting available power.

7.3.4. *Fourth visibility*

Before the 4th visibility it was clear that the coming slot of activity could be the only chance to analyse a solid sample of the comet. It was then decided in agreement with the operations team and the whole science team to give it a try to SD2 combined with only one instrument. Due to the power assessment it was impossible to command the complete second block. A discussion was initiated to select either COSAC or PTOLEMY after the drill for the unique possible sample analysis. It was important to use commands already on board and for COSAC had the shorter experiment it was decided to run it, reduced to only one temperature step.

However PTOLEMY sniffing was kept in the sequence and it was proposed to prepare another PTOLEMY activity for the end of the FSS (CASE analysis).

7.3.5. *Last visibility*

Between the 4th and 5th visibility the Lander was left in stand-by mode after the re-shuffled second block to save the energy still available. The last activities for the FSS period had then to be selected.

Indeed a longer hibernation period was expected for the lander at its final landing site (Abydos) after the batteries were running out of power. A lander rotation was then commanded during the last visibility, placing the largest solar panel to the sun to retrieve a maximum power, increasing this way the chances to be able to exit. At this moment only 3.5 W were produced whereas 5.5 W are necessary to boot the lander and start a charge cycle of the secondary battery.

One last ROLIS image (in addition to the first one retrieved during the 2nd visibility) was scheduled to get more information on the landing site before hibernation. CIVA was not an option because of night time.

PTOLEMY CASE associated with SD2 carousel rotation was also scheduled (re-use from pre-delivery and calibration phase) to give a chance to Ptolemy to have more science data. And CONSERT ranging was finally performed till the end to help the a posteriori localization of Philae.

At the end of the visibility, the primary battery depletion was complete (after the end of the commanded activities).

8. Conclusion

The end of the first science sequence observed in visibility at 0h05 on the 15th of November demonstrated that the battery behavior was nominal and exactly as expected. Each instrument involved in the first science sequence had a chance to operate and retrieve science data despite a not nominal landing. The first science sequence lasted 64 h compared to 63 h expected for the prepared one.

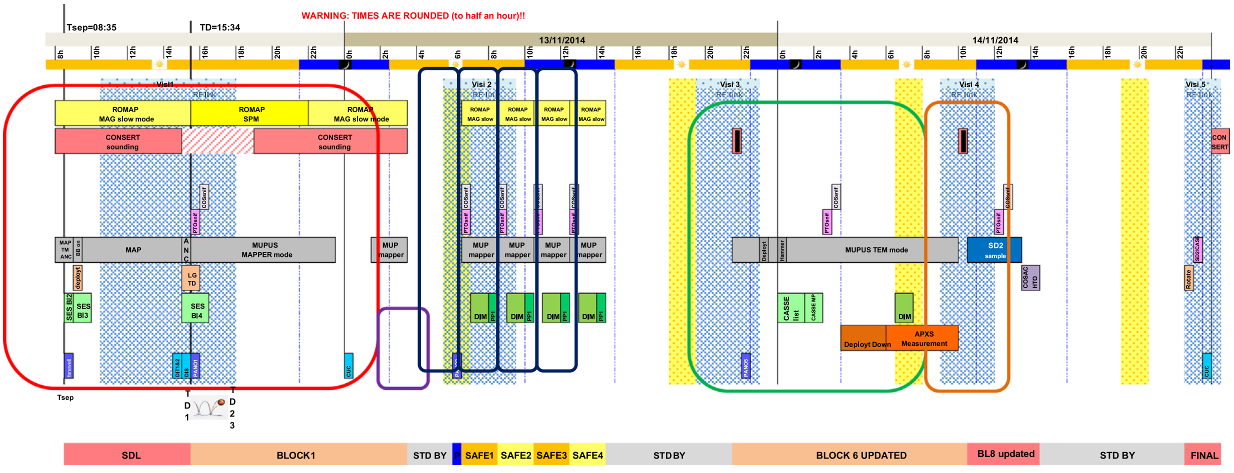


Fig. 13. Schematic sequence performed during SDL/FSS and adapted after the non-nominal landing.

Although the performed sequence and the executed blocks (detailed on Fig. 12) at first sight appears to be very different from the prepared one, in fact it was very similar and derived from the prepared baseline.

The modifications performed during operations on FSS science sequence were only deletions of independent activities, insertion of prepared and validated activities like safe blocks or shortening of longer activity. The skeleton remained the same as well as the prepared models used to assess the available power at each visibility.

When it comes to space exploration the key word is the unforeseen and operations have to be consequently robust and flexible. So the hard point of any mission is to find a compromise for the science planning once the inevitable constraints linked to platform, power budget and data budget are taken into account. The resulting sequence has to mitigate the risks with respecting the science objectives and avoiding stand-by periods or complex decisional processes that would be waste of data or power. This was the rationale for designing the so-called safe block which turned out to be extremely important for Philae (Fig. 13).

Acknowledgments

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