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PHILAE: SCIENCE SCHEDULING AND UNKNOWN CONTEXT, LESSONS LEARNED

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Rosetta is an ambitious mission launched in March 2004 to study the nucleus as well as the coma of the comet 67P/Churyumov-Gerasimenko. It is composed of a space probe 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 a so short notice, first time a lander has landed on a comet nucleus. The space probe Rosetta reached the vicinity of the comet in spring 2014 when it has started to study Churyumov-Gerasimenko with remote sensing instruments. An intense observation phase followed to be able to select a landing site for the Lander. And in November 2014, at a distance of about 3 AU from the sun, Philae has reached its destination on the surface of the comet 67P. Once stabilized on the comet, the lander 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 Centre (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 Centre (LCC) located in DLR Cologne. Nevertheless, the specific context of the Rosetta mission made this task even more complex if compared to usual spacecraft or landers: indeed the teams in charge of the Philae activity scheduling had to cope with huge constraints in term of energy, data management, asynchronous processes and co-activities or exclusions between instruments. In addition to these huge constraints it is important to note that the comet, its environment and the landing conditions remained unknown until the separation time and that the landing site was selected a short time before it had to take place and when the baseline operational sequence was already designed. This paper will explain the specific context of the Rosetta lander mission and all the constraints that the activity scheduling had to face to fulfil 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 designed this way will also be detailed to highlight the difficulties and challenges that the operational team had to face. A specific focus will be given on the landing site selection and the impacts on the scientific operations scheduling. Moreover the actual sequence performed on the comet will also be detailed and analysed to deduce the lessons that could be learned from such an unprecedented endeavour. Indeed as for every mission of exploration the flexibility concept was anticipated but had to face unexpected events.

NOMENCLATURE

AU = Astronomical Units
APXS = Alpha Proton X-ray Spectrometer
CDMS = Command and Data Management System
CIVA = Comet Nucleus Infrared and Visible Analyser
CNES = Centre National d'Etudes Spatiales
CONSERT= COmet Nucleus Sounding Experiment by Radiowave Transmission
COSAC = COmetary SAmpling and Composition experiment
FSS = First Science Sequence
HK = HouseKeeping telemetry
IM = Instrument Memory
LCC = Lander Control Centre
LOR = Lander Operations Request
LIOR = Lander Instruments Operation Request
LTS = Long-term Science
MM = Mass Memory
MOST = Mission Operations Scheduling Tool
MUPUS = MUlti-PUrpose Sensors for Surface and Sub-Surface Science
PDCS = Pre-Delivery, Calibration and initial Science phase
RLGS = Rosetta Lander Ground Segment
ROLIS = Rosetta Lander Imaging System
ROMAP = Rosetta Lander Magnetometer and Plasma Monitor
SAM = Science Activity Management
SESAME = Surface Electric Sounding and Acoustic Monitoring Experiment
SD2 = Sampling, Drilling and Distribution subsystem
SDL = Separation, Descent and Landing phase

SONC = Sciences Operations and Navigation Centre
TM = Telemetry

I. INTRODUCTION: MISSION AND CONSTRAINTS

I.I. ROSETTA AND PHILAE MISSION

Rosetta, an ESA mission launched in March 2004, reached its target, comet 67P/Churyumov-Gerasimenko last year at a distance of 3.5 Astronomical Units (AU) from the sun. This mission is unique by its target, its duration and especially because this is the first time a spacecraft is escorting a comet while getting closer to the sun. The perihelion was reached this year in august. An exceptional device was also on board Rosetta until its delivery in November 2014: the Lander, so-called Philae. It was the first device 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 composed by DLR, CNES, MPS, MPE, ASI, KFKI, UK SA, FMI, STIL, and IWF.

During the 10 years cruise, the operations performed on board Philae were health checks, calibrations, software updates and occasional observation campaigns during flybys. While getting closer to the comet operations become more complex. The comet phase has started at the end of the deep space hibernation period, in January 2014, and covered the approach and all the operations in the vicinity of the comet. The Philae mission was divided into sub-phases: commissioning, calibration and science phase, Landing Site Selection Phase (LSSP), SDL, FSS and LTS. In this paper we will cover mainly LSSP, FSS and LTS in order to focus on the science scheduling activities at CNES.

SDL/FSS main phase covered the first scientific measurements during on-comet operations. The power was provided by the primary and secondary battery until primary battery was empty and the re-charging of the secondary battery was required. This phase lasted several hours.

LTS period should have started several days after the end of FSS phase so after the expected first recharging of the secondary battery and should have been performed up to the end of the Lander diurnal awakening capability (end of 2014 TBC). However as a consequence of its epic landing, it happened after a hibernation period of the lander. The LTS phase will extend until the end of the Lander mission besides it is limited by the lifetime of the whole ROSETTA mission since the orbiter is mandatory for commands and data transmission.

I.II. LANDER GROUND SEGMENT

The ROSETTA LANDER GROUND SEGMENT (RLGS, Fig.1) is composed of two entities:

- The Lander Control Centre (LCC), located at DLR/MUSC in Köln (Germany), in charge of Rosetta Lander operations.
- The Science Operation and Navigation Centre (SONC, Fig.2), located at CNES in Toulouse (France)

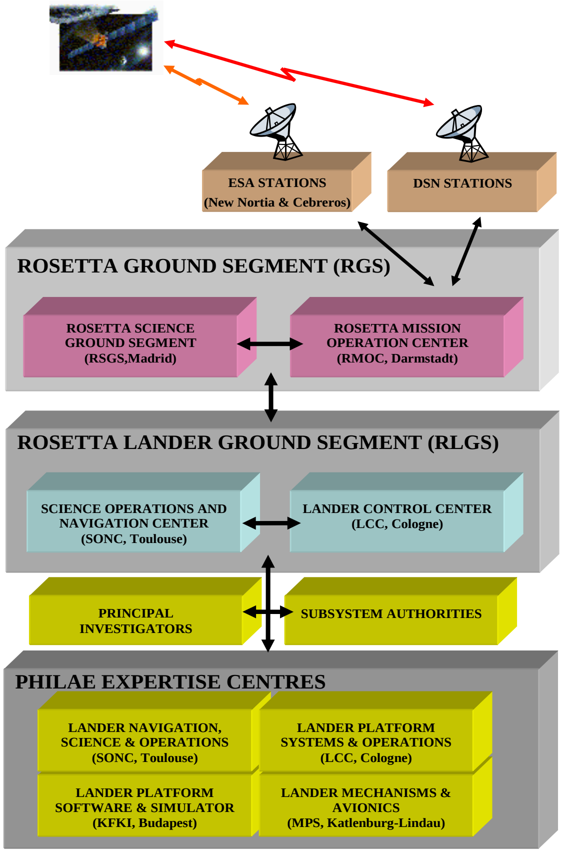


Fig. 1: Rosetta Lander Ground Segment (RLGS) schematic view.

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

Fig. 2: SONC main room at CNES (Toulouse).

The Science Activity Management (SAM) team located at SONC in CNES (Toulouse) is in charge of collecting the scientific needs and the constraints to be applied to produce a science mission plan approved by lead scientists and implemented by the LCC operational team. The main tool developed to perform the scheduling task is called MOST for Mission Operations Scheduling Tool.

PHILAE AND ITS ON BOARD INSTRUMENTS

PHILAE Lander (Fig.3) weights about 100 km and includes ten instruments (18 sub-instruments, each one with specific constraints) that is able to measure chemical and physical properties of the comet. The science payload of the PHILAE lander masses around 30 kilograms, making up nearly one third of the mass of the lander.

APXS (Alpha Proton X-ray Spectrometer) the APXS spectrometer provides information on the elemental composition of the material underneath the Lander.

COSAC (The COmetary SAmpling and Composition) experiment includes a pyrolysis device and two analytic instruments: an eight columns gas chromatograph (GC) and a powerful high-resolution time of flight mass spectrometer. The experiment's aim is to analyse soil samples and identify volatile components.

PTOLEMY is a gas chromatograph-isotope ratio mass spectrometer designed to provide chemical and isotopic analyses of both volatiles (including water) and refractory materials drilled from the comet nucleus.

ÇIVA (Comet Nucleus Infrared and Visible Analyser) is composed of 7 Panoramic cameras (CIVA-P), a Visible Microscope (CIVA-M/V) and an Infrared Spectrometer (CIVA-M/I) designed to characterize the landing site, the 360° panorama as seen from the Rosetta Lander. CIVA is sharing a common Imaging Main Electronics (CIVA/ROLIS/IME) with ROLIS.

ROLIS (Rosetta Lander Imaging System) consists of a highly-miniaturized CCD camera. It has operated as a descent imager, acquiring imagery of the landing site with increasing spatial resolution. After touchdown ROLIS took multispectral images of the comet's surface below the Lander.

CONSERT (COmet Nucleus Sounding Experiment by Radiowave Transmission) is a radar performing the tomography of the nucleus by measuring electromagnetic wave propagation from Philae and Rosetta throughout the comet nucleus in order to determine its internal structures.

MUPUS (MUlti-PUrpose Sensors for Surface and Sub-Surface Science) is dedicated to temperature profile (thermal mapper) of nucleus' subsurface layers to a depth of 40 cm and thermal conductivity of cometary material. It includes a mechanical device designed to insert a penetrator (PEN) into the cometary nucleus and acceleration and thermal sensors in anchors (ANC).

ROMAP (Rosetta Lander Magnetometer and Plasma Monitor) is a combined instrument consisting of a Magnetometer (MAG) and a Simple Plasma Monitor (SPM) which complements the plasma packages onboard the ROSETTA Orbiter. The SPM sensor is able to determine the major solar wind parameters like density, speed, temperature, and flow direction. The MAG sensor is able to determine the magnetic field vector.

SESAME (Surface Electric Sounding and Acoustic Monitoring Experiment) is a set of three experiments: a Comet Acoustic Surface Sounding Experiment (CASSE), a Permittivity Probe (PP) and a Dust Impact Monitor (DIM) sharing a common electronics. The CASSE part investigates acoustically the surface material, while PP measures the dielectric properties of the environment (electrodes are attached to APXS and MUPUS PEN) and DIM is a dust impact monitor.

SD2 (The Sampling, Drilling and Distribution subsystem) is on board to support some experiments as it is able to collect comet surface samples at given depths and distribute them to 26 dedicated ovens mounted on a carousel. Then each sample could be step-wise heated and the resulting gas piped is presented to the dedicated experiment (CIVA-M or PTOLEMY or COSAC).

Most of the experiments onboard PHILAE were tested on ground but not in the real operations conditions.

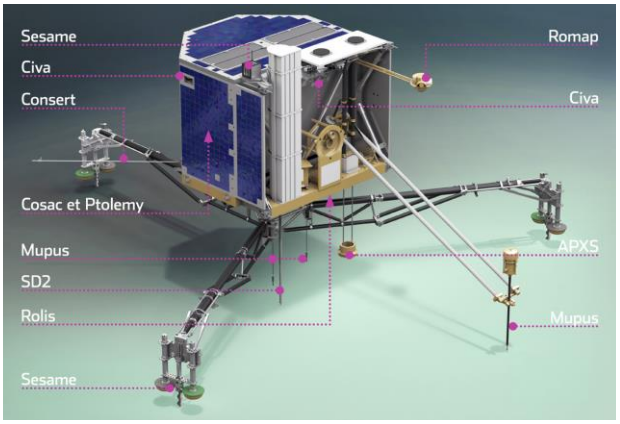


Fig. 3: View of PHILAE and instruments on board.

II. PHILAE SCHEDULING CONSTRAINTS

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 described one by one with the experimenters responsible for the instruments on Philae. Then a trade-off had to be done by the principle investigators and lead scientists to decide their relative importance regarding the full set of science objectives.

The planning of the science sequence requires as a guideline an overall additional ranking of all the Philae science objectives. The rank or order of priority given to the individual objectives indicates their relative importance to be able to design a sequence which aim is to maximize the possible science return of the lander experiments.

Ops constraints

When Philae was delivered from the orbiter, Rosetta was at 3 AU so the time necessary to receive or transmit data to/from Earth was roughly half an hour. Moreover due to Rosetta's orbiting, the visibility between Lander and Orbiter was not permanent and prevented from close loops with Philae. With such a low reactivity on ground the sequence of activities had to be designed to cope with this specificity.

The day/night cycling related to the landing site had also to be considered to prepare the science activities. Indeed some activities scheduling or duration depend on day/night positioning (imaging, ROMAP SPM, SESAME, MUPUS, etc.). Some activities (SESAME DIM, PP) should be scheduled several times a day at different times whereas others had to be performed during night (ROLIS CUC imaging) or day (CIVA panoramas).

Instruments: risks, interferences and co-activities

Some experiments shall operate alone to avoid interferences or corrupted measurements or because co-activities are not mechanically feasible at the same time. Examples of co-activities to avoid are numerous. For example it is impossible to drill while the Lander body is rotating around its z axis and some activities (like SESAME) may be disturbed by mechanical activities.

On the other side some co-activities are expected as SESAME CASSE listening to the hammering of MUPUS experiment.

Some experiments may also require a visibility between Orbiter and Lander (ex: clock tuning CONSERT) or should be close to a RF link because a huge amount of data was expected to be generated (imaging for example). Moreover a soil sampling shall be performed for obvious reason before any sample analysis so SD2 activities are for sure before COSAC GC-MS, PTOLEMY GC-MS and CIVA MI.

The instruments' tests during the cruise allowed determining the incompatibilities and possible co-activities.

Mechanical activities and prerequisites

The body of PHILAE should have rested on three legs with ice screws once the landing gear deployed on the comet's surface. So the orientation had to be determined (based on the housekeeping telemetry from the landing gear) before any mechanical activity on the surface of the comet. Indeed all experiments requiring a deployment (SD2, MUPUS and APXS) had to know the position of the landing gear versus the main body to be sure that legs won't disturb.

It was also important to provide a slot for landing gear activity before any drill to block it and ensure that no obstacle would be under the drill.

Finally it was important to improve the energy potentially produced by solar panels before the end of FSS by placing the balcony in the shadow. That's the reason why the attitude (position of the main body regarding the Sun) had to be determined from Lander telemetry and CIVA-ROLIS images after touchdown.

These mechanical prerequisites and constraints were one of the main driver for the science scheduling and order or experiments.

Power

For the SDL & FSS phases the Lander main sources of energy were the primary and secondary batteries. The level of charge of the primary battery couldn't be monitored but the expected amount of energy was around 1350 Wh. Due to the severe constraints in terms of energy it was impossible to introduce waiting times into the FSS sequence dedicated to real time analysis or decision point. Any waiting time with no instrument activity would have meant science lost.

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. Indeed the expected amount of energy was largely undersized compared to the ambitious science plan.

Data/Mass memory and RF link

As it was soon established that a cometo-stationary orbit was not possible for Rosetta to ensure permanent Lander/ Orbiter visibilities and because the size of Philae mass memory (MM) was only 4Mb, data management was considered as the main constraint for the scheduling itself. Indeed the MM capacity was insufficient regarding the amount of data generated by the experiments and the instruments memories (IM) themselves was too small to cope with the instrument's productions. Moreover the Lander main processor was also limited in the data transfer from instrument to the Mass Memory with data rate depending on the number and type of instruments ON simultaneously and defined priorities.

It was critical to empty the memory at the beginning of the FSS so a visibility was mandatory after the touchdown to transfer most of data collected during descent (7 hours long!). 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.

III. SCIENCE SCHEDULING TOOL DESIGNED FOR PHILAE

The scheduling of scientific measurements for the different phases of Philae mission has 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 by SAM team is called a science sequence. At least one sequence had to be prepared per mission phase.

Mission Operations Scheduling Tool (MOST)

MOST, an under constraint programming software in C++ using ILOG libraries was specifically designed for PHILAE mission. A feasible plan generated shall satisfy a number of constraints induced by energetic resources, data management, and precedence relations on activities, or incompatibility between instruments.

Data management and Power models

To be as close as possible to the real Lander behavior a lot of parameters at Lander and Orbiter levels have to be described and modeled precisely: energy consumption profiles of each unit (instruments including sub-instruments in all modes, subsystems in all modes), data management priorities, data storage in mass memory and dedicated instruments memories, …

The synthetic models for experiments developed in the tool are representative of the power peaks and the results respected the Lander breaker limits.

Moreover, a very important aspect of MOST tools is to simulate the onboard data management process to compute the necessary transfers (to the orbiter then to Earth) of all the science data produced by the instruments. Each experiments on board has its own memory (IM) shared by its activities and collecting data in the course of their production. These data are transferred to a central mass memory (MM) then transmitted to the Orbiter when it is in visibility. All transfers from experiments to the mass memory and from mass memory to the Orbiter are executed by the Command and Data Management System (CDMS).

Each instrument was previously assigned a dedicated allocation in mass memory and a dedicated priority for a dedicated period of activity. Then MOST software was representative of the complex data management. One goal of the scheduling is to ensure that data-producing activities are planned in such a way that no data would be lost.

Operations preparation: sequences scheduling

Inputs

A set of specific inputs was expected before any scheduling task:

- Descent duration
- Orbital context file with day/night cycle, visibilities between Orbiter and Lander
- Operation requests from the lander instruments teams (activities, power consumption and data production expected)
- Power available or estimated for the sequence
- Priority for each active experiment for data management

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 to display data transmitted to the orbiter for each orbiter/lander visibility
- a mass memory management synthesis to display the consumption/production versus time in the mass memory
- the residual energy at the end of the sequence scheduled
- a timeline

IV. SCIENCE PLAN PREPARED

Prepared sequence: details

The baseline scenario defined for the FSS was a sequence of 4 activity blocks described here below in figure 4. Each block combined in an optimized way a few instrument activities. 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.

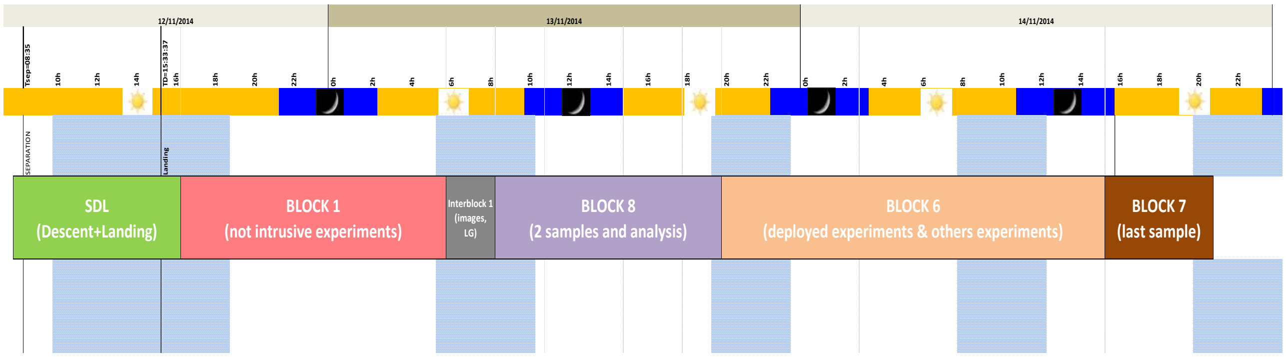


Fig. 4: Prepared sequence for FSS on PHILAE lander: general blocks vs day/night and RF links.

First science block (Block 1)

The first block (Fig.5) was designed to be the continuation of the descent sequence run autonomously at the end of it. It includes CONSERT – ROMAP, MUPUS, CIVA, ROLIS activities and sniffing modes for PTO and COS but most of the experiments are already switched ON before the separation or during the descent.

The aim of the first block was to get results without any prerequisites on the landing status to save energy. So 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 without impacting the block structure itself.

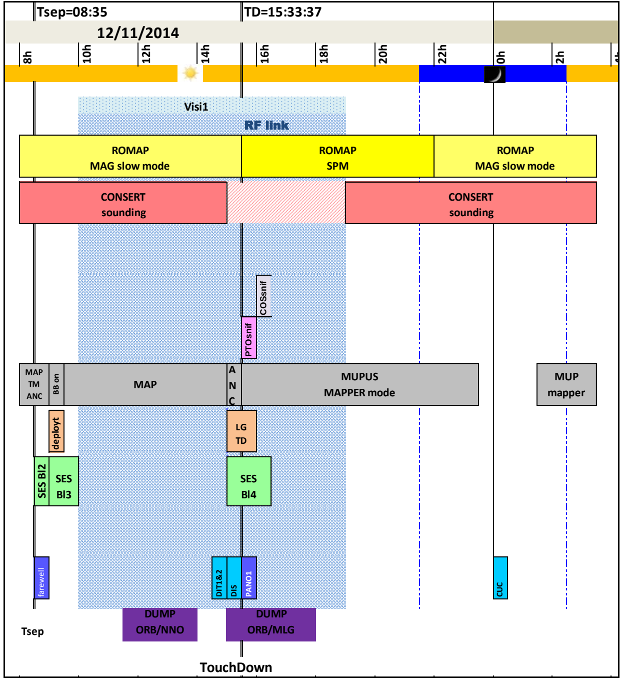


Fig. 5: Schematic view of the first FSS block prepared on PHILAE lander.

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

CONSERT was also switched on before separation and 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 duration in SDL/block 1 was linked to the context and the beginning of MUPUS was relative to touchdown. The experiment was also switched off during CONSERT operation

The first imaging activities after the landing (CIVA and ROLIS) were linked to day/night cycle. So the scheduling wasn't frozen until the landing site, the landing time and trajectory were determined. Note that a first set of CIVA-P 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 surrounding.

It is important to note that sniffing activities (so 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 ops request, all science activities in this first block except ROLIS had to be stopped at the same time in visibility and with a impact on the next block's beginning. So activities' duration had to be updated 15days 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.

Inter-block between first and second blocks

The first visibility after the landing one was critical to retrieve images of the landing area and to prepare the Lander 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.6) with LG activities and panoramas combined as independent items or modules to be performed or not.

The philosophy was to schedule as many cancellable panoramas as possible because inserting an activity was too complex for ops team. The only remaining issue was the data volume in case of shortened visibilities. Indeed the post-landing status and location was not known in advance but CIVA-Panoramas had to be scheduled during visibilities and the RF link at the beginning of the second block should be long enough to transfer all CIVA-P images.

Landing gear (LG) activities were composed of 4 sub-parts: Up, Rotation, Lowering and blocking. The first landing gear slot was scheduled before the second FSS block (so before the first SD2 drilling activities). The aim of this was to rotate the body to optimize the solar power during the next mission phase 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. Note that in any cases it was mandatory to block the landing gear before any mechanical activity.

If the landing gear position would have been an obstacle for SD2 activities or if MUPUS was already able to determine a suitable deployment zone this rotation could have taken these constraints into account. As a consequence the Lander attitude and orientation had to be determined before the following block.

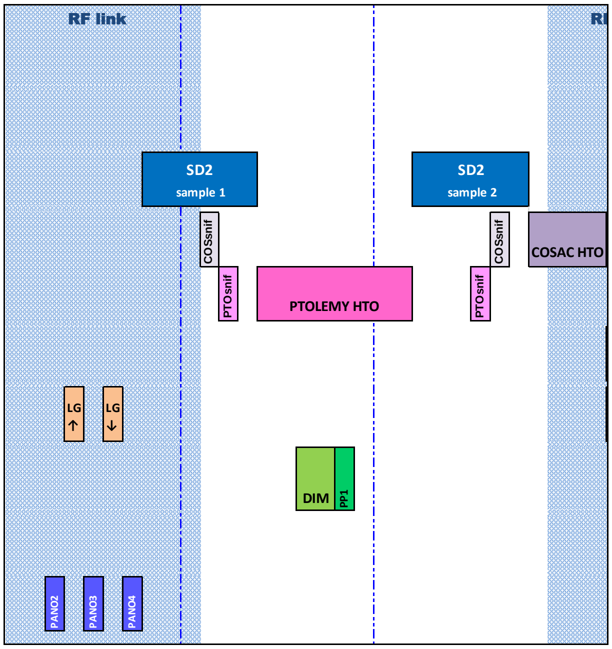


Fig. 6: Inter-block and Second block prepared for FSS on PHILAE lander.

Second science block (Block 8)

The second block of FSS is mainly composed of the SD2 drilling and sample retrievals dedicated to PTOLEMY and COSAC experiment (with high temperature ovens). This activity was one of the main objective of the mission but also one of the most expensive (power speaking) so it was decided to scheduled it as soon as possible to ensure its feasibility from a power point of view but long enough after the landing to be sure of the context.

As well as after the touchdown some sniffing modes were scheduled in case the drill would lift some dust from the comet soil.

Some SESAME DIM and PP activities had also to be scheduled in this block. Indeed DIM should be repeated 4 times so the positioning had to be updated once the day/night cycle at the real landing site will be known. As it was really difficult to find 4 times a day suitable positions for DIM without any risk of disturbance and at the right moments the scheduling had to be revised with the scientists.

The hard point for this block was to adapt the schedule once the orbital context is known to end the block and especially COSAC analysis during a visibility to secure the data management. Indeed it was impossible to predict the data volume associated to the spectra produced during this block.

Third science block (Block 6)

The third block (Fig.7) is mainly dedicated to experiments to be deployed as MUPUS and APXS. These are more risky activities with a critical need of preliminary analysis) so scheduled later in the sequence.

A second Landing gear slot is scheduled at the beginning of the third FSS block (after SD2 activities but before MUPUS deployment).

The aim is at least the lift of the Landing gear to allow MUPUS deployment while LG is in up position. But it may also include a potential rotation to select a suitable deployment zone for MUPUS in agreement with the LTS solar illumination and APXS deployment needs. Anyway if the targeted body orientation is not compatible with APXS deployment a third rotation slot is provided before APXS activity.

The MUPUS deployment of PEN 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).

APXS experiment was scheduled as soon as possible in parallel of MUPUS, to save energy and optimized the sequence, but deployment and retracting movements of APXS are quite long (almost 3 hours for maximum extension) so the measurement had to be reworked to fit in the assessed duration. Due to the lengthy of this block APXS data couldn't be fully retrieved during the fourth visibility but everything was done to get at least partially data in case the battery were emptied 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 into this third block to fulfil the 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.

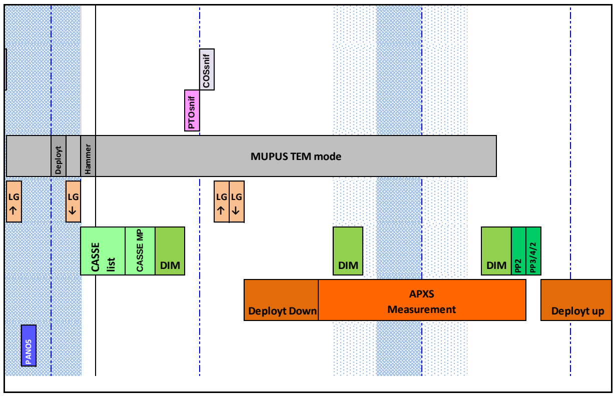


Fig. 7: Third block prepared for FSS on PHILAE lander.

Last science block (Block 7)

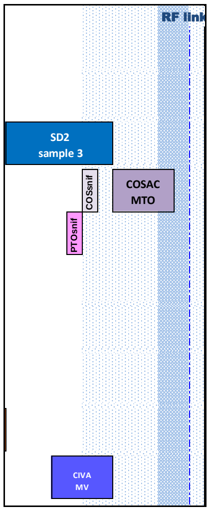


Fig. 8: Last block prepared for FSS on PHILAE lander.

The last block detailed on figure 8 had only a few chances to be doable based on the power assessed in the primary battery. But we had anyway to be prepared not to lose a unique opportunity to complete all the science objectives defined for FSS phase. This last block includes a last drilling to retrieve a soil sample to be analysed by COSAC (so for the first time in medium temperature oven) and imaged by CIVA MV experiment.

Complexity and adaptability

Considering all the constraints previously mentioned it was hard to find a suitable and optimized sequence to optimize the science return with taking care of all the constraints and resources. The combination proposed was the optimized one and extensively tested by LCC ops team before implementation. Once the landing scenario was better known only a few adjustments were possible but had to be done: adjustments of the timeline (and experiments slots) to the most likely visibilities and day/night cycle. Moreover to ensure the mandatory flexibility in such an unpredictable context, we had to determine the key parameters to take care and some adaptations or back-up plans. Even if the blocks were designed to face the expected modifications on the timeline, soon we have realized that the mission was risky and very constrained. So it was mandatory to be prepared to a contingency scenario and be able to "save" as much science as possible through the so-called safe block.

Safe block

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

V. 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 team was involved in the landing site selection process (LSSP). At each milestone (detailed in table1) it was important to evaluate the impacts of the potential sites on the science sequence, assess the robustness of the proposed plan and eventually tune the scheduling to optimize the science as well as the power and data management.

Objectives	Days to Landing	Date	Dist.
Selection of 5 candidate landing sites.	L-79	24/08/2014	50 km
Selection of the nominal and backup landing.	L-58	14/09/2014	30 km
Confirmation of the nominal landing site.	L-30	12/10/2014	10 km

Table 1 : LSSP milestones

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. 9). An exhaustive search was initially performed for points with a satisfying illumination to find acceptable landing trajectories (suitable with Orbiter delivery orbit and lander descent trajectory technical constraints).

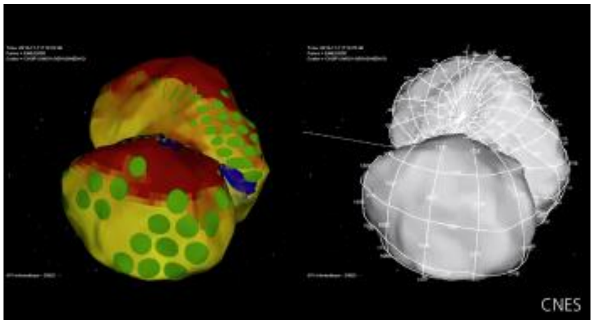


Fig.9: Comet 67-P model and locations of the pre-selected candidate sites (mid-august 2014).

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

At this point SAM 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 hours daylight duration and more than 30 minutes of night). It represented only a rather small part of the comet surface.

First loop: 5 sites assessment

A two-days meeting was held in CNES Toulouse on 23rd and 24th August during which the different technical criteria were presented (flight dynamics, Lander ops and science sequence). The scientific interest of the 10 landing sites were also considered to finally choose the 5 candidate landing sites showed on figure 10 (called A, B, C, I and J).

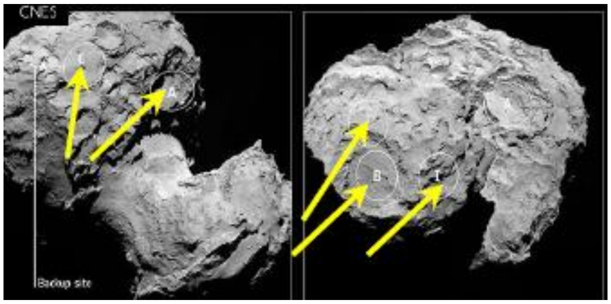


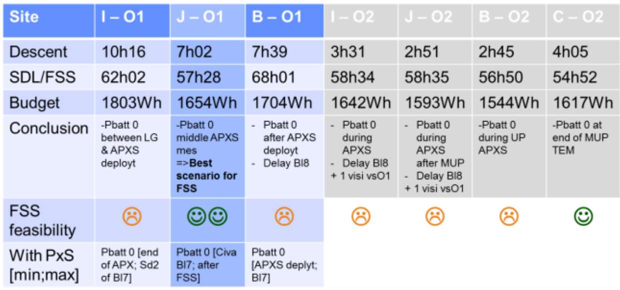
Fig.10: Comet 67-P pictures (OSIRIS) and locations of the 5 sites selected during LSSP process.

Then RMOC provided back 15 days later the operational feasibility analysis and the corresponding trajectory for the two pre-defined scenario strategies and SONC FD provided as inputs for a further analysis by SAM team the associated patterns (day/night dispersion, visibilities and variability).

Context variability: impacts on the plan

The 5 selected sites and particularly their impacts on the science sequence possible once landed were analysed and compared to help the science community to pick their 2 preferred ones. A large set of potential and dimensioning orbital event files (OEF: day, night, visibilities and descent durations…) were used as inputs for MOST runs. The assessment from SAM team is shown on table 2 based one several criteria:

- Main criterion: exhaustion of primary battery the latest in the science sequence
- Additional ones:
    - data retrieved the soonest at the end of FSS
    - low risk of ending FSS during mechanical activities (to end FSS in a safe state)



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]				

Table 2: Assessment of the 5 sites from the science sequence point of view (no safe trajectory for site A so only 4 sites left).

This study demonstrated that descent duration was not the only driver for SDL/FSS feasibility. Indeed, unexpectedly, the visibility pattern also impacts a lot the instruments scheduling so power consumption.

For example, a permanent RF link during the whole descent visibility as requested by the ops team (roughly 6h) could be very useful but increases the consumption for site J: 66Wh more so 3h less for FSS.

Nevertheless none of the reachable/selected sites provided a context ensuring a complete feasibility of the third block (MUPUS, APXS) with PBatt only. The estimated ends of sequence (baseline prepared) for the different sites if not supported by solar power are marked (red and purple lines) on figure 11 below.

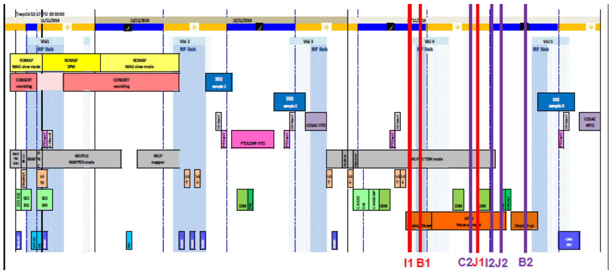


Fig.11: Potential landing sites assessment during LSSP and impacts on SDL/FSS sequence.

So whatever the final site solar power would be critical for the mission.

The opportunity of communication between Orbiter and Lander during the Long Term Science (LTS) phase, from December to March was also studied taking into account the LTS orbit for Rosetta and taken into account in the final ranking.

Nominal and Back-up sites

For each site the variability of the visibilities pattern was studied in order to select the more homogeneous site and the more suitable. All impacts were assessed with the help of MOST tools.

Data management associated to the site RF visibilities (including dispersions) was studied to ensure that the memory could never be full and loose science data (Fig.12).

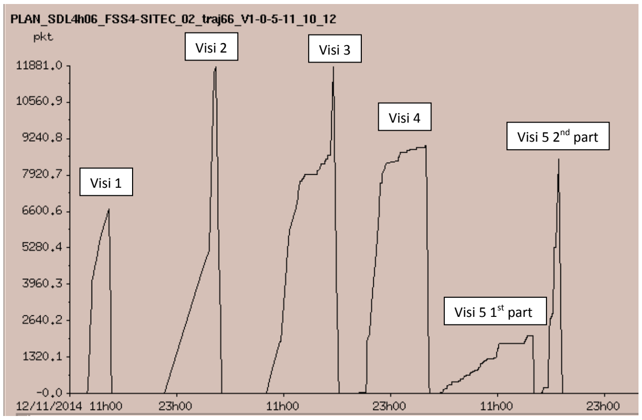


Fig.12: Data management analysis during LSSP assessment of site J.

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 figure 13 shows that the main criterion was the time frame between touchdown and the second visibility: the favorable case for science being when the delay is the shorter.

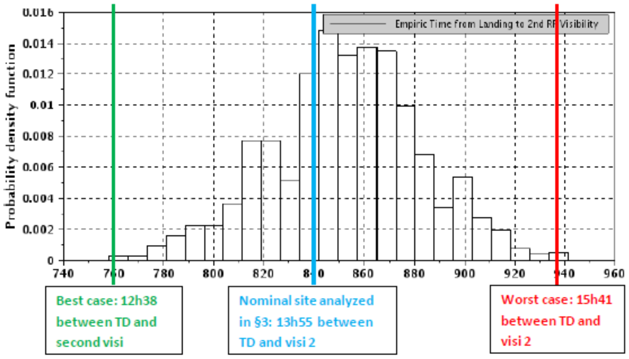


Fig.13: Visibility pattern analysis (and impacts on SDL/FSS sequence) during LSSP assessment of landing area J.

Finally 13th and 14th September a two-day LSSP meeting was held in CNES Toulouse to decide for the final ranking. 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 (located on picture 14) was finally chosen as the nominal landing site and site C as the backup landing site.

Delivery date

Then ESOC announced that Lander delivery will occur on 12th November 2014 afternoon instead of 11th November morning as stated before. So the complete analysis had to be redone by SONC and the science sequence had to be adapted.

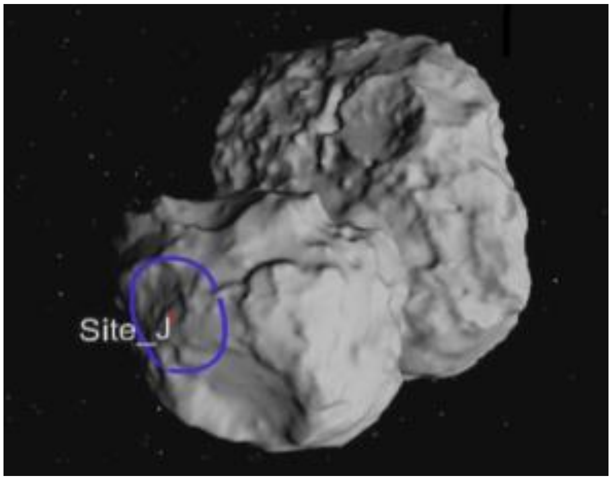


Fig.14: Comet 67-P model and location of the selected nominal landing site called AGILKIA (initially J).

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

So solar power was more and more mandatory to allow the 3rd block achievement (in some cases it cannot be achieved even with solar power).

However updated OEF file didn't show a huge impact on day/night cycles so 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.

VI. OPERATIONS

Once the landing site is selected:

As many activities of Block1 are implemented and uploaded regarding orbital events from the nominal OEF, a different landing location inside the ellipse will impact the synchronization of these activities. (Examples: CONSERT pause, MUPUS pause, CUC position vs night)

Moreover SESAME activities that could be impacted by a landing elsewhere might be re-scheduled during operations once we know where we have landed.

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

The final baseline updated once the landing site was selected is schematically given in figure 14 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 for including the Lander system activities and encoding the commands

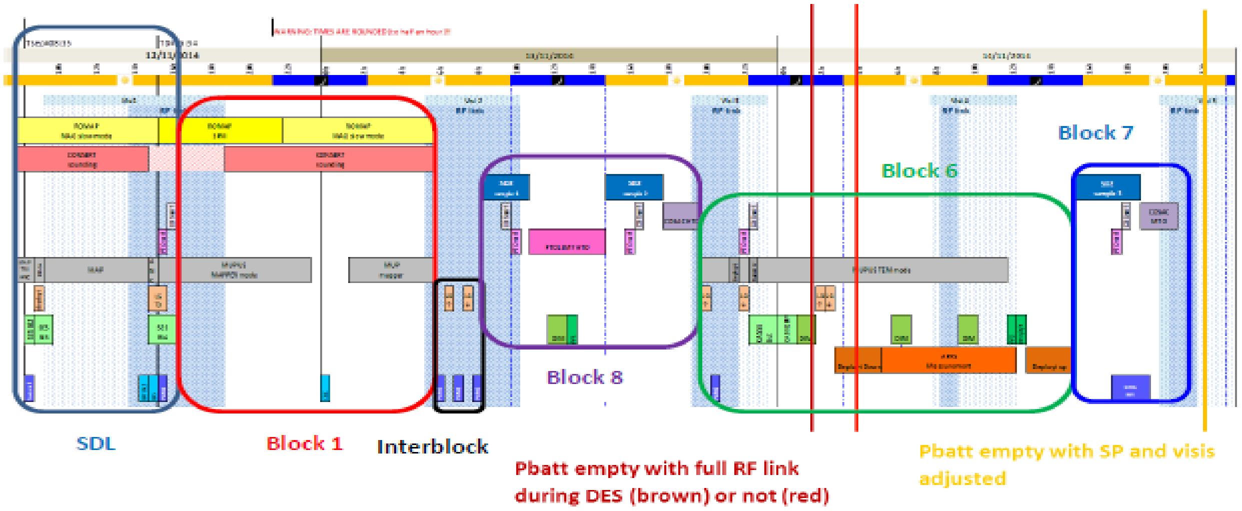


Fig.14: Schematic sequence designed for SDL/FSS and adapted to the nominal landing site selected after LSSP. (1st vertical red line is the expected end of power with Pbatt only and the 2nd is the one including solar power).

On comet phase: Team organisation

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 ops team in charge of the Lander commanding. Decisional meetings were held at LCC but in close loop with the rest of SAM team located at SONC (Toulouse). Indeed our modelling tool, data servers and flight dynamics team had to stay in our facilities. To ease SONC engineers to follow operations a CNES tool customized to monitor instruments on Philae was also used.

Performed sequence

On the 12th of November 2014 a GO Lander is given by the Lander authority and the Rosetta delivered nominally Philae at 08h35 for its long descent toward the comet 67P. The link was correctly established during the descent and all instruments scheduled during its 7h duration. This SDL sequence produced the wonderful and now famous images taken by CIVA of the orbiter and by ROLIS of the approaching surface.

First visibility

Despite the Lander was healthy and followed perfectly the expected trajectory, once the touchdown is confirmed at 15h34 it was soon detected that Philae was not anchored to the soil. So the first CIVA panorama the operational team was eager to get was taken while Philae is up in the air so unusable and prevented the Lander for starting the next block and following the prepared science sequence.

At the end of the first visibility the strange behaviour of the Lander and the first corrupted images received couldn't be explained. It was unconceivable to follow blindly the prepared FSS. All the science team involved in the first block of activity were participating to a brainstorming based on their preliminary data to understand the situation while the ops team including SAM team had to decide the science activities to be commanded on-board. Indeed the power delivered by the primary battery would have been wasted if no science engaged.

Second visibility

The only choice regarding the unknown landing situation 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. Then the most efficient block possible to get science data without endanger the lander was the safe block. It was the extra-block designed by SONC and already tested at LCC, ready to be commanded and it had to be repeated 4 times to cover the estimated but unconfirmed inter-visibility period. So during the second visibility these following activities were uploaded and data from the 1st block were received. The set of data included an amazing 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 was stabilized the sun light could rarely illuminated Philae (much less than expected on Agilkia). Nevertheless the CIVA panorama scheduled during the inter-block was fortunately able to be taken during the 1.5 hour of the comet day!

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

Third visibility

Then 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 we had to postpone the expected following block with SD2 activity combined with COSAC and PTOLEMY high temperature analysis. In order to take advantage of the available power a customized block was then designed from the former third one including MUPUS, 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 Philae location. And because the block had to be completed before the visibility used to retrieve data APXS was also shortened.

At each visibility a power assessment was done using MOST tool and prepared models for performed 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.

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. So it was decided in agreement with the ops team and the whole community to give a try to SD2 combined with only one instrument. Due to the power assessment it was impossible to command the complete second block skipped at the beginning of the sequence. So a hard discussion was initiated to select either COSAC or PTOLEMY after the drill. It was important to use commands already on board and because COSAC was the shorter experiment it was decided to run it but reduced to only one temperature step. However PTOLEMY sniffing was kept and it was proposed to prepare another PTOLEMY activity for the end of the sequence if power available (CASE easier than high temperature analysis because without a drill).

Last visibility

Between 4th and 5th visibility the Lander was left in stand-by mode after the re-shuffled second block to save the few energy still available and last activities on the comet had to be selected.

The proposed plan included:

- A lander rotation to increase the chances to be able to exit hibernation by placing the biggest solar panel to the sun to retrieve a maximum power. At this moment only 3.5W were produced whereas 5.5W are necessary to boot the lander and start a charge cycle of the secondary battery.
- A last image ROLIS (in addition to first retrieved during the 2nd visibility) to get more information on the landing site before hibernation. CIVA was not an option because it would be night.
- A SD2 carousel rotation then PTOLEMY CASE (re-use from pre-delivery and calibration phase) to give a chance to Ptolemy to have more science data.
- CONSERT ranging till the end to help the a posteriori localization of Philae.

Finally during the fifth visibility between Philae and Rosetta, we saw the primary battery depletion just after the end of the prepared activities at 0h05 on the 15th of November. That demonstrated that the battery behaviour was nominal and exactly as expected. Each instrument involved in the first science sequence had a chance to retrieve science data and despite a not nominal landing the sequence was a huge success.

The first science sequence lasted 64 hours against 63h for the prepared one.

The performed sequence detailed on Figure15 seems to be very different from the prepared one at first sight but it is in fact very similar. All 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 long activity which structure allowed doing so. The skeletons remained the same so were the prepared models used to assess the available power at each visibility.

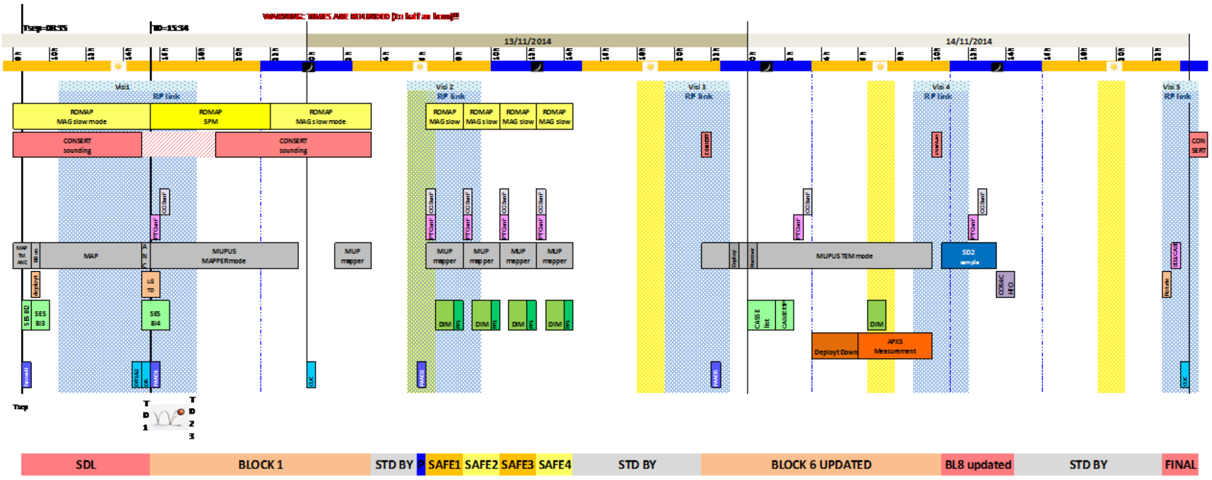


Fig.15: Schematic sequence performed during SDL/FSS and adapted after the non-nominal landing.

VII. CONCLUSION AND LESSONS LEARNED

Even a successful mission like Philae needs to be followed by a lessons learned exercise to enlighten the concepts to be kept in mind for the future:

- Tests and rehearsal with the whole community are mandatory especially when numerous partners and locations are involved
- The ops loop driven by Philae design with GO given in visibility and a complex mass memory management was hardly consistent with an optimized science planning
- Scheduling tools and models to assess power and data necessary in such an unpredictable context but the right level of details has to be found to satisfy the need with being flexible. They have to be remotely usable to simplify the process.
- Flexibility is necessary if no real-time interactions are possible and the environment is unknown. A detailed commands library and much more instruments tests could have been useful.
- co-location of the people involved in operations is necessary (especially if no rehearsal)

When it comes to space exploration the key word is the unforeseen and as a consequence operations have to be 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 critical for Philae.

Such a complex plan was difficult to design due to the specific context of the Rosetta/Philae mission (complexity, duration, limited resources…). And as always such a success could only be possible with a close collaboration between the teams and adapted processes and tools.

VIII. ACKNOWLEDGEMENTS

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