ARTICLE IN PRESS

Acta Astronautica ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/aa

The CONSERT operations planning process for the Rosetta mission

Yves Rogez [a,g,*], Pascal Puget [a,g], Sonia Zine [a,g], Alain Hérique [a,g], Wlodek Kofman [a,g], Nicolas Altobelli [b], Mike Ashman [b], Maud Barthélémy [b], Jens Biele [e], Alejandro Blazquez [c], Carlos M. Casas [d], Marc Costa Sitjà [b], Cédric Delmas [c], Cinzia Fantinati [e], Jean-François Fronton [c], Bernhard Geiger [b], Koen Geurts [e], Björn Grieger [b], Ronny Hahnel [f], Raymond Hoofs [b], Armelle Hubault [d], Eric Jurado [c], Michael Küppers [b], Michael Maibaum [e], Aurélie Moussi-Souffys [c], Pablo Muñoz [d], Laurence O'Rourke [b], Brigitte Pätz [e], Dirk Plettemeier [f], Stephan Ulamec [e], Claire Vallat [b]

[a] *Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France*
[b] *European Space Astronomy Centre/European Space Agency, PO. Box 78, 28691 Villanueva de la Cañada, Spain*
[c] *Centre Nationald'Etudes Spatiales (CNES), 18 av. E. Belin, 31401 Toulouse, France*
[d] *European Space Operation Centre/European Space Agency, Germany ESOC/ESA, Germany*
[e] *Deutsches Zentrum für Luft und Raumfahrt. DLR-RB/MUSC, 51147 Cologne, Germany*
[f] *Technische Universitaet Dresden, Helmholtzstraße 10, d-01069 Dresden, Germany*
[g] *CNRS, IPAG, F-38000 Grenoble, France*

ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form
1 February 2016
Accepted 11 March 2016

Keywords:
Rosetta
Philae
CONSERT
Operation
Planning
Method

ABSTRACT

The COmet Nucleus Sounding Experiment by Radio wave Transmission (CONSERT / Rosetta) has been designed to sound the interior of the comet 67P/Churyumov-Gerasimenko. This instrument consists of two parts: one onboard Rosetta and the other one onboard Philae. A good CONSERT science measurement sequence requires joint operations of both spacecrafts in a relevant geometry. The geometric constraints to be fulfilled involve the position and the orientation of both Rosetta and Philae. At the moment of planning the post-landing and long-term science operations for Rosetta instruments, the actual comet shape and the landing location remained largely unknown. In addition, the necessity of combining operations of Rosetta spacecraft and Philae spacecraft makes the planning process for CONSERT particularly complex.

In this paper, we present the specific methods and tools we developed, in close collaboration with the mission and the science operation teams for both Rosetta and Philae, to identify, rank and plan the operations for CONSERT science measurements. The presented methods could be applied to other missions involving joint operations between two platforms, on a complex shaped object.

1. Introduction

The COmet Nucleus Sounding Experiment by Radio wave Transmission (CONSERT) instrument onboard the European Space Agency spacecraft Rosetta and Philae, is a radar designed to study the internal structure of the nucleus of the comet Churyumov-Gerasimenko (67P/C-G). It uses measurements of electromagnetic propagation between the Philae lander, fixed on the comet"s surface, and the Rosetta orbiter [1]. Measurements give the propagation delay and the signal amplitude for each trajectory. During data acquisition, the propagation delay and geometry are used to calculate the additional delay caused by propagation through the nucleus. This additional delay is directly related to the dielectric permittivity of the medium that is traversed and can be used to identify the electrical properties of the material found in the comet nucleus. At the same time, absorption can be derived from the radiowave path loss as the signal propagates through the nucleus; this makes it possible to identify the class of refractory materials found in the nucleus. For each acquisition (a sounding), the signal is transmitted in all directions by the CONSERT unit onboard Philae (LCN). The part of the signal that is penetrating inside the nucleus is the one of interest for scientific purposes. Thanks to electromagnetic coupling between the lander CONSERT antennas and the near subsurface material, most of the energy radiated by the CONSERT antenna penetrates into the comet nucleus. The signal wavefront travels through the nucleus before reaching the surface again. At that point, one part of it is transmitted in the

---

[*] Corresponding author at: CNRS, IPAG, F-38000 Grenoble, France.
E-mail address: yves.rogez@obs.ujf-grenoble.fr (Y. Rogez).

http://dx.doi.org/10.1016/j.actaastro.2016.03.010

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

vacuum and the other one is reflected back into the nucleus. Depending on the incidence angle of the wave and the surface normal, total reflections can occur. In that case, no wavefront is transmitted through the surface. The part which goes out from the nucleus propagates in the coma. We consider the permittivity of its medium practically equal to 1, due to its very low density and low level of ionization. Finally, the wavefronts cross the Rosetta trajectory. The CONSERT unit onboard Rosetta (OCN) receives several wavefronts, with different propagation delays and different energies. When passing a dielectric interface, the wavefront is separated into a transmitted wavefront, which keeps about 95% of the incident energy, and a reflected one. By regard to the incidence angle when reaching the surface, the wavefront can also perform a total reflection; in this case all the wavefront energy is passed to the reflected one. Total reflections represent a small wavefront extension that could be neglected for operational analyzes. That's why for CONSERT science we focus only on the wavefront that performs transmissions through the comet surface. We can observe that the comet nucleus focuses this wavefront. We call it the main wavefront and it constitutes the signal of interest for CONSERT. Wavefronts that perform only one reflection are called the secondary wavefront. Wavefronts that perform more than one reflection inside the nucleus are considered as almost undetectable in CONSERT science signal (Fig. 1).

Thus, compiling all the measurement points on a segment of Rosetta trajectory line, we sound a slice of the comet nucleus. Furthermore, combining numerous slices from different Rosetta orbit segments, we can perform a tomography of the nucleus. Great emphasis is placed on obtaining good measurements of the mean dielectric properties and on the detection of large size embedded structures or small irregularities within the comet nucleus. For further details on CONSERT science, please refer to [2,4]. Taking data from various Rosetta orbit segments is the main goal of the CONSERT operations during the Long-Term Science (LTS) phase of the mission. The final landing site location, local topography and orientation of Philae were unknown during the preparatory phase of the LTS, several months before their execution. However, operation methods were designed and tested during the two years before the landing to prepare the CONSERT science sequences (from end of year 2012 to November 2014).

This paper describes the specific methods and tools we have developed to achieve CONSERT operations in this context, for the LTS period; nominally from end of November 2015 to end of January 2016. More generally, it is intended to provide indications and experience feedback for any mission to a complex shape body object involving an instrument with joint operation of an orbiter and a lander.

2. The CONSERT instrument

The CONSERT experiment consists of a rough tomography of the comet nucleus performed by the instrument. It works as a time domain transponder between the lander unit and the orbiter unit. Basically, a 90 MHz sinusoidal waveform is phase modulated by a pseudorandom code or Phase Shift Keying Coding. Such frequency, in the radio range, is a trade-off between the losses during the propagation inside the comet material, the galactic noise, the bandwidth and the size of the antenna. The basic measurement for CONSERT is the time delay along the propagation path between Philae and Rosetta. To retrieve valuable information on comet interior dielectric properties, this time measurement precision has to be better than 0.1 μsec, which leads to very high constraints in terms of clock frequency stability ($\Delta f/f = 10^{-12}$) for both lander and

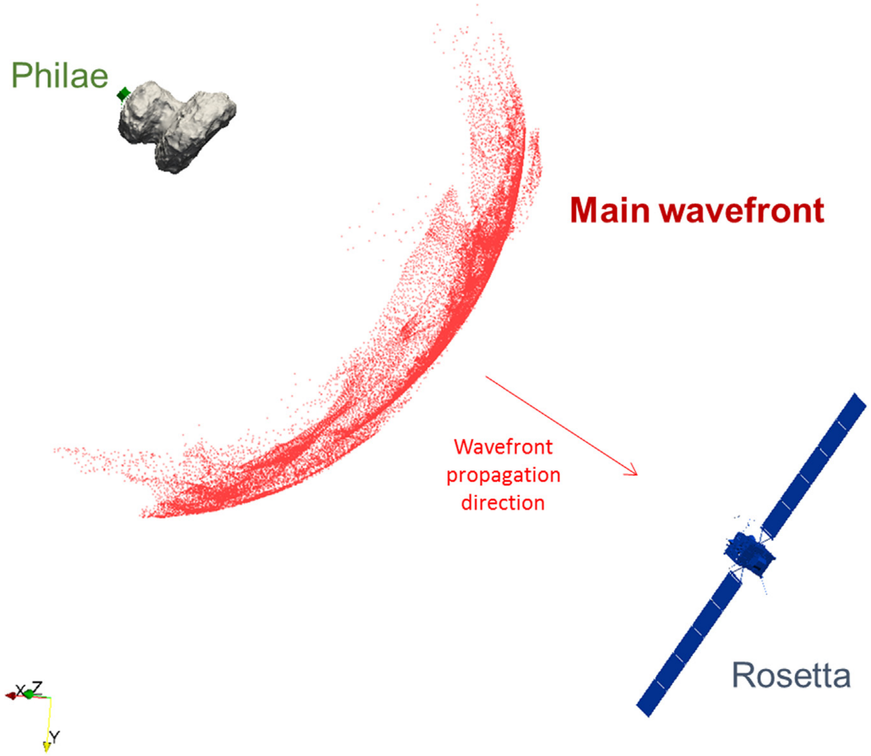


Fig. 1. Constraint on Philae and Rosetta relative position. The main wavefront that traveled through the comet nucleus is represented by the red points cloud. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

orbiter parts, as well as precise synchronization between clocks. This stability has to be assured during a complete CONSERT operation sequence: with margins, the required duration is 10 h. This hard constraint is relaxed thanks to the transponder structure of the instrument. For each sounding, a first wave propagation is transmitted from OCN to LCN to synchronize the two devices. The signal is then mirrored by LCN to OCN in a second wave, along the exact same propagation path to perform the actual science measurement. This requires a tuning phase at the beginning of the CONSERT sequence. The purpose of this phase is to synchronize the clocks of lander and orbiter CONSERT units by adjusting in frequency with $\Delta f/f < 10^{-7}$ and in time with Δt less than a few ms. The actual stability on the clocks is valid during 30 h (Fig. 2) [3]. In practice, this is achieved with stabilized oven controlled crystal oscillator Sorep EWOS513 [5].

After the tuning phase, during the sounding phase, the two units work autonomously until the end of the sequence. For a single measurement point in this sequence, the sounding cycle is: OCN transmits the signal and LCN listens and then LCN receives the signal, processes it and transmits a new signal back when OCN listens. To improve the signal to noise ratio, OCN and LCN units actually listen 1024 signals and perform a coherent integration in addition to the signal compression. This "ping-pong" cycle is repeated typically every 2.5 s. A complete CONSERT operation sequence is composed of the following phases (Fig. 3):

- **Warming up:** the instrument needs some time to obtain the right functioning temperature allowing the appropriate clock stabilization.
- **Tuning:** this critical phase, mandatory after the warming up, needs a direct signal between orbiter and lander allowing to match the frequency of both clocks and to synchronize both calendars.
- **Waiting:** as the instrument is ready to work, it waits until occultation between lander and orbiter, to perform the science measurements.
- **Science sounding:** during this phase the signal between orbiter and lander needs to go through the comet nucleus. As each individual sounding (typically every few seconds) gives only information integrated along the ray, the most efficient observation will need to cross as much as possible of the comet section. In addition, observations at grazing angles allow obtaining information on the roughness and layering at ground level.

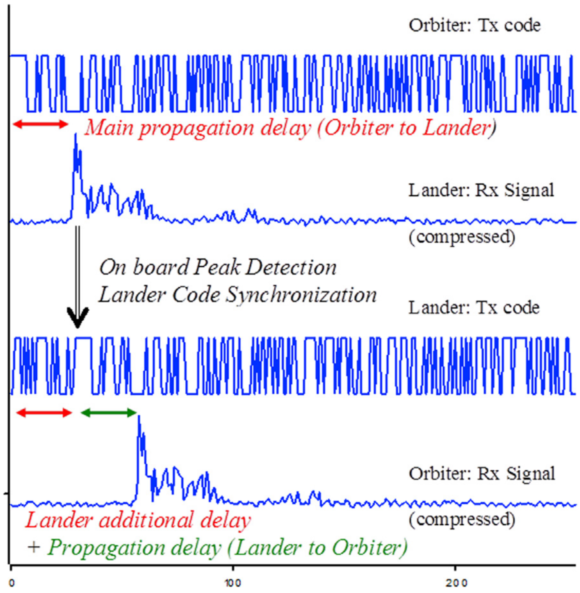


Fig. 2. Lander synchronization principle [3].

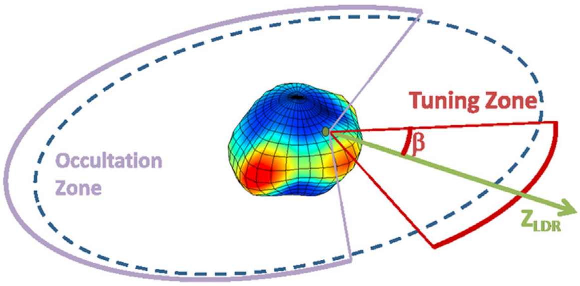


Fig. 3. CONSERT science sequence. Rosetta orbit is shown by the blue dashes. Lander Z axis (Z_{LDR}) vector shows the lander 'up' axis and position. Warm-up and tuning occur when Rosetta and Philae are in visibility, in the tuning zone (red), science sounding in the occultation zone (purple). Calibration takes place just after exiting the occultation zone. As a remark, this picture presents the preliminary shape model that was used before Rosetta arrived to 67P/C-G. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In addition a **calibration** might be done, optionally, in continuity after the science sounding; these measurements will allow a better processing of the CONSERT science data. By acquiring the signal during the visibility period, just next to the science measurement phase, we can evaluate the Lander additional delay (Fig. 2) with comparable thermal and measurement conditions as the sounding. It is useful also to characterize the current noise background at acquisition time.

Finally, in order for the different CONSERT operation phases to be synchronized between lander and orbiter units, the time references between OCN (from Orbiter On Board Time) and LCN (from Lander On Board Time) must not differ by more than 20 s at the beginning of operations. LCN and OCN shall be turned ON with a time accuracy of $\pm$ 10 s by regard to the absolute time reference.

The amplitude of the received signal is also determined by the CONSERT antenna properties: each CONSERT unit on lander and orbiter has its own antenna system with its gain and polarization properties.

The antenna system on Philae consists of two orthogonal orientated monopoles located in the x-y-plane. Fig. 4B shows the accommodation of the orthogonal oriented monopoles on the lander. Each rod has a length of 700 mm, a diameter of 5 mm and is matched to a 50 Ω coaxial cable. One monopole is fed with a phase shift of 90° in order to generate a left hand elliptic polarized (LHEP) wave towards ground whereas a right hand elliptic polarized wave is radiated in the upper hemisphere. The radiation diagrams of Philae above the surface are shown in Fig. 5 for the center frequency of 90 MHz in two perpendicular planes. On the OCN two pairs of two crossed dipoles with a length of 1.525 m are used to provide a LHEP wave (Fig. 4A). One pair consists of two active elements whereas the other one is passive and serves as reflector. The active cross is driven by two orthogonal signals, which results in a LHEP wave that is propagating towards $+Z$ with regard to Fig. 4A. In this direction the antenna achieves a realized gain (LHEP) of approx. 3.6 dBi at a frequency of 90 MHz. Radiation patterns at 90 MHz center frequency are given in Fig. 6 for two orthogonal planes.

Due to coupling with ground, landing gear and central body of Philae and due to coupling with solar panels, High Gain Antenna and spacecraft body aboard the Rosetta orbiter both antenna systems don't generate pure circular polarized waves. The different axial ratios of transmitter and receiver lead to polarization losses depending on the relative orientation between Philae and

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

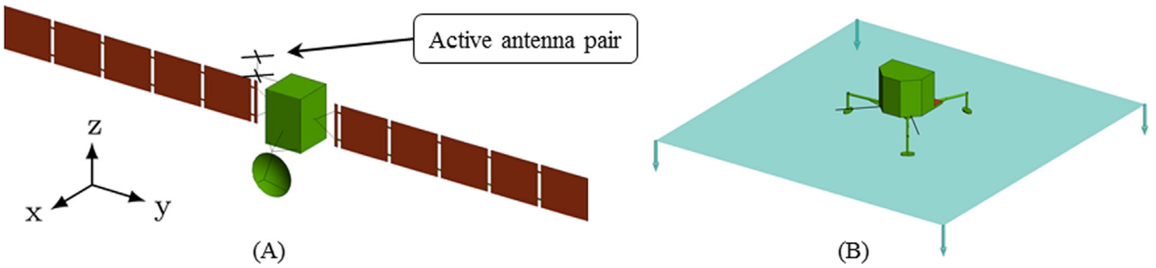


Fig. 4. CAD model of Rosetta (left) and Philae (right) with coordinate system.

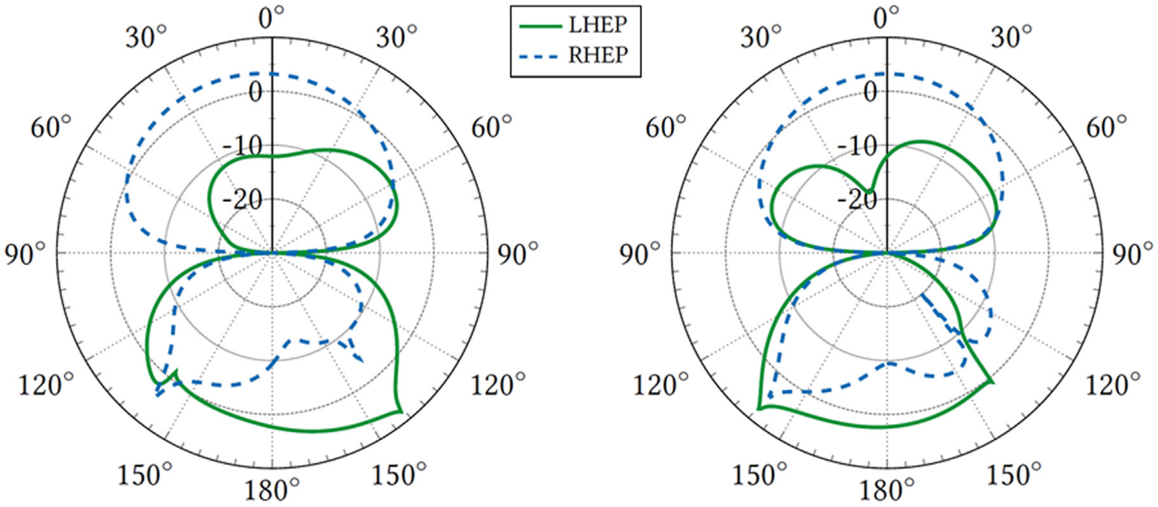


Fig. 5. Realized gain in dBi of Philae for an orientation of the landing gear of 35°, $f=90$ MHz, $\varepsilon_r=2.5$, tan $\delta=0.02$; left: x-z-plane; right: y-z-plane.

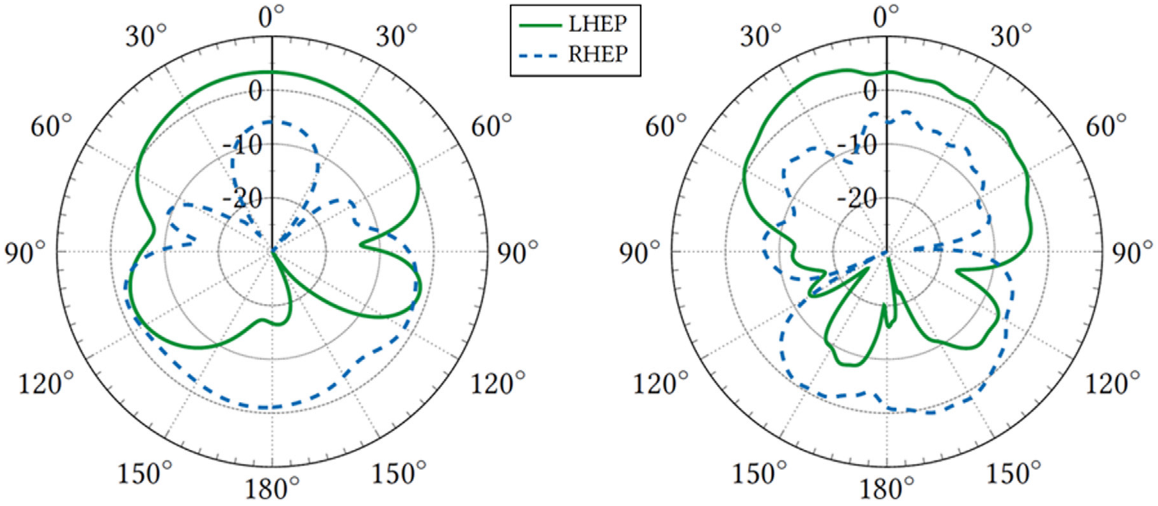


Fig. 6. Realized gain in dBi for the orbiter, $f=90$ MHz; left: x-z-plane; right: y-z-plane.

Rosetta. Therefore the impact of these losses has to be considered for the link-budget calculations as shown in [6]. As we can see in Figs. 5 and 6, the antennas are designed to provide a matched polarization between CONSERT Lander and CONSERT Orbiter in the sounding configuration. In this phase, the signal of interest is transmitted from Philae $-Z$ axis and received on Rosetta $+Z$ axis, with matched polarization. This ensures the best link budget between LCN and OCN for science measurements. At a typical 30 km distance from Rosetta to comet center, the aperture of the CONSERT lander antenna towards the comet interior is about 90° while the aperture of orbiter one towards the comet nucleus (in $+Z$ axis in Fig. 6) is about 110°.

During the tuning phase, we have seen that the lander and the orbiter are in visibility. That means that the line of sight link budget is drastically reduced, mainly due to the polarization that now mismatches: lander and orbiter polarization are fixed and in tuning phase, then orbiter $+Z$ axis now faces lander $+Z$. This implies a far harder constraint on both the orbit position and distance for which the tuning could be performed. Despite the polarization losses an appropriate line of sight link budget could

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

be achieved for the typical 30 km distance from Rosetta to comet center.

CONSERT is one of the eleven instruments on board of Rosetta, and also one of the ten instruments on board of Philae. As we wrote above, the CONSERT instrument is split into two parts: the Lander CONSERT instrument onboard Philae (LCN) and the Orbiter CONSERT instrument onboard Rosetta (OCN). Both are needed to perform a science sequence. To achieve operations planning and execution of both parts, our team had to interact in cooperation with four operation centers: the Rosetta Science Ground Segment (RSGS, ESAC Madrid), the Rosetta Mission Operation Center (RMOC, ESOC Darmstadt), the Philae Science Operations and Navigation Center (SONC, CNES Toulouse) and the Philae Lander Control Center (LCC, DLR Köln). SONC and LCC together form the Rosetta Lander Ground Segment (RLGS). Rosetta and Philae operation teams implement different concepts to manage the scheduling processes and commanding logics of their instruments. Through a collaborative work, we have designed and established a global process that copes with both planning concepts and tools, and the different commanding workflows, taking into account the CONSERT operational constraints. All the pertinent constraints were identified and quantified thanks to this iterative preparation work.

3. CONSERT operational constraints analysis

So, the CONSERT measurement quality is determined by the antenna gain and polarization losses. It is strongly dependent on the geometry of measurement: the relative geometry of Philae, 67P/C-G nucleus and Rosetta. We can deduce a set of geometrical constraints to ensure a good CONSERT link budget during science measurement, tuning and calibration phases.

The geometry of the CONSERT system is driven by Philae and Rosetta's relative positions and orientation. As Philae is fixed on the comet nucleus surface and Rosetta is orbiting relatively slowly around it, their relative movement is dominated by the comet nucleus rotation period, which is 12h24m. Depending on the CONSERT operation sequence phases, we can derive constraints on geometric parameters, which constitute the base inputs for operation planning. In this chapter, we will describe the requirements for the CONSERT operations and their implications on Rosetta and Philae operational constraints.

In a first approximation, before the close approach of the comet, we had to make assumptions on the comet shape for the geometrical description of the CONSERT operations. At that time, the convex shape model presented in Fig. 3 was the only information available, obtained from Earth observations. In order to simplify these first analyses, we decided to assume a spherical shape of the comet nucleus. By regard to this very first model, the spherical approximation with 1.91 km radius has a mean error of 220 m. Obviously, this is quite far from reality, as we realized when Rosetta arrived at the comet in summer 2014. However, this approximation allowed a sufficient first order understanding of the operation constraints. To give an idea of its scale, 67P/C-G nucleus typical size is 3–5 km. The Rosetta distance to comet center varies from 10 km to hundreds of km. We have then refined our methods after the close approach of the comet and real 67P/C-G shape availability.

To achieve good science return with CONSERT, we have first to fulfill a proper sounding phase. For this, we have to be sure that the main wavefront (the directly transmitted wavefront with no reflection), travels through the comet nucleus from Philae and reaches the Rosetta CONSERT antenna: this imposes a constraint on the relative positions of Philae, Rosetta and 67P/C-G nucleus (Fig. 1). To perform the tomography of the nucleus, we need to sound a varied set of comet slices (Fig. 7), and try to maximize the travel distance of the signal inside the nucleus. In the case of the CONSERT wavefront, we do not have in practice planar slices, due to potentially complex propagation inside the nucleus and refraction effects at the surface. The footprint is the projection of Rosetta position on the nucleus surface by regard to the comet center point. The footprint velocity must be less than 1 m s^{-1}. Due to the irregular shape of the comet, in some particular cases, small variations on Rosetta position could lead to large variations in the projected position at the surface (e.g. when the footprint jumps from one lobe to the other). In practice, by regard to Rosetta velocity range on its trajectory, this last constraint is always fulfilled when distance from Rosetta to comet center is above 10 km.

Besides its presence at receiver, the signal must be strong enough. This requires that the distance between Philae and Rosetta does not exceed 30 km and both antenna patterns of LCN and OCN are in a good relative orientation. As Philae is fixed on the comet surface and the CONSERT orbiter unit is fixed on the Rosetta spacecraft, this induces a near-nadir pointing constraint on Rosetta

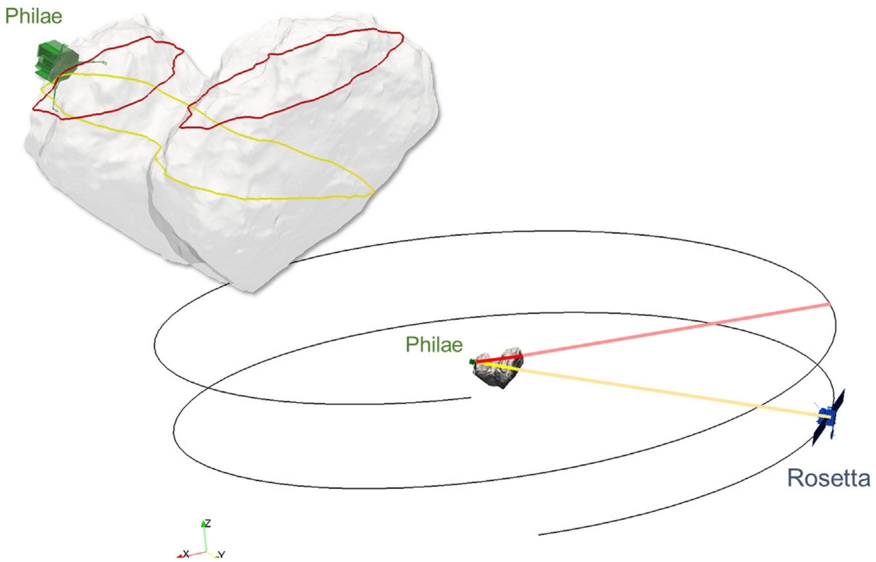


Fig. 7. Simplified view of two different sounded slices of the nucleus, shaped by the Rosetta orbit, not taking into account surface refraction and interior potentially complex propagation.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

during all the sounding phase. The sounding measurements that do not fulfill those constraints are expected to have a poor signal to noise ratio. In addition, the calibration of the signal, which allows an improvement of measurements quality after processing, imposes that LCN and OCN are in visibility at the end of the science sounding phase. That means that a clear and direct propagation in vacuum is possible between Philae and Rosetta for at least 20 min or 10° on orbit (Fig. 8).

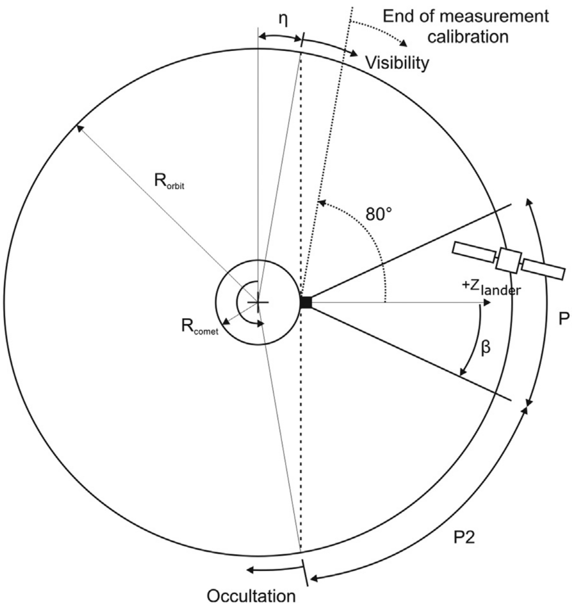


Fig. 8. Sounding and calibration phase constraints parameters definition. P1 represents the tuning zone and P2 the waiting phase.

As stated in 2, we need to synchronize our two instruments before the sounding phase. This tuning phase requires that Philae and Rosetta are in visibility of each other, with additional constraints on their relative orientation and distance [6]. There, the orbiter position must be included in the lander cone of axis $+Z$ lander with an angle $\beta=20^\circ$ for distances >25 km (Fig. 9). Similarly, the lander position must be included in the orbiter cone of axis $+Z$ orbiter with an angle $\theta=20^\circ$ for distances >25 km. A third angle α defines the angle between orbiter $+Z$ axis and the direction from orbiter to lander. This angle tells us how far we are from the optimal link budget in OCN antenna radiation pattern. As the lander is fixed on the comet surface in a comet fixed reference frame, we can derive the α angle requirement to a constraint only on orbiter pointing $+Z$ direction. With the spherical comet shape approximation, that means the orbiter pointing should be nadir. All these angular parameters come from the antenna radiation pattern analysis. The link budget during the tuning phase, with mismatched polarization configuration between LCN and OCN antennas gives us a strong constraint on the distance between Philae and Rosetta, although the waves are propagating in vacuum. The distance between the lander and the orbiter shall not exceed 30 km during the tuning phase. The tuning constraint must be adhered to otherwise the whole CONSERT science sequence will be lost.

The lander $+Z$ vector is defined by the orientation of Philae after the landing. This parameter is a matter of particular importance for the tuning phase success and furthermore for the CONSERT operations. At the time of planning the operations for LTS and FSS (First Science Sequence) we didn't know it, so we had to make assumptions on the lander $+Z$ axis. In a very first approach, we have considered this vector as radial with a spherical approximation on the comet shape. When comet shape models became available, we used the normal at the surface for a given

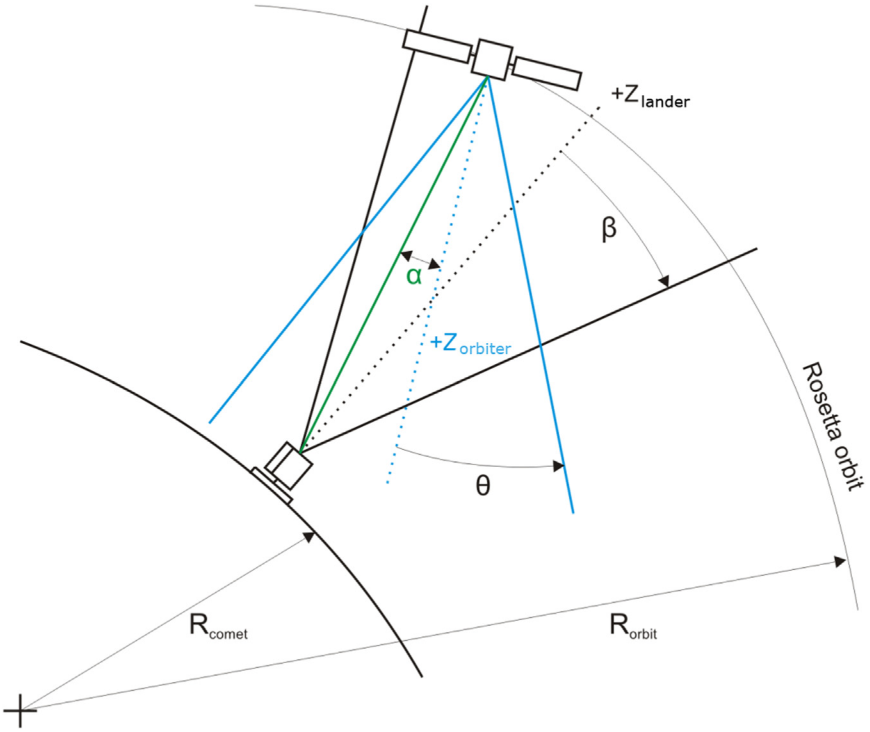


Fig. 9. Tuning phase constraints parameters definitions. The β cone angle defines a cone around the Lander $+Z$ axis (Z_{LDR}) within which the Orbiter must be located and remains during the tuning phase. The θ cone angle defines a cone around the Orbiter $+Z$ axis (Z_{ORB}) within which the Lander must be located and remains during the tuning phase.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

lander location. With the actual shape model, it is in general far from the radial vector. Considering this vector as the surface normal is an approximation, assuming that Philae has landed on a perfect flat area – which is not exactly the case in reality. Thus, after the landing, we used the reconstructed real lander $+Z$ axis as provided by SONC flight dynamics team.

Values for all parameters have been quantified in regards to the CONSERT instrument performances and 67P/C-G geometrical parameters (Table 1). In practice, Philae is fixed at the comet surface on its landing location and orientation. Thus, all these geometrical constraints will only impact the Rosetta attitude (α and θ angles) and position (β angle, R_{Orbit}) to be fulfilled.

We have identified all the constraints that must be adhered to achieve good CONSERT measurement. Most of them induce geometrical requisites on both Rosetta and Philae spacecraft. So we have analyzed the orbiter and the lander constraints to be able to express our requirements for operation planning.

In order to achieve its scientific objectives, the Rosetta spacecraft shall be able to handle complex navigation at low altitude orbits around an irregular body with weak and asymmetric gravity field, within a dust and gas coma. The $2.8 \times 2.1 \times 2.0$ m sized spacecraft is propelled by thrusters. The attitude is controlled accurately by four inertia wheels. The electrical power supply for sub-systems and instruments is assured overall by 32 m long solar panels, mounted on one-axis actuators. One side of the platform is dedicated to instruments; this side is pointed towards directions required for the implementation of the different instrument observations. The pointing is often close to nadir. To ensure a sufficient and stable power supply, solar panels are constantly pointing to the Sun. An absence of this operational requirement would endanger the mission. To ensure a sufficient and stable powering, solar panels are constantly pointing to the Sun while the steerable high gain antenna is finely pointed in the direction of Earth to maintain the communication link with on-ground operation centers.

After the FSS, the baseline orbit shape is near circular in the terminator plane. The terminator is the orthogonal plane to the direction given by the Sun towards the comet center. Placing the spacecraft in orbits on the terminator plane is the solution to mitigate constraints. It allows orienting the solar panels towards the Sun while limiting the drag effect of the coma in the nucleus vicinity. In addition, the instrument side of the platform could be pointed in the direction of the comet at the same time. In this way, the platform is able to receive Sun light power all the time, as the spacecraft cannot operate on batteries. The shape of the Rosetta orbit, in the comet fixed frame in which Philae is also fixed, is dominated by the comet nucleus rotation. The typical period of 67P is 12h24m. The distance to the comet center is mostly driven by safety rules: preventing the platform from nucleus outgassing dangers, allowing star tracking for attitude control, predictable dynamics for navigation. The typical revolution period of Rosetta is approximately 7 Earth days at 20 km and 15 Earth days at 30 km. To allow for illumination conditions different from those at the terminator and to be able to get closer to the nucleus surface, for short periods a limited set of fly-bys are also performed by Rosetta.

The baseline pointing proposed by RMOC is the “illuminated point” pointing. In this pointing configuration, Rosetta points to the mid-point (in terms of angle as seen from the spacecraft) between a point on the terminator and the illuminated limb. The point on the terminator and the limb are chosen in the comet-sun-spacecraft plane. This baseline pointing has been defined for the lander delivery period (MTP 9) and provided as a baseline for next MTPs. It is near to nadir pointing when the distance is above 15 km. This base pointing is within our requirement. This proposition is discussed with all other orbiter instruments teams and results in an overall trade-off. Most of time, the baseline “illuminated point” pointing has been updated by specific instrument requests. Although this is the most common case, the Rosetta pointing for some segments of the orbit are imposed by RMOC for the navigation manoeuvers, and cannot be adapted to instruments needs. In those segments, the pointing has to be considered unpredictable at the planning cycle time: it is updated a few days before execution by RMOC itself. For trajectory definition, the nominal process begins with RSGS and instrument teams. They elaborate simplified draft trajectories, following the baseline rules set by RMOC. Then RMOC analyzes these propositions to assess their feasibility and provides a long-term trajectory based on the draft input. This iterative process results in a trajectory and pointing that optimize scientific interests and navigation safety. For the lander delivery period (MTP 9), the orbit was fixed by RMOC flight dynamics based directly on the Lander communication and CONSERT operation requirements.

Therefore, the Rosetta orbit definition has a major impact on the CONSERT operation planning process. However, this analysis only addresses half the problem: we had also to investigate the Philae constraints impact on our measurements.

The Philae lander is a ~100 kg lander that was ejected from the Rosetta main spacecraft on 12 November 2014. Its descent to

Table 1
CONSERT geometrical constraints parameters. The last column gives an indication on the technical origin of the constraint.

PARAMETER	CONSTRAINT VALUE	ORIGIN
Tuning phase		
R_{Orbit}	< 30 km	Antennas patterns, link budget with mismatched polarization, no coherent integration
α[*]	Nadir off-pointing $< 5°$	Antennas patterns, polarization mismatch
β	$< 20°$ if $R_{\text{Orbit}} > 25$ km $< 25°$ if $R_{\text{Orbit}} \in [15;25]$ km $< 40°$ if $R_{\text{Orbit}} < 15$ km	LCN antenna pattern
θ	$< 20°$ if $R_{\text{Orbit}} > 25$ km $< 25°$ if $R_{\text{Orbit}} \in [15;25]$ km $< 40°$ if $R_{\text{Orbit}} < 15$ km	OCN antenna pattern
Sounding phase		
R_{Orbit}	< 30 km	Antennas patterns, link budget with propagation through the nucleus
α[*]	Nadir off-pointing $< 5°$	Antennas patterns
Footprint velocity	< 1 m s^{-1}	Coherent integration: Rosetta position is considered fixed during a single sounding
Travel distance inside the nucleus	As large as possible	By regard to the interior material dielectric attenuation
Occultation phase duration	As large as possible, > 2 h	
Calibration phase		
Calibration phase duration	> 20 min, if possible	

[*] The constraint on α angle between lander Z and orbiter Z is simplified by a global nadir off-pointing requirement.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

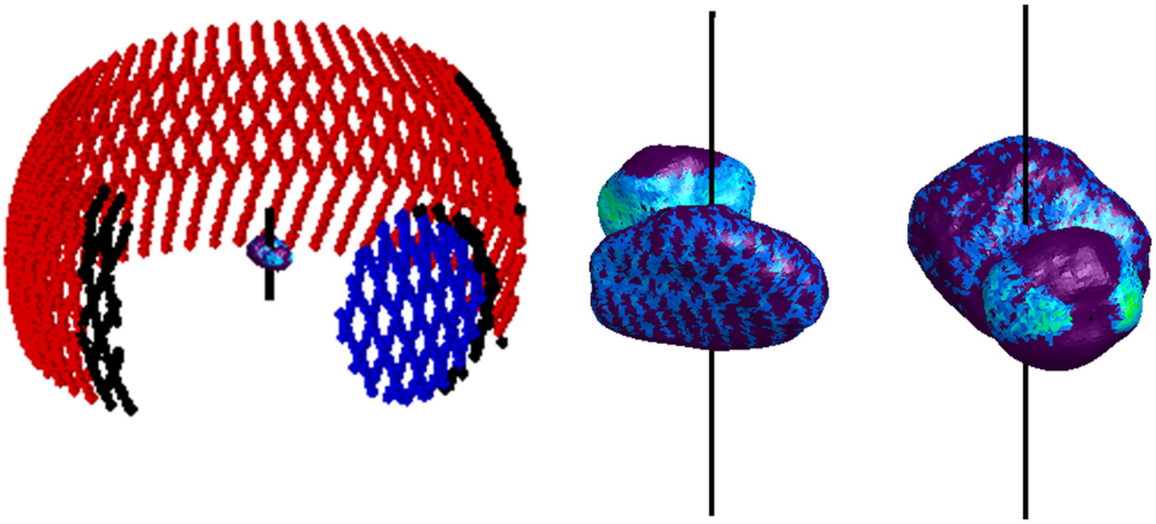


Fig. 10. CONSERT opportunities, lander at equator. On the left, the colored gridlines represent the sampling of Rosetta positions in a comet fixed frame, there at 20 km on a terminator orbit. The comet nucleus is represented in the center with the *Z* axis as a black line. The blue zone shows where the tuning is possible, thus a CONSERT sequence can start. The red zone shows where the sounding of the nucleus is possible, thus CONSERT measurements are possible. Pictures on the right present two views of the comet nucleus, showing the projection of the gridlines on the surface of the comet, in blue to green colored dots. It gives an idea of the global coverage of CONSERT soundings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

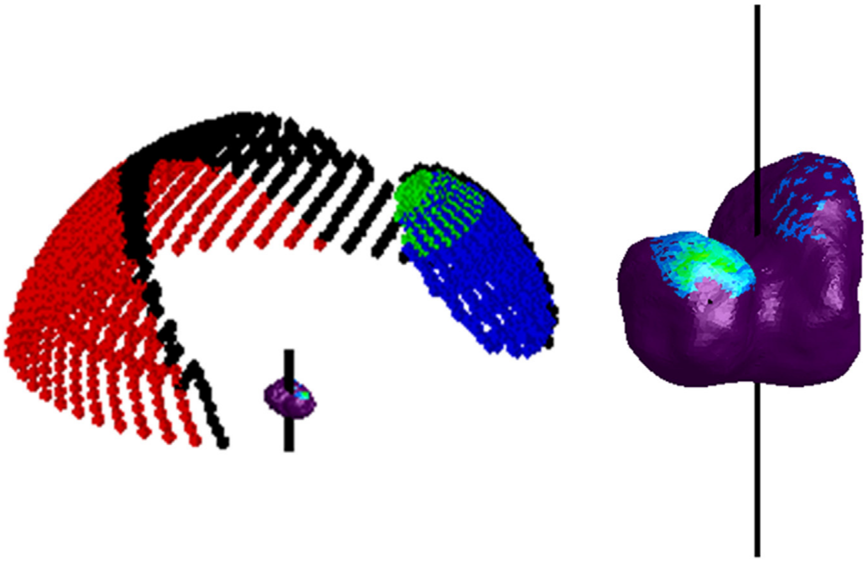


Fig. 11. CONSERT opportunities, lander at higher latitude. Here, the green zone shows where a tuning is possible, but ensues to useless CONSERT measurements (black zone) that do not pass through the nucleus. We can see that the tuning zone is restricted and the number of CONSERT operations limited. Furthermore, the coverage of CONSERT sounding of the nucleus is limited. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

the soft-landing on the comet nucleus surface was purely ballistic. At touch-down, with the three landing legs already deployed, harpoons were planned to be fired to anchor Philae on the surface – unfortunately, this last step didn't work and the lander bounced and landed in an unknown location and orientation. Philae sub-systems and payloads are powered by six solar panels and two electrical batteries. The primary battery, which cannot be recharged, was the main energy source during the First Science Sequence (FSS), just after the touch-down. This guarantees a minimum set of science operations on the lander. The secondary battery, which can be recharged through the solar panels, can be used for Long-Term Science (LTS) operations. The nominal science sequence of Philae in LTS begins with the hibernation phase during which the secondary battery is empty as no energy is received from the Sun. When the platform is at a sufficient temperature ($> -45\,^{\circ}\mathrm{C}$) and has enough power available (at least 5.5 W), it wakes-up and the on-board computer boots. As the Sun illuminates the lander, it warms the lander up and then the secondary battery charging starts if enough power is available on the solar panels and when the necessary thermal conditions are reached. As soon as the communication link is established with Rosetta, which demands at least 19 W of power, it uplinks all the telemetry data stored from previous science sequences and downlinks the new commands set. Then, the science sequence can begin until the Sun sets or the secondary battery is empty. Finally, the lander returns to its hibernation state, waiting for the Sun in order to start charging the secondary batteries again.

The CONSERT geometrical constraints driven by Philae position and orientation are fixed and supposedly known after landing. In practice this was not the case, but for the method definition we present in this paper, this had to be assumed. Philae operation

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

opportunities are defined by two main parameters: the power availability and the communication link with Rosetta.

The baseline functioning of the lander described above implies that the CONSERT science sequence must begin when Philae is illuminated by the Sun, in the morning of comet day. Thereby, the Sun direction has to be taken into account in the constraint analysis for CONSERT. Indeed, a CONSERT nominal science operation lasts for a complete comet rotation. Thus, it requires the lander secondary battery to be fully charged at sunset on Philae. Exceptionally, if the lander battery is fully charged, the illumination requirement could be relaxed, following LCC specific analysis and agreement. The CONSERT science sequence could then start in the evening, but never during the comet night.

At wake up, Philae's first activity is to upload remaining telemetry to Rosetta. This can be done only when a communication link has been established between the two platforms. Just after, new platform and instruments science sequence commands are downloaded to Philae and then science operations can start. These communication consume energy, thus it enforces the need for the lander to be illuminated by the Sun at that time. Geometrically, this implies that Philae and Rosetta are in visibility at the beginning of the CONSERT science sequence. Fortunately, it corresponds to the tuning visibility requirement, considering a relaxed value on the visibility cone angle β (40–50° typically for distance < 150 km). This visibility period shall last for at least 1h30 with 30 min dedicated to lander–orbiter communications.

In addition, to fulfill the ± 10 s time range constraint on CONSERT units ON between lander and orbiter units, Philae must have updated its on-board time (LOBT) before the beginning of science operations. This also requires a link being established between Philae and Rosetta and Philae to be kept alive until CONSERT operation starts.

One can easily deduce that the landing position and orientation of Philae on the surface of the comet has a strong impact on the geometrical constraints. The complex shape of the nucleus has made the global analysis more difficult to perform. Assuming simple straight-line propagation through the nucleus, we have analyzed the geometrical parameters all together with different assumptions on the landing site position. We considered the lander Z axis to be normal to the surface at the given landing location. The results depend mostly on Philae's attitude. The number of CONSERT science sequence opportunities – i.e. the number of sounding slices of the comet nucleus – and the coverage of our soundings are maximized if the lander $+Z$ is oriented parallel to the comet equatorial plane (Figs. 10 and 11).

The sounding phase for the science measurement follows directly the tuning phase. That means that the possible reachable zone of the nucleus for CONSERT sounding (red on Figs. 10 and 11) is defined by the tuning opportunity zone (blue on Figs. 10 and 11). At first order the movement of Rosetta is driven by comet rotation. This gives the relation between the two phases: roughly they belong to a circle perpendicular to the comet nucleus axis of rotation. As the blue zone corresponds to the intersection between the LCN β cone angle and the Rosetta trajectory, and this cone axis is defined by Philae's attitude, we can define a strong relation between lander $+Z$ orientation with regards to the comet rotation axis and the ratio of the nucleus that CONSERT will be able to sound. For instance at a Rosetta typical 30 km distance, if lander $+Z$ makes a 90° angle with comet rotation axis, tuning can occur at elevation angles of $-20°$ to $+20°$ w.r.t. the lander, this leads to an almost complete nucleus coverage for the sounding phase (Fig. 10). On the contrary, if lander $+Z$ angle with comet rotation axis is reduced to 30°, the tuning elevation range will be $+40°$ to $+80°$ which leads to a very small coverage of the nucleus sounding.

A finer look at Rosetta orbits shows us that its motion around the nucleus is not totally negligible by regard to the comet nucleus rotation speed. When on its circular terminator orbit, the Rosetta ground track is ascending the latitude values half of the time. Respectively, the orbit is “descending” from North to South on the other half of the Rosetta orbit. A complete Rosetta orbit at 20 km is covered in roughly 14 comet days. In order to optimize the number of available CONSERT sequences, when the sun rises on Philae (most likely the beginning of a CONSERT science operation), we should be descending on the Rosetta orbit. With Philae in the northern hemisphere – which is the only possible option regarding to the nucleus shape, it ensures the avoidance of tunable but useless CONSERT sequences. Following Earth observation convention, the orbit is better if it crosses the equatorial ascending node at 18:00.

4. Landing Site Selection Process

From August to October 2014, LCC, SONC and the Philae instrument teams along with RSGS and RMOC teams had to define the target landing location for the lander during the Landing Site Selection Process (LSSP) [7–10,16]. The LSSP started by a pre-selection of 10 promising reachable landing areas which have been determined by SONC flight dynamics team (named from A to J). All teams then had to reduce this to 5 ranked landing sites: I, C, J, A and B (Fig. 12) to finally choose 1 site with an alternative backup site. This process allowed the trade-off for all navigation, operation and Philae instruments science constraints.

Thanks to the analysis presented in the previous section, we developed a refined simulation method taking into account the physical propagation of the wavefront through the nucleus surface

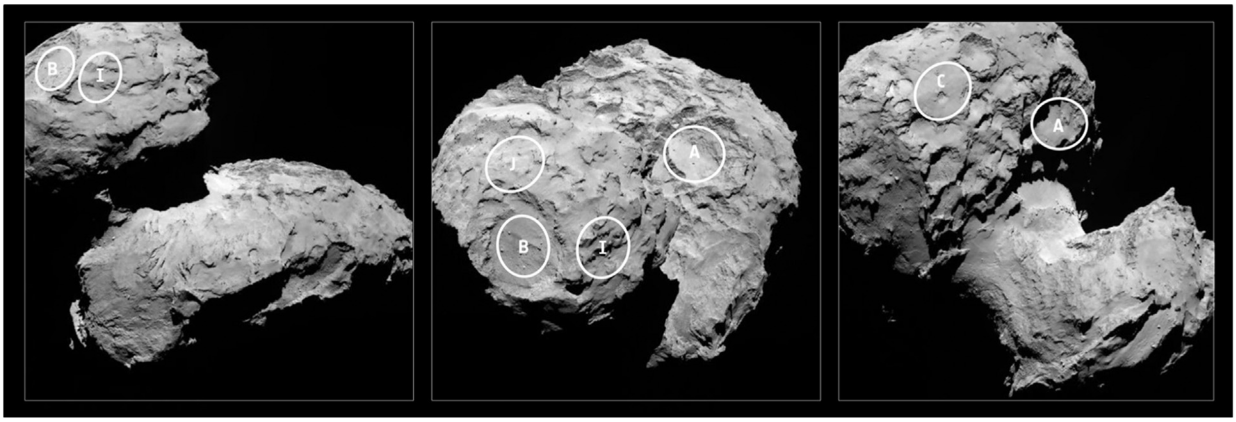


Fig. 12. LSSP 5 candidate landing sites.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

and the local orientation of Philae. This enabled us to define site B and J as the best landing points for CONSERT operations. Then we mapped a set of CONSERT sequence quality indicators in the 500 m vicinity of each proposed location. This range corresponds to the typical size of the landing dispersion ellipse of lander descent trajectories. We computed these maps for a set of orbit parameters: Rosetta distance to center, obliquity of the orbital plane by regard to the comet Z axis, ascending or descending orbits.

The most relevant indicator is the evaluation of what we call the sounding ratio (color mapped in Fig. 13). To evaluate the value of this indicator on a single location of the map, we compute a simulation of the signal propagation for all possible Rosetta positions on a virtual sky sphere (all colored dots on Fig. 14). This represents the total number of samples N_t. These samples are distributed regularly with regards to their respective covered area on the sky sphere. We determine the sounding samples that could be reached in practice, taking into account the tuning constraint (gray zone in Fig. 14). Then we count the number of samples N_{mw} that receive a signal from the main wavefront (dark blue, green and red dots on Fig. 14) and are included into the reachable soundings zone. The sounding ratio is given by $\frac{N_{\mathrm{mw}}}{N_t}$, which is a good approximation of the sky sphere area ratio that CONSERT can cover, and by extension of the possible coverage for the nucleus tomography.

As we can see in Fig. 13, the sites B and J present the best probability to land on a site that will allow for good CONSERT observations. In a dedicated meeting involving all collaborators, a global trade-off for all instruments and operational safety constraints was made and the site J was finally selected as the nominal landing site.

5. Operations planning

The landing site selection along with the operation requirements we have now identified and quantified give us the keys to implement the CONSERT sequences for the best science return. Moreover, the CONSERT operations have to be implemented according to the planning process of Rosetta for CONSERT Orbiter and Philae for CONSERT Lander. We have also to ensure the consistency of all the commanding on both platforms. CONSERT science operations were intended to take place since Philae has landed, until its end of life, initially planned in February 2015. Thereby, these operations must be planned before the landing. When comparing process timelines for Rosetta and for Philae (Table C.1), one can observe the fact that CONSERT operations must be defined before the landing, and furthermore before any landing site selection and comet shape knowledge. The next sections will describe in more details this planning logic on Rosetta and Philae and will present how the nominal processes have been adapted and how the CONSERT operation planning process has been designed to cope with this complexity.

The Rosetta nominal planning process defines all the procedures and tools that allow the implementation of operations onboard Rosetta platform. This implementation is achieved through a progressive iterative process between RSGS, RMOC and instrument teams. The planning process that we describe in this paper was the one implemented in 2014 and early 2015. In later periods of the mission, this planning process was changed, with much shorter turn-around times. This change was due to safe mode occurred on Rosetta, with issues on the star trackers sub-systems.

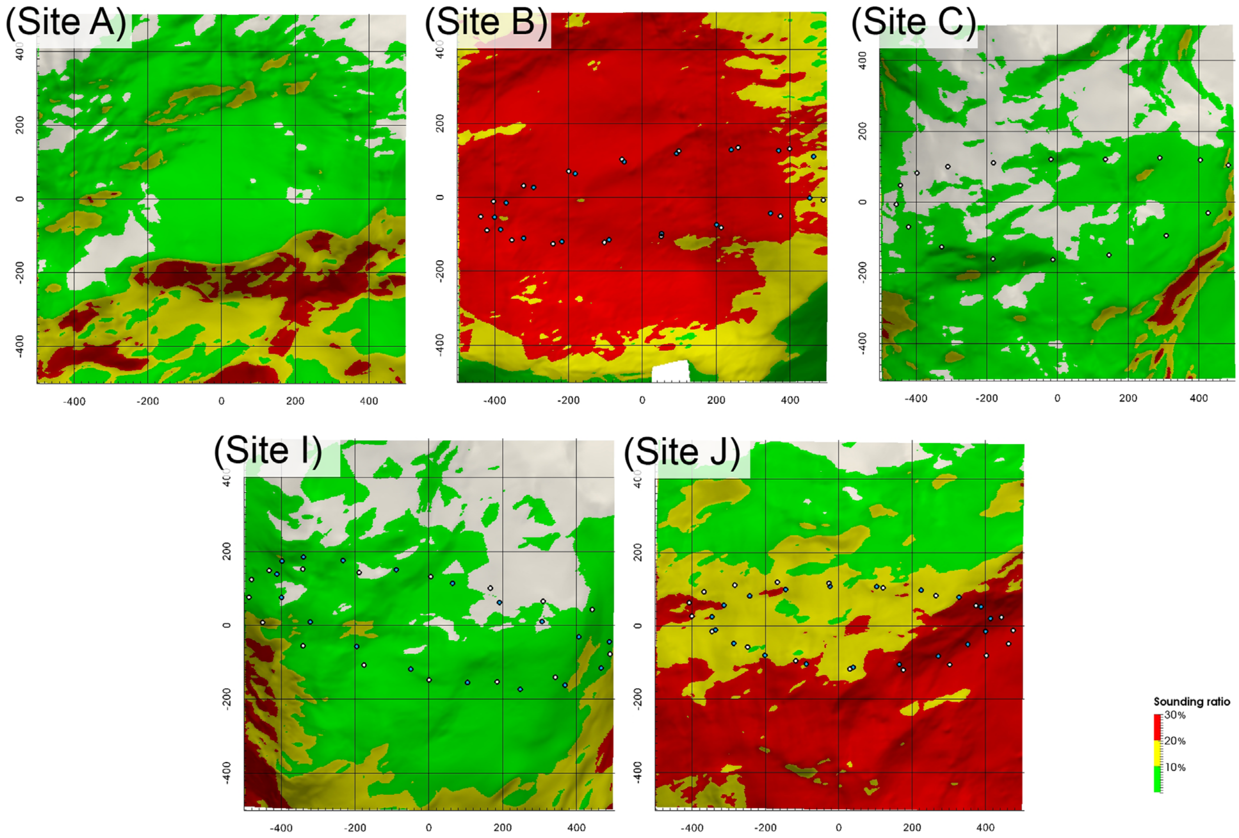


Fig. 13. LSSP landing site evaluation on CONSERT requirements. Each map corresponds to a landing site in Fig. 12. The sounding ratio in % is mapped in color. Red and yellow zone suggest that the locations will allow CONSERT to collect sufficient useful data. If Philae lands in green regions, then CONSERT will have a low efficiency on its science sequences. Gray landing regions will not allow CONSERT observation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

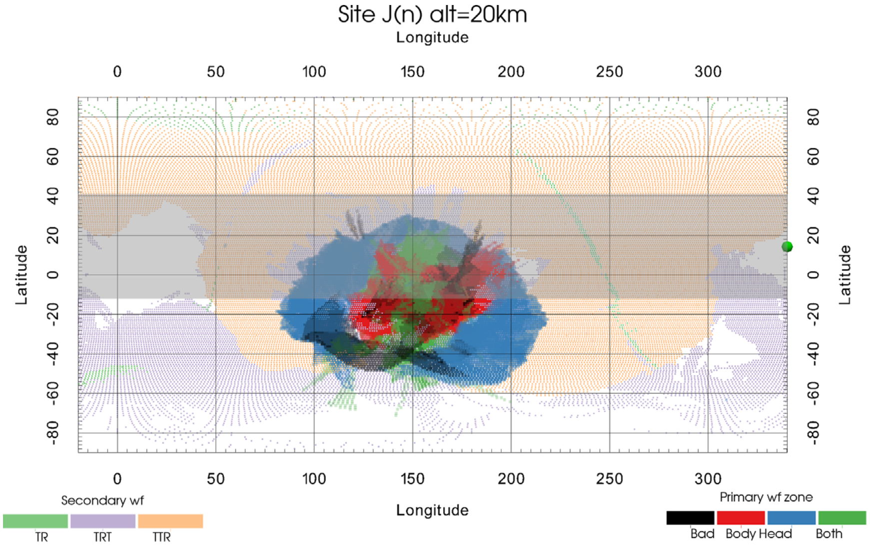


Fig. 14. Sample sky map representation. The main wavefront is shown on the sky map. Red, blue and green respectively represents the parts of the wavefront (wf) traveled through the main lobe of the nucleus (body), the small lobe (head) and both. Black color indicates parts of the wavefront passing through the unknown part of the shape model (not observed due to lack of illumination in the early phases of the mission). The secondary wavefront (with one reflection inside the nucleus) is shown in light color in the background. The grayed area corresponds to the elevation range w.r.t. Philae location (green dot on the right) accessible due to the tuning constraint. Primary (main) wavefront zone accessible by CONSERT is the intersection between the dark colored dots and this grayed rectangle.

The duration and complexity of the Rosetta near-comet science mission – two years, 11 instruments, a lander, the first time around an active comet nucleus, impelled the operation teams to design a time-segmented planning process, analyzing all constraints and requests from a large overview level to the exact detail of commands. The nominal planning process has been designed by RSGS and RMOC as “Russian dolls” cycles with different levels of refinement in the operation definition. The Long-Term Planning (LTP) covers 4 months and is intended to converge on a trajectory and define first pointing and rough observations requests for all payload instruments. The Mid-Term Planning (MTP) covers in general 4 months and concludes on the pointing requests and gives a good estimation on resources (data volumes and power consumption) and first draft of commanding. Each of these cycles is followed with a RMOC analysis phase. The Short-Term Planning (STP) covers one week of operation. During this planning cycle, instrument teams can fine-tune their observations and finalize all commands. Finally, in the Very Short-Term Planning (VSTP), RMOC process the requests and implement them. In this cycle, RSGS can fine-tune a limited set of requests in case of contingency. At last, RMOC send the final commands to the Rosetta spacecraft for execution. Please refer to Appendix D for further details.

CONSERT is a very sensitive instrument in the 85–95 MHz range. During the Rosetta cruise phase, tests have been performed with all the other instruments. We concluded that for the CONSERT orbiter unit, interferences occur mostly with the coolers of VIRTIS and RPC/MIP, or if at least three of OSIRIS, ROSINA, GIADA, RPC/LAP, RPC/IES or RSI operate at the same time. The interference issues between instruments are assessed and resolved along with RSGS during the MTP cycle.

The same work has also to be performed on Philae's side. The lander planning process is initiated by the determination of Philae operation opportunities identification by SONC-Flight Dynamics and LCC teams. They provide event files (OEF) computed from RMOC Rosetta trajectory and pointing, the Sun and 67P/C-G relative positions and orientations and also the Philae location and orientation. This file contains all orbital events of interest for lander platform and payload teams. These events have been identified and defined along with SONC, LCC and Philae instrument teams. For Philae platform, the relevant events have been derived from the constraints expressed in 0. From these events, instrument teams are able to know the time periods in which operations on Philae are possible. For CONSERT, it mainly consists of the tuning and occultation slot boundary date and times, based on the geometrical constraints. The event files are also sent to RSGS for Rosetta global planning at the beginning of the MTP cycle. Based on a generic Long-Term Science (LTS) Lander Instrument Operation Request (LIOR) document, the instrument teams provide SONC with a specific LIOR for each sequence. The LIOR takes the form of a text document containing commands, parameter values, timings, and energy and data volume consumption, along with the operation specific constraints. SONC collects the LIORs for all lander payloads, analyzes and solves eventual conflicts by iteration with the instrument teams. CONSERT interferences on lander occur with SESAME, SD2 and MUPUS. Once instruments activities respect all constraints and are consistent with the resources (data volume and power budget) a science plan is produced. Afterwards, the operation requests are sent to LCC for validation of implementation consistency. Complete lander payload sequence implementations are tested on the Ground Reference Model (GRM). Lander Operation Request (LOR) and the final lander science timeline (SOCOP) are sent back to RSGS for implementation of the lander activities on the orbiter platform. These planning interactions are performed at Rosetta MTP level in order to be able to solve conflicts between lander activities and other orbiter payload. Finally, following the RSGS planning process in the STP cycle, the lander commands are included in the global commanding bundle to be uploaded to the Rosetta spacecraft which will then send the commands to Philae as soon as the communication link is established.

As a remark, to prepare the identification of CONSERT observation opportunities, RMOC with RSGS provide the trajectory, pointing and timing definitions along with 3D comet shape model updates through SPICE kernel [11] files, on the project repository. These are the main inputs for our analyses. Other useful tools are provided as Web services to consult trajectories in 3D, mission schedule, time conversions, etc., as well as to check consistency of edited request files. RLGS also provides the instrument teams with input information (trajectories, landing sites and Philae status, comet shape and thermal models) through dedicated Web services

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

(called W3SONC).

CONSERT observation definitions have to fit with these two planning processes. On one hand, given these workflows, we have to be able for CONSERT to define operation opportunities very early in the mission schedule: at end of LTP cycle plan. In practice, LTS lander phase beginning at end of November 2014 operations should have been planned at MTP level in August 2014. On the other hand, the lander planning process is strongly linked to the landing event. No CONSERT Long-Term Science operation can be completely defined before knowledge of the Philae position and orientation. This constitutes the most problematic issue for CONSERT operations planning. This issue appears clearly in Table C.1: the LTP and MTP cycles take place when the landing site is completely unknown. RSGS first addressed this problem by defining shortened cycles for the planning of operations just before and after the landing [12]. These particular cycles, as known as "red bar cycles" allows to better fit the SDL (Separation Descent Landing) and FSS trajectories. Nevertheless, the time lines are still too different for CONSERT operations planning in LTS. The commands for both CONSERT orbiter and lander units (OCN & LCN) are delivered through the RSGS process. This means the OCN instrument within the RSGS planning process effectively stops at the beginning of STP cycle, subsequently being handled by lander operation requests from RLGS.

In collaboration with RSGS and RLGS, we solved this problem by overbooking the CONSERT operations planning with all possible sequence opportunities, and progressively descoping them when accurate information on landing configuration is available. Since the number of CONSERT opportunities was not considered to be excessive (e.g. of the order of 1 per week), this was considered to be a practical and acceptable solution.

In practice, we have defined a specific process for the CONSERT operation. At the end of LSSP, considering the nominal landing site and lander *Z* axis normal to the comet nucleus surface, with RMOC trajectory and pointing, we identify all the CONSERT science sequence opportunities that satisfy all the geometrical constraints. We have named them the "Windows of Opportunity" (WoO). By applying variability on the lander position and orientation, we have got the periods in the planning where CONSERT science could be done. These periods are composed of a set of coalescent WoO. It represents roughly 25% of the overall LTS. This corresponds to the large reservation bar in purple in Fig. 15. In the time period of these slots – and especially for MTP 10 for which CONSERT had a high level of priority for Rosetta operations), other instruments are aware of the fact they could get "last minute" unpredictable constraints coming from CONSERT operation. Thereby, they were able to anticipate this by planning more flexible operations, compatible with CONSERT pointing and preventing specific interferences. Then, we have ranked the WoO by regard to the science return expected quality, and RLGS rank them by regard to the operational feasibility and complexity. In the RSGS planning process, we could reserve the pointing request, power and data resources and ensure there were no interference with other orbiter instruments inside this CONSERT large opportunity window slots. This could be done on time in the RSGS planning schedule, so OCN could work in favorable conditions. As soon as we have got accurate knowledge of landing site position and Philae orientation, we have selected the optimum configuration among the pre-computed ones. We used the ranking of the WoO to select one per STP cycle. All other WoO were descoped. The WoO which were kept still include some margin for any eventual "last minute" fine tuning. Next, we have refined the RSGS planning with exact CONSERT operation sequences on time at STP level. Commands for OCN and LCN are then sent via LCC, and routed by RSGS to RMOC thanks to the Lander Operation Requests (LOR) derived from the Lander Instrument Operation Request (LIOR) provide to SONC. A final check by CONSERT, LCC and RMOC is then done on the final detailed commanding program (the "stack") just before upload to Rosetta platform. One can see on Fig. 15 an example of this process.

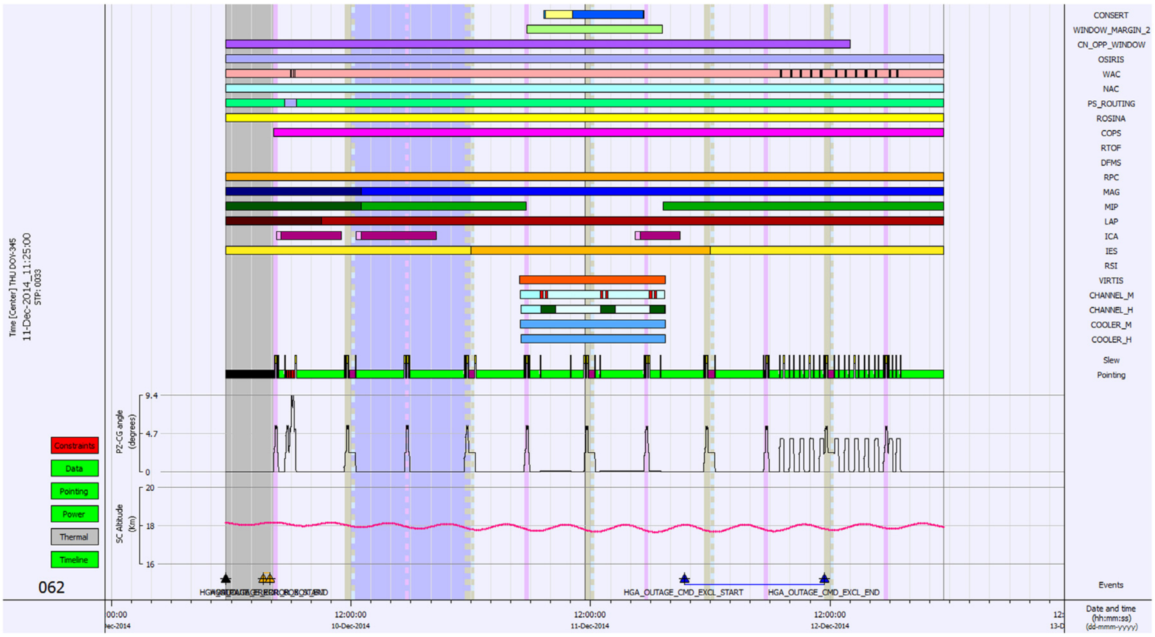


Fig. 15. MAPPS view for CONSERT operation planning in a part of MTP 10. The purple "CN_OPP_WINODW" corresponds to the CONSERT complete period of operation opportunity. One can guess that the VIRTIS operation must probably be shifted in time if the final CONSERT operation slot is kept at this date. We can see that the pointing request (PZ–CG angle) is compliant with CONSERT constraint $<5°$ during the entire CN_OPP_WINDOW slot. We also see this slot margin shown in light green 'WINDOW_MARGIN_2' bar. The actual operation is included as yellow and blue bar. At the end of the process, the purple and light green bars will disappear in the RSGS planning, leaving only the actual CONSERT operation describing exactly what is operated (in blue and light yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

6. CONSERT opportunity selection process

In order to implement this solution as an operational planning process, we have developed a set of specific methods and software tools. We describe them in the following section. Along this chapter, we will use the MTP 10 RSGS planning period as a sample case. The MTP 10 execution period just follows the landing, so it was particularly difficult to handle and then constitutes a good example. Its scheduling is detailed in Table C.1.

In a first approach, RSGS provided us with regularly updated geometry parameters (Table 2). In order to evaluate a particular orbitography and landing configuration, beyond our global geometric constraints understanding, we felt the necessity to develop our own automated tool. It provides a systematic identification of the CONSERT instrument operation WoO. This tool has been validated by regard to the event files provided by SONC Flight Dynamics team. The software tool is based on the SPICE toolkit provided by the Navigation and Ancillary Information Facility of NASA. This code library contains a large set of data format specifications, functions and utility tools to allow users to handle the complexity of planetary observation orbitography. The choice for this technology was straightforward as it constitutes the main tool for orbitography data exchange between the RSGS and the instruments teams. The program loads the SPICE kernels provided by RSGS containing the trajectory, timing and pointing information. The kernels also embed the comet nucleus shape generated from NavCAM images (RMOC). With a typical time sampling of 1 min, it computes all the geometric parameters (Table 2).

From these parameters, a chronogram is built on the overall trajectory; it is composed of operation events. The computation of the events has been cross-validated with events produced by RLGS flight dynamics team (Table E.1). A CONSERT WoO is identified when a tuning phase is possible. Once a WoO has been found, it is populated with all helpful events: day and night ephemeris, tuning, communication link with Philae, occultation times. Then, a view of the chronogram is drawn as a simple spreadsheet, the WoO interaction document (Fig. F.1). To help the discussions with RSGS and RLGS, the planning cycle information is indicated for each WoO. Once done, a first analysis of each WoO is made by the program. Firstly, they are tested against the orbiter distance criterion. Based on a threshold for the lander–orbiter distance during the WoO, they are marked as ‘optimal’ by green coloring or ‘out of limits’ by red coloring. WoOs are never automatically dropped.

This first analysis is completed by the calculation of a set of derived values that will help the manual ranking of the WoOs and the commanding of operations (Table 3). Two of these values are used in the early analysis process to understand in which lander status we will be during a specific WoO. CONSERT can operate only when communication is possible between Rosetta and Philae, and when Philae is able to provide sufficient power. By studying the geometric setting of Philae on the comet surface, Rosetta and the Sun, we finally defined seven configuration cases (Table G.1). Only three of them allow operating CONSERT on the lander, by reason of operational complexity or impossibility.

Having a large number of WoO found by the automatic orbitography analysis tool, we have to then assess their scientific relevance. In that purpose, we have developed a simulation software (SimSERT) of the experiment. It takes as input the comet nucleus shape model, the internal permittivity model, the Rosetta orbitography and the Philae landing site location. For CONSERT operation planning purposes, we assumed a homogenous dielectric permittivity in the nucleus interior. During the planning activities for CONSERT we had to make assumptions on the comet interior relative permittivity value. With respect to the knowledge of comet nuclei at this time, we defined this value to 2.0. After the FSS operations and science analysis have been performed in early 2015, we found that the relative permittivity value for 67P/C-G was 1.27 [4]. Using a ray-tracing algorithm [13,14], it computes the propagation of CONSERT radiowaves from the lander through the

Table 2
CONSERT base geometry parameters.

PARAMETER	DESCRIPTION
Time UTC	Sampling date and time in UTC.
Longitude (°)	Rosetta spacecraft longitude in the comet frame.
Latitude (°)	Rosetta spacecraft latitude in the comet frame.
Distance (km)	Distance from Rosetta to the comet center.
L–O distance (km)	Distance from Rosetta to Philae.
Emission angle (°)	Angle between orbiter *Z* axis and lander *Z* axis.
Angle above horizon (°)	Angle formed by the Rosetta position and the horizon plane at landing location.
Visibility	Boolean value indicating if Rosetta is visible from lander, taking into account comet nucleus shape occultation.
Illumination angle (°)	Angle between lander *Z* axis and the sun direction.
Illumination status	Boolean value indicating if the landing position is reached by the sun light, taking into account comet nucleus shape occultation.
Section (km)	The length of the segment from lander to orbiter, inside the comet nucleus. This information is separated into two parameters giving the section of the head and body of the nucleus that is traversed.

Table 3
Main CONSERT indicators derived from WoO chronogram.

INDICATOR	DESCRIPTION
CONSERT science	
Tuning emission angle (°)	The emission angle at the tuning window center. This indicates the confidence we can have in the tuning success.
Tuning window duration	The total duration of the tuning window. This indicates the margin we can expect to set the tuning phase of the operation sequence.
Occultation section (km)	The comet nucleus section amount crossed by the signal path at the center of occultation window. This gives an idea of the tomography interest for the WoO.
Latitude evolution	By looking at the evolution of the latitude of Rosetta in comet frame during the WoO, we know if we are in ascending or descending orbits configuration.
Lander operation	
Communication link with illumination duration	The total cumulative duration with available sun power and communication. This indicates the margin for the operation sequence initiation on the lander platform.
Configuration case	Indicates in which lander configuration the WoO is starting, giving helpful information on the operational complexity or feasibility.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

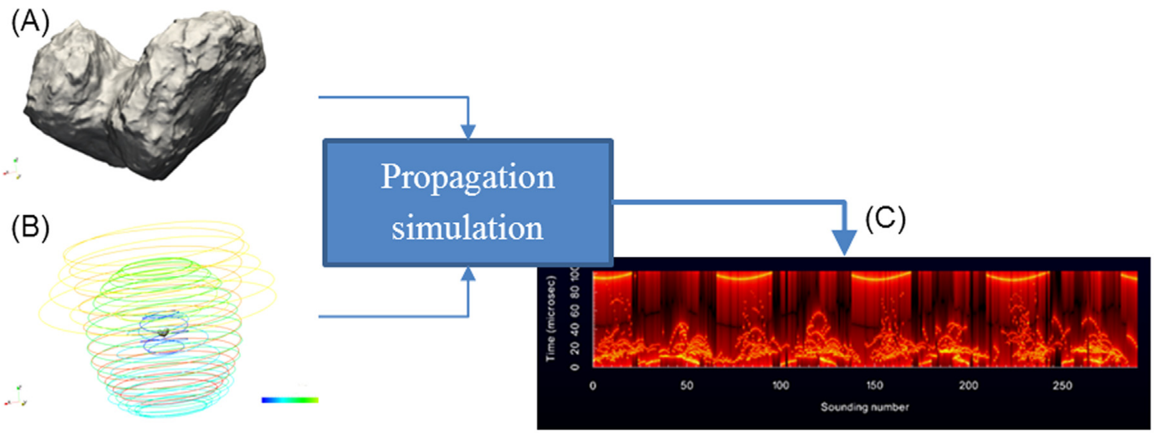


Fig. 16. SimSERT simulation software.

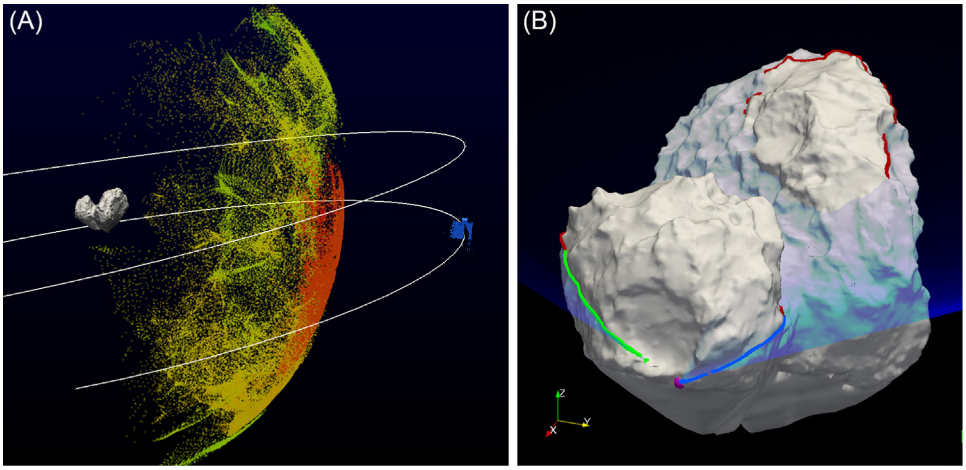


Fig. 17. (A) Sample view of CONSERT simulated wavefront traveling into the vacuum between the nucleus and Rosetta (in blue, with its white line trajectory). The color represents the signal power, red is the stronger. (B) Drawing of intersection between the nucleus surface and the path of the signal received on the orbiter. The intersection is represented by green, red and blue lines on the surface. The transparent blue surface represents the sweep of the line joining the lander and the orbiter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

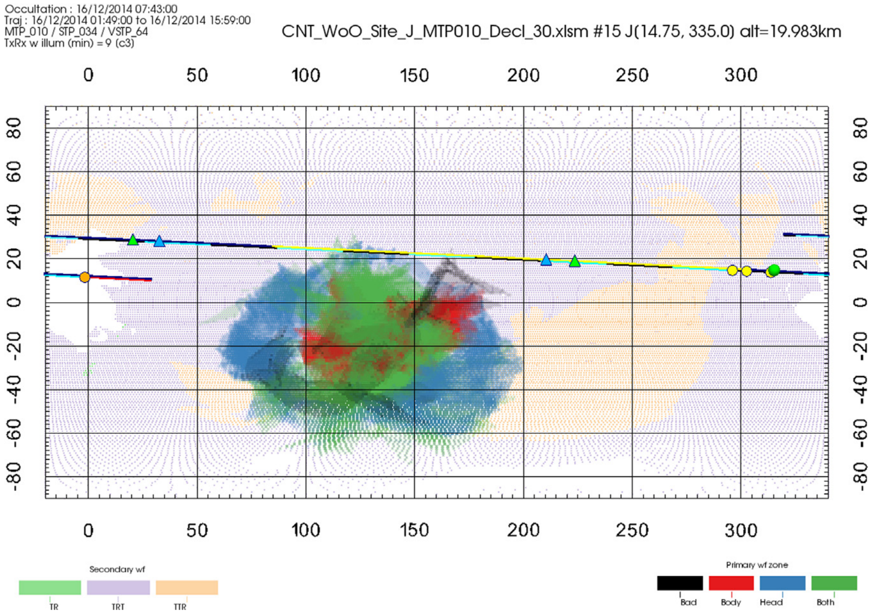


Fig. 18. Complete sky map representation for sequence analysis. Description of wavefront colors is given in Fig. 14. One can see the orbitography markers placed on the trajectory line (yellow). Beside this line, one colored segment portion corresponds to one hour of operation. Each marker type corresponds to a specific CONSERT event like tuning phase start/stop (yellow dot) and occultation start/stop (blue triangle). In this example, we can see a case which is not favorable, as the trajectory is very tangential to the main wavefront. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

comet nucleus and the vacuum environment all around the nucleus. The output results of the software are the electromagnetic signals received at each orbiter position point, sampled along the given trajectory. Two main inputs feed the simulation software: the comet shape model (Fig. 16, *A*) and the orbit data (Fig. 16B). In addition, configuration parameters define the nucleus interior dielectric properties: a homogenous permittivity and dielectric attenuation are assumed for operation planning purposes. The output of the simulation is the complete radar signal expected on the trajectory. We can also output intermediate results to interpret this complex signal: for example, we can extract separated wavefronts detection and the region of the nucleus they traveled through. A set of visualization and statistical analysis tools allow us to dig into the heavy datasets of results and extract the relevant information for operation planning.

A stated before, an operation sequence will return interesting science data if the main wavefront crosses the Rosetta orbit. SimSERT has the feature to extract this main wavefront from the complete simulated signal. Thus, in output results analysis, we will identify easily which trajectory sampling points receive the main wavefront signal. For a given landing position, trajectory segment, and hypothesis on nucleus interior permittivity, we count the amount of time on this segment during which OCN is expected to receive the CONSERT science signal from the main wavefront. This duration indicator will help us to quickly identify and eliminate the “bad” WoOs, in a systematic way – a typical bad WoO corresponds to orbits which traverse tangentially or border the main wavefront. For the best WoO candidates (and especially for those which are intended to be executed) we use our 3D visualization tool to get into deeper details in the signal analysis. We study the shape of the wavefront along the trajectory, its expected power estimation and eventually its path through the nucleus (Fig. 17).

In addition to these analysis tools, we use “sky map” projections of the wavefronts, with the orbiter trajectory in overlay. This type of representation has been very useful to understand the overall WoO configuration, and to merge in a comprehensive manner a lot of complex information (Fig. 18).

This qualitative analysis gives us additional information to perform the CONSERT science quality ranking. Additionally, these tools are used for a small number of trajectory segments that the automatic WoO identification program cannot handle. In practice, only fly-by trajectories were analyzed separately from the WoO process. The specificity of the fly-bys is that instrument teams have more flexibility on the orbiter trajectory: we can adapt the timing of the orbit. That means that we are able, by iterating with RSGS and RMOC, to set the date and time at which Rosetta is in visibility of the lander. In this way, we are ensuring the tuning phase success. Fly-bys represent a limited set of segments which last roughly 20 h, so they can be managed manually for CONSERT operations analysis.

We assume that in the nominal case, we could operate CONSERT one or two time per STP. Thus, we perform the ranking of WoOs belonging to the same STP period. The idea is to select the best one that would be finally operated. The ranking is made in two steps: firstly, the CONSERT team evaluates the science return quality indicator, and secondly RLGS evaluates the operation complexity indicator. As this ranking is not automated and made on a case by case basis, it is helpful to set comments to argue the choices. By this method, we are able to prepare and fine-tune our observation operations in a very short time.

All the methods we have described consider a fixed Philae location and orientation. To handle the lack of knowledge in Philae configuration, we apply sensitive variations on lander position and lander Z direction. For each variation case, the WoOs are identified and processed. Then a summary view (Fig. 19) of all these variations is computed and gives us the general overview of the possible CONSERT operation slots and their possible evolution. This view shown in Fig. 19 includes essential information needed for CONSERT planning in a single view. The header row indicates date, time and the distance from Rosetta to the comet nucleus center. Each row corresponds to a geometry configuration case: one landing site location, here with variations on the lander *Z* axis declinations from 5° to 50° on landing site J. Each colored cell shows one single WoO (corresponding to one row in the WoO interaction document). Green indicates the optimal WoOs (case #0 in Table G.1), purple and blue ones are the possible WoOs with different lander configuration cases. The figures inside the cells give the configuration case (as described in Table G.1). Hashed cells are WoOs for which the main wavefront won't be detected, as computed by SimSERT program. Thus, these are useless. Black markers indicate where Rosetta navigation imposes the pointing, and so where no CONSERT operation could actually take place there. Contoured columns show the WoOs which present issues with respect to these pointing constraints. Red indicates a tuning issue (no CONSERT operation is possible), and the yellow one a sounding issue (part of the sequence could be lost). Finally, the yellow horizontal bars correspond to the slots planned for CONSERT, also called “CN_OPP_WINDOW” in RSGS planning. We can see that they comprise all the periods during which CONSERT operations are possible considering variations on Philae orientation. One can compare Fig. 15 which corresponds to 10/12/2014 to 13/12/2014 operations.

It allows, in the early steps of the MTP cycle, to define enlarged periods in which CONSERT is suspected to be operated. We perform the conflict detection and resolution work on the orbiter – for pointing and instruments interferences – on this whole enlarged period (see the second yellow cells group in Fig. 19 corresponding

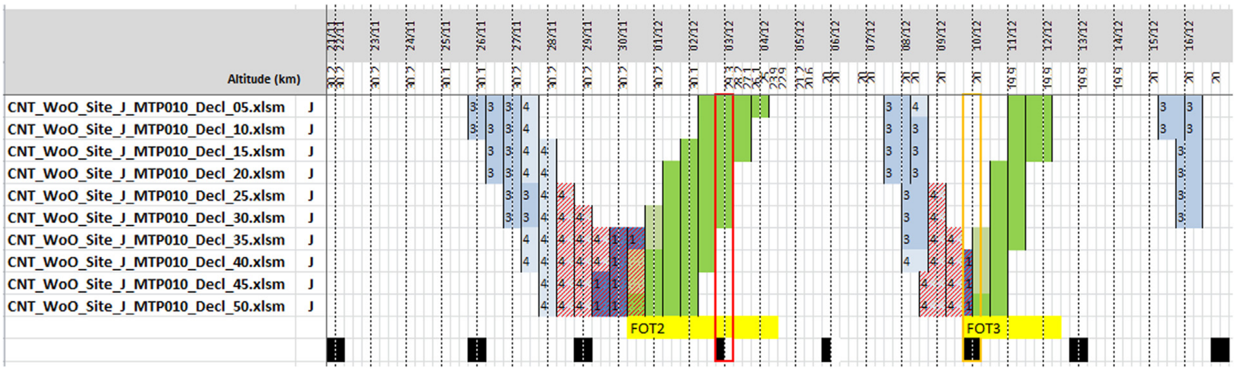


Fig. 19. Sample view of the WoO summary for MTP 10. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

to purple bar in Fig. 15). With regards to the data volume and power consumption reservations, we consider the best case: two CONSERT observations planned per STP. So, we overbook the RSGS planning but we limit the overbooking of the resources. At the end of MTP cycle, when the landing position and orientation become known, we reduce the CONSERT opportunity window to one or two of the best ranked WoO inside the next STP. In Fig. 19, one or two cells correspond to the light green bar in Fig. 15. All other WoOs in this STP are descoped. At that time (end of MTP, beginning of STP cycle), a final check on interferences with any other Rosetta instrument is performed over the CONSERT WINDOW_-MARGIN bars. There, with the best understanding of the landing configuration we have, we refine the timings and commanding parameters to set the final operation requests, which finally correspond to the light yellow and blue bars in Fig. 15. Finally, the OCN and LCN operation sequences are sent to the RLGS commanding using LIOR. Following a proper checking at CONSERT, lander and orbiter levels, the commands are uploaded to Rosetta and executed. After the science sequence is executed on the comet, the telemetry is downloaded from Rosetta to Earth communication stations. Then we can retrieve our data through Data Delivery System using the RSGS and SONC interfaces. In addition to using these data for scientific results, we process and analyze them in order to refine our next planned operations.

7. Conclusion

In this paper, we have presented the CONSERT instrument objectives and functioning, in the scope of the Rosetta and Philae mission. We have identified and described all the operational constraints that must be fulfilled to ensure a good science return from this experiment. By analyzing these requirements, with the collaboration of all operational teams, we could implement specific tools and methods that meet the standard RSGS and RLGS planning processes. Thereby, CONSERT was ready for the Long-Term Science operations on Rosetta and Philae.

Unfortunately, only one sequence of science measurements have been achieved during the First Science Sequence (FSS) operation phase: the first 67P/C-G revolution immediately following Philae's landing (12 November 18:56 to 13 November 04:00 UTC). This very first operation sequence was planned and commanded in a very specific way because it includes the landing phase. The analysis of the data retrieved [4] from this measurement sequence was complicated by the lack of knowledge of the final landing location. Indeed, Philae did not land nominally and bounced to an unexpected region of the nucleus. Thanks to additional operations of ranging made by CONSERT in visibility with Philae at the end of the FSS, we could set a 21 × 34 m area in which the lander is located [15]. Inside this area, SONC-FD fine-tuned the Philae location by analyzing illumination and communication link conditions. Its orientation has been estimated by SONC-FD and ROMAP teams [8–10,15,18].

The tools and methods were implemented for the planning of the first two months following the landing. It has proved its effectiveness in the planning process despite the unexpected landing which subsequently prevented any operational execution.

The complexity of CONSERT operations in the scope of the Rosetta mission was mostly due to the complexity of the Rosetta planning itself. In particular, the unexpected comet shape, in-situ constraints and the relatively high number of instruments on board have made the planning process difficult. Thanks to this experience, our team gained fruitful know-how in order to operate any other lander–orbiter combined instrument for future missions.

Acknowledgments

Rosetta is an ESA mission with contributions from its member states and NASA.

Rosetta's Philae lander is provided by a consortium led by DLR, MPS, CNES and ASI.

The CONSERT instrument was designed, built and operated by IPAG, LATMOS and MPS and was financially supported on Rosetta project by “CNES, France”, “CNRS, France”, “UGA, France”, “DLR, Germany” and “MPS, Germany”.

The authors would like to thank the teams of Rosetta (RMOC and RSGS) and Philae (LCC and SONC) for making possible the CONSERT operations.

They also thank the OSIRIS teams for the provision of the comet nucleus shape models.

Most of the computations presented in this paper were performed using the CIMENT infrastructure (https://ciment.ujf-grenoble.fr), including the Froggy platform, which is supported by the Rhône-Alpes region (Grant CPER07_13 CIRA), the OSUG@2020 labex (reference ANR10 LABX56), the Equip@Meso project (reference ANR-10-EQPX-29-01) of the program Investissements d'Avenir supervised by the Agence Nationale pour la Recherche and France-Grille (http://www.france-grilles.fr).

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

Appendix A. CONSERT specifications

In Table A.1, the main CONSERT instrument specifications are summarized [5,17].

Table A.1
Main parameters of the Philae Lander and Orbiter CONSERT instruments [17].

SPECIFICATION	VALUES
Mass	3 kg on Orbiter, 2.3 kg on Philae
Average power	3 W on Orbiter and on Philae
Peak power	11 W on Orbiter and on Philae
Clocks	10 MHz Sorep micro-OCXO (Oven Controlled Crystal Oscillator)
Nominal operation	$\Delta f/f < 2\ 10^{-7}$
Degraded mode if offset	$2\ 10^{-7} < \Delta f/f < 4\ 10^{-7}$
Transmission	90 MHz carrier, BPSK modulation
Pseudo noise code	255×100 ns$=$25.5 μs
Code repetition	Up to 200 ms
RF power	2 W/Orbiter, 0.2 W/Lander
Receiver	Band 86–94 MHz (-3 dB), linear phase
Gain range	30–90 dB with AGC
Demodulation	I and Q “synchronous” detection
ADC	8 bits 10 MHz ADC on each channel
Processing	
Real time coherent integrations	1024 code periods (26 ms, $+30$ dB on SNR) 256 periods ($+24$ dB on SNR), in degraded mode.
On-board the Lander	Code compression ($+24$ dB on SNR) and peak detection
Telemetry (**data rate**)	Orbiter: 8 kbits/measurement point ~ 65 Mbits/Orbit Lander: ~20 Mbits/Orbit (depending on how often the complete set of data will be transmitted)

Appendix B. CONSERT operation commanding

The implementation details of a single CONSERT science sequence consists in the definition of the command parameters in Table B.1.

All these parameters are set for each science sequence. Depending on their actual value the CONSERT instrument will consume more or less energy and data volume, mostly with the delta sounding value and number of soundings. These consumptions are evaluated and specified for each observation request.

Table B.1
CONSERT science operation commanding parameters.

PARAMETER	DESCRIPTION	TYPIC VALUE
Sequence		
OCN start time	The UTC date and time when CONSERT sequence starts, OCN is switched ON	
OCN stop time	The UTC date and time when CONSERT sequence ends, OCN is switched OFF	
LCN start time	LCN shall be switched ON with less than 10 s delay by regard to OCN ON	
LCN stop time	LCN is switched OFF before OCN to allow pure noise measurement	10 min
Tuning		
Tuning start	After switch ON, CONSERT units warms-up and are waiting to start the tuning phase. This parameter sets this waiting time.	6 min (hard coded)
Sounding – ***These parameters have a strong influence on power and data volume budgets***		
Sounding start	After the tuning phase, the units wait for the beginning of sounding. This parameter sets the duration of this waiting time.	2 h
Delta sounding	Time step between each sounding.	2.5 s
Number of soundings	The total number of soundings to perform for the whole sequence.	11,500 (10 h sequence)
LCN FIOV	On the lander unit, the data volume is more critical than on OCN. This parameter allow to store the complete signal measurement only each specified number of soundings. This limits the overall data volume in lander telemetry.	25

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

Appendix C. Comparison of Rosetta and Philae mission schedule by regard to the landing

See Table C.1

Table C.1
Rosetta and Philae mission phases and operation planning. We focus there on the first nominal science operation phase for the lander (beginning of LTS). It occurs one week after the landing and Philae's FSS.

Rosetta spacecraft activity		Rosetta planning process for end of November to mid December 2014 operations		Philae landing site knowledge	Philae mission phase	
20/01/2014	Wake-up from hibernation					
	SC Post-Hibernation Commissioning (PHC)		*Planning of previous operations*			
17/03/2014						
	Payload PHC Comet detection, rendez-vous and approach	14/04/2014	Long Term Planning (LTP4): RSGS provides Rosetta trajectory request	Unknown	Mid-July 2014	First comet shapes
01/08/2014	Comet characterization, global mapping	01/09/2014	RMOC analysis Rosetta trajectory frozen		24/08/2014	Landing Site Selection Process (LSSP)
29/09/2014	Close observation	29/09/2014	Medium Term Planning (MTP10): RSGS provides attitude and resource envelopps request			
		22/10/2014	RMOC analysis Attitude and resource envelopes frozen		13/10/2014	Lander Delivery Preparation (LDP)
24/10/2014	Lander delivery and relay orbit	29/10/2014	Short Term Planning (STP30): Finalization of commands	Planned but still uncertain		
		03/11/2014	Finalization for STP31			
		10/11/2014	Finalization for STP32		12/11/2014	Separation, Descent and Landing (SDL) First Science Sequence (FSS)
		17/11/2014	Finalization for STP33		15/11/2014	Long Term Science (LTS)
21/11/2014	Escort phase begins Execution of STP30	24/11/2014	Finalization for STP34	Known (in case of successful landing)		
25/11/2014	Execution of STP31		*LTP/MTP/STP planning cylces continue…*			
02/12/2014	Execution of STP32					
09/12/2014	Execution of STP33					
16/12/2014	STPs exeution continue during escort phase…					
					March 2015	End of Mission
Sept. 2016	End of Mission	July 2016				

Appendix D. RSGS planning cycle

Below is the nominal planning process for Rosetta operations (Fig. D.1):

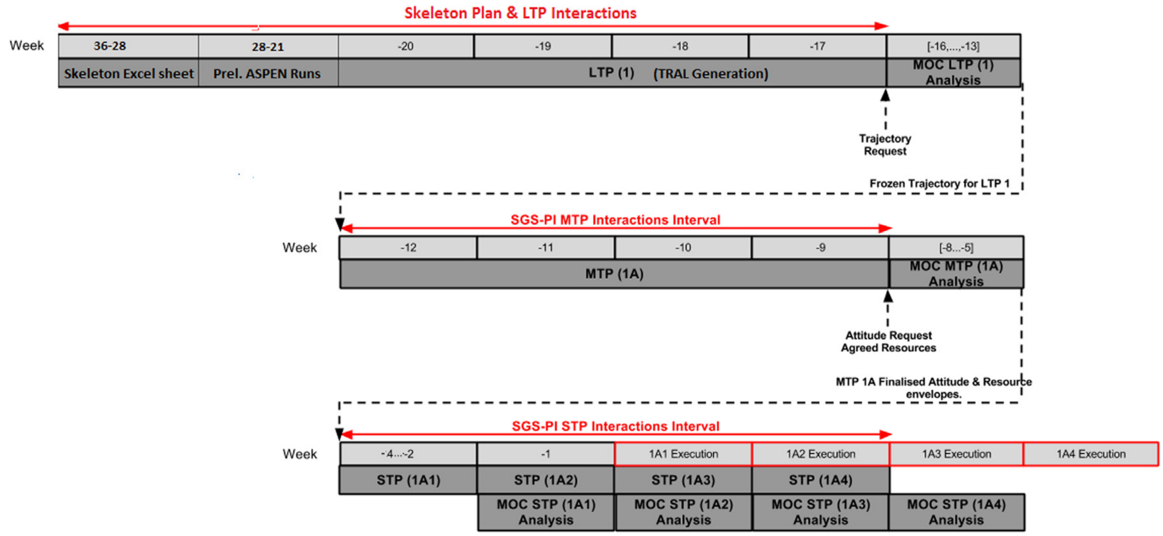


Fig. D.1. The three nominal RSGS planning cycles.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

1. Skeleton Planning, or Long-Term Planning (LTP): This planning cycle covers 4 months of operations and results into delivery of a trajectory request 4 months before their execution start. In the preceding months, the trajectory requests are defined through negotiations within and between Science Discipline Groups (DG). It takes into account two levels of comet activity. The instrument teams distributed within DG discuss and adjust the proposed orbits and set their preferences of pointing and the type of observations they will perform, with 6 h granularity. This is done using skeleton planning spreadsheets in which conflicting observation request between instruments can be highlighted and fixed. An envelope of the shared data volume and power needed is also estimated.
2. Medium-Term Planning (MTP): It covers 4 weeks of operations and occurs 2 months prior to their executions start. The main objective of this 2 months iteration cycle is to finalize exact pointing requests and resource sharing (data volume and power consumption), along with a first draft of operation commanding. The resource envelopes are computed from commanding definition files (ITL) and instrument operation slots are defined through events files (EVF). The pointing requests are defined in a single file for the whole MTP (PTRM). These complex iterations are facilitated thanks to the visual software tool MAPPS and exchange platforms (with version control and automated checking systems) through specific formatted files dedicated to pointing, commanding and resource requests. At the end of an MTP cycle, the ITL and EVF files are processed and consolidated request files are sent to RMOC for analysis and validation (PORM).
3. Short-Term Planning (STP): It covers 1 week of operations and file delivery occur 1 week prior the execution start. The purpose of this cycle is to finalize and validate the commanding of payload. RMOC then checks and validate the final commands.
4. Very-Short-Term Planning (VSTP): During the execution period of a STP cycle, three to four days of operations are treated in a VSTP on RMOC side. At this level, operations could be fine-tuned by RSGS only in case of contingency. At last, RMOC sends the final command to the spacecraft for execution.

All those interactions are done through computer network exchanges but also thanks to weekly teleconference to handle teams' negotiations and arbitrations. This describes the nominal planning process; contingency operations are not treated here.

At the end of each cycle, RSGS provides to RMOC the resulting planning products of the payload teams' iterations. RMOC analyzes and validates them so the next cycle can then begin (Fig. D.1).

Appendix E. CONSERT operational events definitions

See Table E.1.

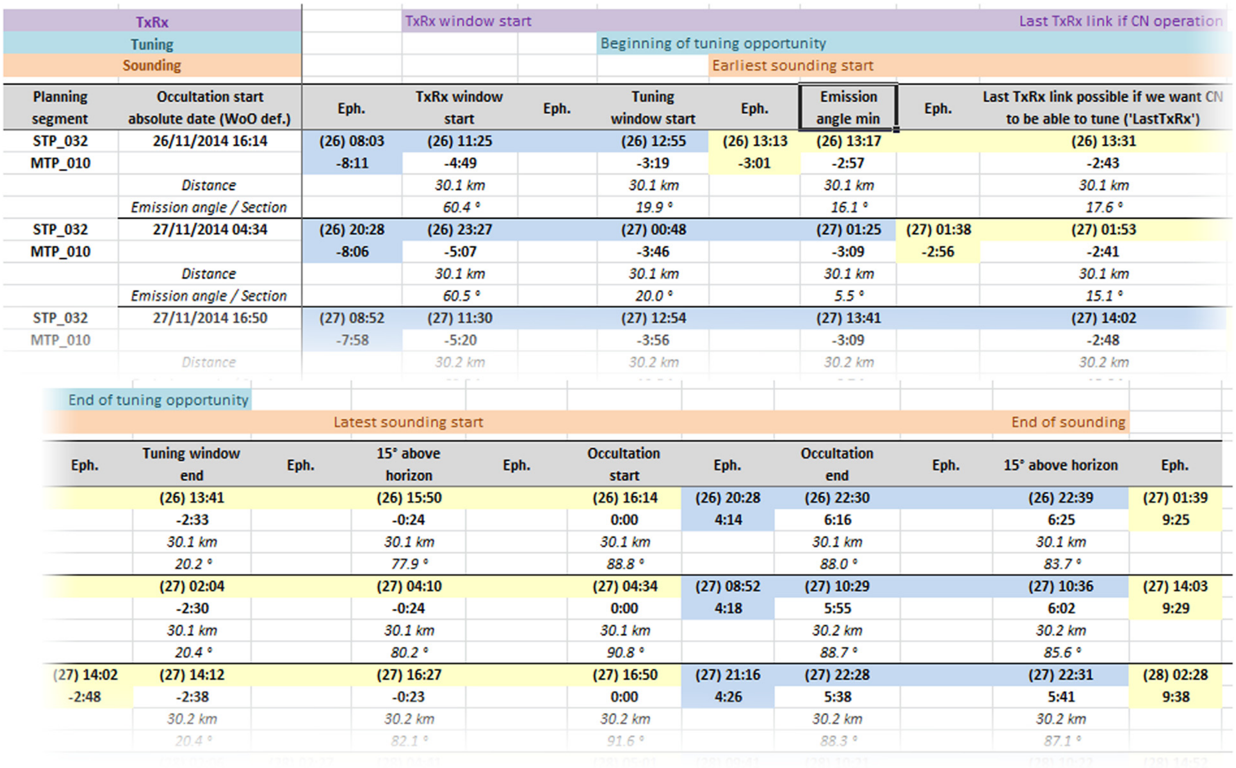
Table E.1
RLGS operation events.

EVENT	DESCRIPTION
CONSERT events	
BOCN / EOCN	Beginning and end of the occultation phase. This includes the margin in visibility.
BCTZ / ECTZ	Beginning and end of the tuning phase.
Lander events	
AORF / LORF	Acquisition and loss of signal Lander–Orbiter. Communication link between Rosetta and Philae is possible between these two events.
BLEC/ELEC	Beginning and end of the lander in eclipse. Sun light reaches Philae outside these two events.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

Appendix F. CONSERT windows of opportunity detection tool

See Figs. F.1 and F.2.



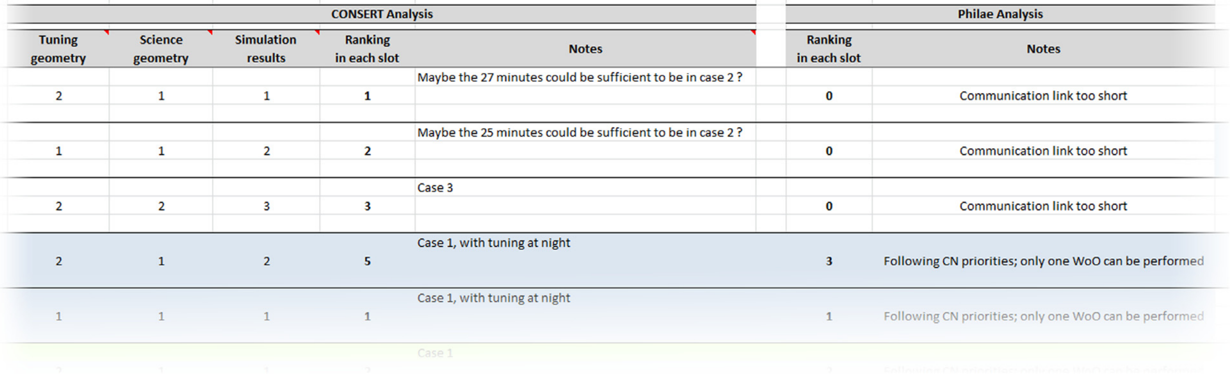
TxRx — TxRx window start — Last TxRx link if CN operation
Tuning — Beginning of tuning opportunity
Sounding — Earliest sounding start

Planning segment	Occultation start absolute date (WoO def.)	Eph.	TxRx window start	Eph.	Tuning window start	Eph.	Emission angle min	Eph.	Last TxRx link possible if we want CN to be able to tune ('LastTxRx')
STP_032	26/11/2014 16:14	(26) 08:03	(26) 11:25		(26) 12:55	(26) 13:13	(26) 13:17		(26) 13:31
MTP_010		-8:11	-4:49		-3:19	-3:01	-2:57		-2:43
	Distance		*30.1 km*		*30.1 km*		*30.1 km*		*30.1 km*
	Emission angle / Section		*60.4 °*		*19.9 °*		*16.1 °*		*17.6 °*
STP_032	27/11/2014 04:34	(26) 20:28	(26) 23:27		(27) 00:48		(27) 01:25	(27) 01:38	(27) 01:53
MTP_010		-8:06	-5:07		-3:46		-3:09	-2:56	-2:41
	Distance		*30.1 km*		*30.1 km*		*30.1 km*		*30.1 km*
	Emission angle / Section		*60.5 °*		*20.0 °*		*5.5 °*		*15.1 °*
STP_032	27/11/2014 16:50	(27) 08:52	(27) 11:30		(27) 12:54		(27) 13:41		(27) 14:02
MTP_010		-7:58	-5:20		-3:56		-3:09		-2:48
	Distance		*30.2 km*		*30.2 km*		*30.2 km*		*30.2 km*

End of tuning opportunity
Latest sounding start — End of sounding

Eph.	Tuning window end	Eph.	15° above horizon	Eph.	Occultation start	Eph.	Occultation end	Eph.	15° above horizon	Eph.
	(26) 13:41		(26) 15:50		(26) 16:14	(26) 20:28	(26) 22:30		(26) 22:39	(27) 01:39
	-2:33		-0:24		0:00	4:14	6:16		6:25	9:25
	30.1 km		*30.1 km*		*30.1 km*		*30.1 km*		*30.1 km*	
	20.2 °		*77.9 °*		*88.8 °*		*88.0 °*		*83.7 °*	
	(27) 02:04		(27) 04:10		(27) 04:34	(27) 08:52	(27) 10:29		(27) 10:36	(27) 14:03
	-2:30		-0:24		0:00	4:18	5:55		6:02	9:29
	30.1 km		*30.1 km*		*30.1 km*		*30.2 km*		*30.2 km*	
	20.4 °		*80.2 °*		*90.8 °*		*88.7 °*		*85.6 °*	
(27) 14:02	(27) 14:12		(27) 16:27		(27) 16:50	(27) 21:16	(27) 22:28		(27) 22:31	(28) 02:28
-2:48	-2:38		-0:23		0:00	4:26	5:38		5:41	9:38
	30.2 km		*30.2 km*		*30.2 km*		*30.2 km*		*30.2 km*	
	20.4 °		*82.1 °*		*91.6 °*		*88.3 °*		*87.1 °*	

Fig. F.1. CONSERT windows of opportunity chronogram in the WoO interaction document. In this extract, we can see three WoO rows: the two first columns give information of the global schedule of the WoO. Each column corresponds to specific events. Yellow and blue cells designate respectively day and night at landing site.



CONSERT Analysis					Philae Analysis	
Tuning geometry	**Science geometry**	**Simulation results**	**Ranking in each slot**	**Notes**	**Ranking in each slot**	**Notes**
2	1	1	**1**	Maybe the 27 minutes could be sufficient to be in case 2 ?	**0**	Communication link too short
1	1	2	**2**	Maybe the 25 minutes could be sufficient to be in case 2 ?	**0**	Communication link too short
2	2	3	**3**	Case 3	**0**	Communication link too short
2	1	2	**5**	Case 1, with tuning at night	**3**	Following CN priorities; only one WoO can be performed
1	1	1	1	Case 1, with tuning at night	1	Following CN priorities; only one WoO can be performed
				Case 1		

Fig. F.2. Ranking with comments columns in the WoO interaction document.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

Appendix G. CONSERT with Philae operations configuration cases

See Table G.1.

Table G.1
CONSERT WoO configuration case for lander operation.

#	CONFIGURATION	DESCRIPTION
0	**Optimal**	All the constraints are fulfilled for Philae and CONSERT operations. Sufficient time is available to boot Philae, download the commands (TC) from Rosetta, upload the remaining telemetry (TM) and then perform the CONSERT tuning, in that order.
1	**Philae TxRx window starts at sunset**	Sunset arrives before Philae is able to transmit all its telemetry to Rosetta, with margins. With respect to the data volume to be uploaded to Rosetta, LCC evaluates finely if CONSERT tuning can take place at the end of the initialization sequence of Philae.
2	**Philae TxRx window too short at sunset**	Here, the margins are not available. Nevertheless, it is possible to envisage the possibility of doing the CONSERT tuning between Philae TC upload and TM download. LCC analyze the specific situation and decide whether or not it is acceptable.
3	**Philae TxRx window too short at sunrise**	The situation is similar to #3 but here at sun rise. The situation is more acceptable because solar power will become available, instead of disappearing.
4	**Tuning window by night**	The entire tuning slot occurs by night. If we want to operate CONSERT in this situation, LCC must leave Philae ON since the last TxRx window of the comet day before. This difficult configuration will be operated only in case of exceptional situation.
5	**Philae TxRx window starts at extreme sunset**	This is the extreme case of #2, with all initialization operation of Philae to be done in the early period of the night. The consequences are the same as #4.
6	**Impossible**	The tuning is not possible at all, mostly due to a too short TxRx window.

Appendix H. List of abbreviations and acronyms

ACRONYM	DESCRIPTION	ACRONYM	DESCRIPTION
67P/C-G	67P/Churyumov-Gerasimenko	**OEF**	Opportunity Event File
CNES	Centre National d'Etudes Spatiales	**OSIRIS**	Optical, Spectrocopic and Infrared Remote Imaging System
CONSERT	Comet Nucleus Sounding Experiment by Radiowave Transmission	**RLGS**	Rosetta Lander Ground Segment
DLR	Deutsches Zentrum für Luft und Raumfahrt	**RMOC**	Rosetta Mission Operation Centre
ESAC	European Space Astronomy Centre	**ROMAP**	Rosetta Lander Magnetometer and Plasma Monitor
ESOC	European Space Operation Centre	**ROSINA**	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis)
FSS	First Science Sequence	**RPC**	Rosetta Plasma Consortium
GIADA	Grain Impact Analyser and Dust Accumulator	**RSGS**	Rosetta Science Ground Segment
GRM	Ground Reference Model	**RSI**	Radio Science Investigation
LCC	Philae Lander Control Center	**S/C**	Spacecraft
LCN	Lander CONSERT unit	**SD2**	Sample and Distribution Device
LHEP	Left Handed Elliptic Polarization	**SDL**	Separation Descent and Landing
LIOR	Lander Instrument Operation Request	**SESAME**	Surface Electrical Sounding and Acoustic Monitoring Experiments
LOBT	Lander On-Board Time	**SimSERT**	Simulation for Sounding Experiment by Radiowave Transmission
LOR	Lander Operation Request	**SOCOP**	Specific On-Comet Operation Plan
LSSP	Landing Site Selection Process	**SONC**	Philae Science Operations and Navigation Center
LTP	Long-Term Planning	**SONC-FD**	SONC Flight Dynamics
LTS	Long Term Science	**STP**	Short-Term Planning
MTP	Mid-Term Planning	**VIRTIS**	Visible and Infrared Thermal Imaging Spectrometer
MUPUS	Multi-Purpose Sensors for Surface and Subsurface Science	**VSTP**	Very Short-Term Planning
OCN	Orbiter CONSERT unit	**WoO**	Window of Opportunity

References

[1] W. Kofman, et al., Comet nucleus sounding experiment by radiowave transmission, Adv. Space Res. 21 (1998) 1589–1598, http://dx.doi.org/10.1016/S0273-1177(97)00952-6.

[2] A. Herique, et al., A characterisation of a comet nucleus interior: inversion of simulated radio frequency data, Planet. Space Sci. 47 (1999) 885–904.

[3] W. Kofman, et al., The Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT): a short description of the instrument and of the commissioning stages, Space Sci. Rev. 128 (2007) 413–432, http://dx.doi.org/10.1007/s11214-006-90340-9.

[4] W. Kofman, et al., Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar, Sci. Rev. 349 (2015) 6247, http://dx.doi.org/10.1126/science.aab0639.

[5] Y. Barbin, et al., The CONSERT Instrument for the Rosetta mission, Adv. Space Res. 24 (1999) 1115–1126.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010

[6] R. Hahnel, S. Hegler, Ch Statz, D. Plettemeier, S. Zine, A. Herique, W. Kofman, CONSERT line-of-sight link budget simulator, Planet. Space Sci. 111 (2015) 55–61, http://dx.doi.org/10.1016/j.pss.2015.03.011.

[7] A. Accomazzo, S. Lodiot, V. Companys, Rosetta mission operations for landing, Acta Astronaut (2016), http://dx.doi.org/10.1016/j.actaastro.2016.01.013.

[8] S. Ulamec, et al., Rosetta Lander – landing and operations on comet 67P/Churyumov-Gerasimenko, Acta Astronaut (2016), http://dx.doi.org/10.1016/j.actaastro.2015.11.029.

[9] T. Martin, et al., Flight dynamics analysis for Philae Landing Site Selection, in: Proceedings of the 25th International Symposium on Space Flight Dynamics, Munich, 2015.

[10] E. Canalias, et al., Philae's Flight Dynamics challenges: report of the landing on a comet, in: Proceedings of the 66th International Astronautical Congress, IAC-15,C1,1,1,x28720, Jerusalem, 2015.

[11] C.H. Acton, Ancillary data services of NASA's navigation and ancillary information facility, Planet. Space Sci. 44 (1) (1996) 65–70.

[12] M. Ashman, et al., Rosetta science operations in support of the Philae mission, Acta Astronaut., 2016, this issue.

[13] M. Born, E. Wolf., Principles of optics, Pergamon Press, New-York, 1970.

[14] M. Benna, et al., Generation of 3D synthetic data for the modeling of the CONSERT experiment. (the radio tomography of comet Wirtanen), IEEE Transaction on antennas and propagation 52 (3) (2004) 709–716, http://dx.doi.org/10.1109/TAP.2004.825564.

[15] A. Herique, et al., PHILAE localization from CONSERT/ROSETTA measurement, Planet. Space Sci. 117 (2015) 475–484, http://dx.doi.org/10.1016/j.pss.2015.08.020.

[16] S. Ulamec, J. Biele, A. Blazquez, B. Cozzoni, C. Fantinati, P. Gaudon, K. Geurts, E. Jurado, O. Küchemann, V. Lommatsch, M. Maibaum, H. Sierks, L. Witte, Rosetta Lander – Philae: landing preparations, Acta Astron. 107 (2015) 79–86.

[17] A. Herique, et al., Rosetta rendezvous and CONSERT operations in 2014: a chimeric surface model of 67P/Churyumov-Gerasimenko, Planet. Space Sci. (2012), http://dx.doi.org/10.1016/j.pss.2012.03.003.

[18] P. Heinish, et al., Attitude reconstruction of Rosetta's lander Philae using two-point magnetic field observations by ROMAP and RPC-MAG, submitted to Acta Astronaut., this Issue.

Please cite this article as: Y. Rogez, et al., The CONSERT operations planning process for the Rosetta mission, Acta Astronautica (2016), http://dx.doi.org/10.1016/j.actaastro.2016.03.010