FLIGHT DYNAMICS ANALYSIS FOR PHILAE LANDING SITE SELECTION

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Abstract: *Among the main challenges encountered by the flight dynamics teams for Rosetta and Philae missions was the selection of the landing site. A large amount of data regarding the target body Churyumov-Gerasimenko was unknown before Rosetta would arrive in the comet vicinity. Only at that moment the selection process could be started with the availability of measurements performed by the Rosetta instruments.*
In consequence, the time allocated to comet observation and characterization was quite short due to the restrained availability of comet data and the fact that the Philae landing had to occur before the passage of the comet at a distance of 3 Astronomical Units from the Sun. Therefore the setup of an operational organization was mandatory in order to carry out this selection process under severe time constraints.
The Philae Landing Site Selection Process (LSSP) aimed to find a nominal site and a backup that complied with the multiple constraints of Rosetta and Philae as well as mission constraints for long term operations on the comet. Obviously, the site required scientific approval as well. The Landing Site Selection Process (LSSP) was mainly driven by the observations necessary to characterize the comets in the various mission phases.
This paper addresses the operational context, the mission constraints as well as the flight dynamics analyses carried out for the Philae landing site selection process. It describes the relations between the Rosetta approach trajectory, the model availability, the flight dynamics analysis and the LSSP decision steps.

Keywords: *Philae, Landing site selection, Comet descent trajectory, Comet 67P/Churyumov-Gerasimenko*

1. Introduction

Philae, the lander of the ROSETTA mission successfully reached the surface of the comet Churyumov-Gerasimenko on 12 November 2014. The controlled landing on the comet, accomplished by the joint work of the ESA, DLR, CNES and scientific teams, is an outstanding achievement and will probably mark the history of space exploration. The Science Operation and

Navigation Center (SONC), located in CNES Toulouse, was in charge of flight dynamics (FD) support for the lander team.
Rosetta, a cornerstone mission of the European Space Agency (ESA) Horizon 2000 program, reached its target comet 67P/Churyumov-Gerasimenko in August 2014 after a 10 years cruise in the Solar System. Since july 2015, Rosetta moved closer to the comet allowing more and more accurate observations and scientific measurements.
These preliminary data contributed to a comprehensive characterization of the comet resulting in different models necessary for the landing site selection and descent preparation. In order to minimize the risks these comets models have been used for flight dynamics and system analysis to fine tune the design of the descent and landing scheme. While the scientific interest of the Landing Site has of course been an obvious driver for the selection, some technical constraints due to Lander and Orbiter design had to be fulfilled. Undeniably, safe landing had the highest priority.
In the end scientists and engineers agreed upon the selection of one site which was called Agilka. The Philae lander succeeded in reaching it with an amazing accuracy. But unfortunately, due to a double failure of the hold-down thrust and of the anchoring harpoons, Philae bounced off the comet surface and came to rest only after 1h50min. Yet it was able to carry out its main mission and most of its 10 instruments made first in-situ analyses of a comet.

2. Organization

Rosetta is operated by ESA from Rosetta Mission Operation Center (RMOC) at ESOC, (Darmstadt, Germany). Rosetta science operation planning is performed at Rosetta Science Ground Segment (RSGS) at ESAC (Villafranca near Madrid, Spain). Philae is operated from the LCC (Lander Control Centre) at DLR (Cologne, Germany) and from the SONC (Science Operations and Navigation Centre) at CNES (Toulouse, France). Both centers constitute the Rosetta Lander Ground Segment (RLGS).
Within the framework of the determination of the landing scenario and the selection of the landing site, all centers were activated with different charges and shared responsibilities. The RMOC was in charge of the Rosetta trajectory which has to be consistent with the Lander descent trajectory and the selected landing point. RLGS is in charge of analyzing the comet characteristics in order to propose landing sites feasible in term of delivery scenario and descent trajectory and that complies with Philae constraints.

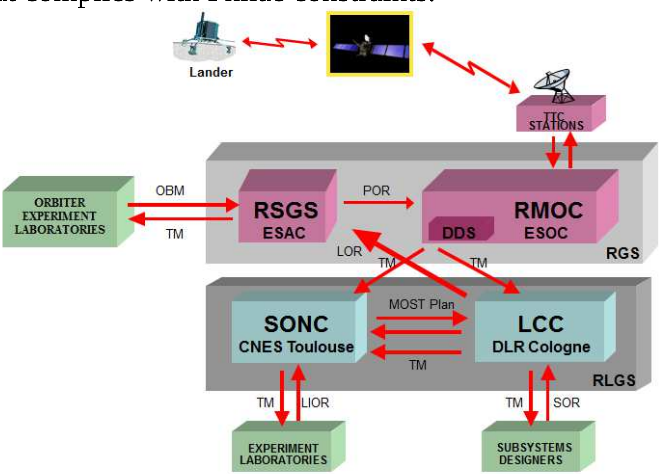


Figure 1 : Lander and Orbiter Science and Control Centers

3. Models Availability and Landing Site Selection Process (LSSP)

3.1 LSSP timing

The selection of the Landing Site was determined by two main drivers:

- Availability and accuracy of the characteristics of the comet
- Landing before the Sun distance at 3 AU.

These two features have set the schedule of the selection process. This complex and critical process was conducted from July to October 2014.

Three main deadlines were identified. In the subsequent table the reference date for landing was 11th November 2014.

Table 1 : LSSP milestones

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

3.2 Nature of analyses and models

As Rosetta was approaching the comet, the observations became more and more accurate. These observations were used to derive input data and comet models for LSSP analyses. The following matrix sums up the type of analyses, the needed input data and the flight dynamics products.

Table 2 : Models and flight dynamics analysis

Model	Origin	Purpose
Comet Ephemerides	RMOC	Illumination analysis Trajectory analysis
Rotational state	RMOC OSIRIS	Define the transformation EME 2000 to Comet Fixed Frame
Global DTM	RMOC OSIRIS	Illumination analysis Trajectory analysis
Local DTM	OSIRIS	Local slope analysis
Gravity Field	RMOC CNES GRGS	Trajectory analysis
Outgassing	RMOC LATMOS	Trajectory analysis
Boulder distribution	OSIRIS	Landing Risk analysis
Rosetta and Philae trajectories	RMOC	Trajectory analysis / cross check

SONC decided to use all available models for the LSSP. The advantages were a cross validation between models and a sensitivity analysis of the results with respects to the input data. The drawback is that it induces more combination cases to study and thus requires more time. The final trajectory was computed by using the operational (RMOC) models.

Table 3 : LSSP objectives and Flight dynamics analyses

Objectives	Type of analyses	Input data	Technical products used for selection
Preliminary analyses	Parametric analyses assuming various comet masses	- First global DTM - Comet rotation & ephemeris	Accessibility maps
Selection of 5 candidate landing sites.	Whole comet analyses	- Global DTM - Comet rotation & ephemeris - Gravity field - Outgassing model	- Global topographic analysis, - Global illumination maps - Reachable areas Illumination of the lander (short and long term) RF links opportunities (short and long term)
Selection nominal and backup landing.	Analysis of Feasibility for 5 pre-selected sites	- Local DTMs, - Comet rotation & ephemeris - Gravity field update - Outgassing model update	- Local slopes analyses around the landing sites, - Local illumination analyses, - Expected dispersions for landing trajectories - RF links opportunities
Confirmation of the nominal landing site.	Analysis of nominal and back up site	- Boulder statistics - Last updates on gravity field and outgassing models	- Risk at landing (landing on a boulder), - Refined local slopes and - Illumination conditions analyses, - refined dispersion analyses for landing trajectories

All Digital Terrain Models (DTM), whether global or local, were polyhedron constructed with triangular faces. OSIRIS and RMOC DTM were rather consistent with few differences. ORISIS reference frame used for the DTM was aligned carefully on RMOC reference frame. However some residual misalignments subsisted. Some parts of the comet were always in the night and thus no reconstruction could be made.

4. Rosetta, Philae and mission constraints

4.1 Rosetta constraints

The Rosetta constraints were mainly related to the safety and the navigability of the orbiter during the delivery scenario.

- In order to ensure Rosetta safety, Rosetta must be farther than 5 km from comet surface.
- The relative navigation of the Orbiter around the comet was performed thanks to optical navigation based on the NAVCAM measurements. In order to ensure proper illumination of the comet, the sun beta angle should stay between 0 and 20 degrees whereas the phase angle had to be maintained between 0 and 135 degrees.
- Flying “terminator orbits” (sun beta close to 0) also ensured the orbiter navigability and safety as the outgassing was minimum for such local hours.
- The orbiter off pointing shall be limited in order to guarantee proper orientation of solar panels with respect to the Sun and to guarantee the telecommunication link with the Earth.

4.2 Philae constraints

4.2.1 Philae descent and landing equipments

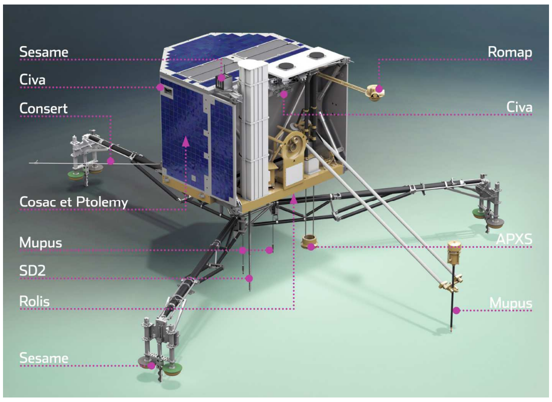


Figure 2: The Philae Lander and its payload

The Philae Lander is has a carbon fiber honeycomb structure. It has a power system including a solar generator, a central data management system and an S-band communications system, using the Rosetta orbiter as a relay. Philae carried a flywheel to stabilize the lander around its Z-axis during descent, and an Active Descent System (ADS), a thruster with a total ΔV capability of 1.85 m/s. It was planned to activate the ADS to perform a hold-on thrust after touchdown. The Philae Landing Gear consisted of a foldable tripod with legs and feet and a central structure hosting several mechanisms to execute the various LG functions. The main task of the Landing

Gear (LG) was absorption of the kinetic energy at touch-down during the landing on the comet. In addition the LG provided a mechanical interface for the anchors harpoons, which were attached to the LG's central structure and should have been activated after landing detection to avoid Philae bouncing after touchdown

4.2.2 Descent and touch down constraints

The Philae constraints were mainly related to the touch down condition and the descent duration. They are summarized in the following figure and table.

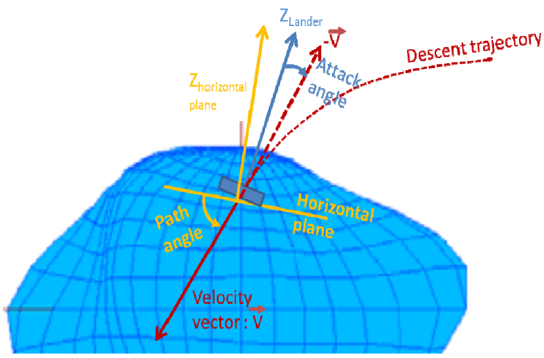


Figure 3: Philae landing conditions

Table 4 : Philae constraints

Philae descent and landing constraints			
Descent duration	30 min	360 min	
Attitude angle	0 deg	30 deg	Nominal value: 0 deg
Path angle	-90 deg	-60 deg	Nominal value: -90 deg
Attack angle	0 deg	30 deg	Nominal value: 0 deg
Velocity at impact	0,2 m/s	1.1 m/s	For landing detection /structural safety
Visibility orbiter lander	0 h	1 h	

The post landing visibility between Rosetta and Philae is guaranteed thanks to an orbiter maneuver.
Philae was separated from the Rosetta Orbiter with an adjustable ejection device, the Mechanical Separation System (MSS) that able to deliver a ΔV impulse ranging from 5 $cm.s^{-1}$ to 50 $cm.s^{-1}$. In case of separation mechanism failure, an emergency spring could also separate the Lander from the Orbiter with a 18.74 cm/s fixed impulse several seconds after the nominal separation time. But this was not necessary. Philae then descended to the surface of the comet on a pre-calculated ballistic trajectory, stabilized around its Z-axis by the internal fly-wheel. At touchdown, harpoons should have anchored Philae to ground and the ADS should have been fired to minimize any possible re-bouncing. This was not the case.

4.2.3 Long term science constraint

In order to ensure the proper functioning of Philae for the long Term Science Phase, the landing site should fulfils the illumination constraints provided in Table. 5.

Table 5: Illumination constraints

Illumination constraints		
	Value	Comments
Minimum	6.2h	About half of the period
Maximum	11.9h	30 minutes of night

4.2.4 Philae delivery scenario

The design of the delivery strategy encompassed the definition of Rosetta pre delivery maneuver, the selection of the separation strategy and the selection of a landing point. The selected strategy had to fulfill the Philae landing constraints and to be compatible with Rosetta requirements in term of navigability and safety.

The Orbiter trajectory for Philae delivery included several maneuvers. The pre delivery manoeuver was performed between 2 and 3 hours before the separation sequence was triggered. This maneuver brought the orbiter from the pre-delivery orbit (elliptic orbit 10 km x 20 km) to the separation trajectory. Due to the degrees of freedom introduced by the pre-delivery maneuver, it was then possible to have access to a large domain of points in the surface of the comet with acceptable conditions. A post-delivery maneuver is executed 30 minutes after separation (once attitude perturbations due to Lander separation have been damped) to optimize Lander - Orbiter visibility at landing.

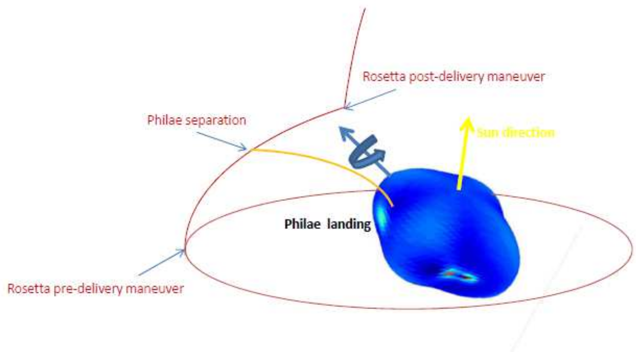


Figure 4 : Orbiter trajectory for Philae delivery.

Two operational strategies have been defined by RLGS for the Lander separation:

- O1 strategy: the separation ΔV tuned to the same value as the emergency separation ΔV (0.1874 m/s). With this strategy, in case of an emergency separation, the reached point at the comet surface was the same as the nominal targeted landing point. The drawback was its descent duration which was longer.
- O2 strategy: with the separation ΔV to be tuned between 0.3 m/s and 0.5 m/s. In practice, it was always tuned to its maximal value of 50 cm/s in order to limit the descent duration. Yet, for this strategy, in case of an emergency separation, the actual reached point would

be very far from the targeted one. Most often the Lander would have not impacted the comet surface.

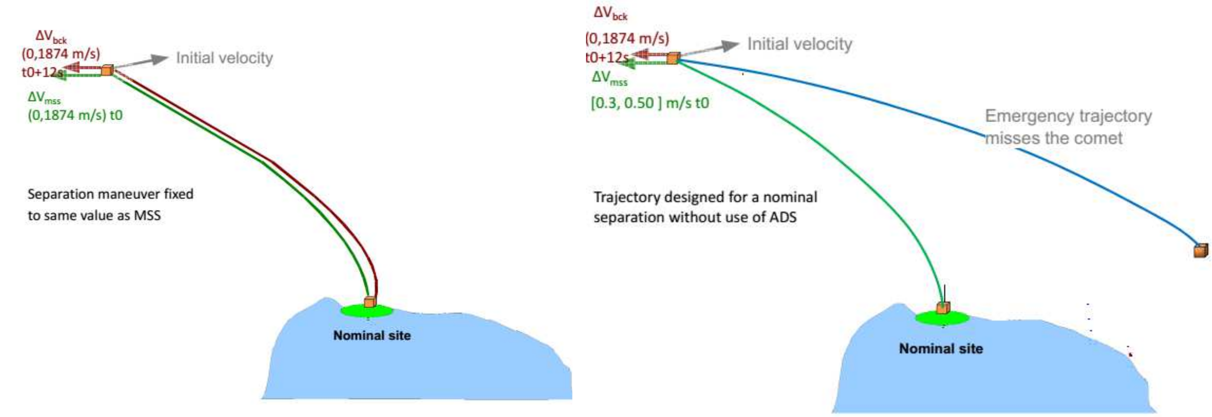


Figure 5 : Lander separation strategies O1 (left) and O2 (right)

5. Flight dynamics analyses for landing site selection

5.1 Preliminary analyses

The Philae landing site selection process started on the 25th July 2014 with the delivery of the first global shape model by OSIRIS team. It ended on the 12th October with the confirmation of site J (“Agilkia”) by RLGS. In the scope of the Landing Site Selection Process, the SONC Flight Dynamics (SONC-FD) team in Toulouse was in charge of computing the technical data for the selection. At that time, the target date for landing was 11th November 2014. Several loops of Flight Dynamics analyses were carried out with an improving knowledge of the comet nucleus and coma characteristics. A selection of several landing site were proposed and finally Agilkia was chosen.

Mid-July 2014, the OSIRIS camera aboard Rosetta showed the first images of the comet nucleus where the global shape was clearly visible. These first pictures were a real surprise for engineers and scientists since they revealed that comet 67/C-G had actually in two parts. Fig. 5 left is an image taken by OSIRIS camera from a distance of 12000 km on the 14th of July. Following this first set of images, the OSIRIS team delivered on 25th July the first comet model set (SHAP1 comet model set, fig. 5 right), including a global Digital Terrain Model (DTM) with an approximate horizontal resolution of 500 m. This model gave the first realistic overview of the comet nucleus. The total volume of the comet was estimated to be 20.28 km3.

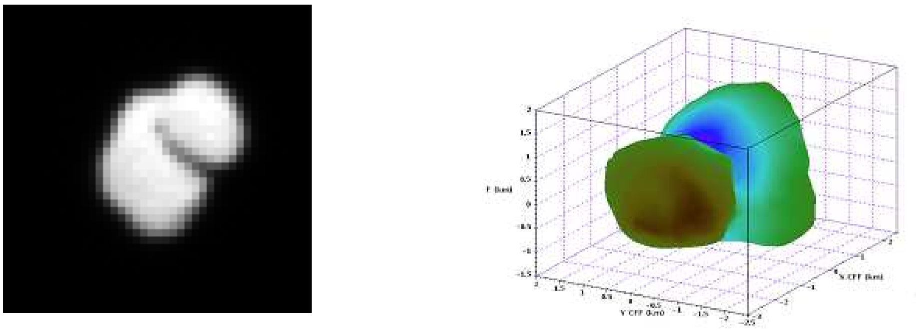


Figure 6 : Comet 67P/C-G seen by OSIRIS camera on 14th July 2014 (left, distance 12000km) and OSIRIS SHAP1 global DTM (right)

Associated with the shape model, the OSIRIS team delivered the orientation parameters of the comet, extrapolated up to till end of 2014. The comet rotation period was estimated at12.4043h at that time and to be stable.

Table 6 :Orientation parameters for the OSIRIS SHAP1 global DTM.

Pole declination in EME200	Pole right ascension in EME2000	Period
63.5 deg	72 deg	12.4043 h

Using the shape and the orientation parameters, the illumination conditions at comet surface for landing day (11th November at this step) have been computed (fig .6).

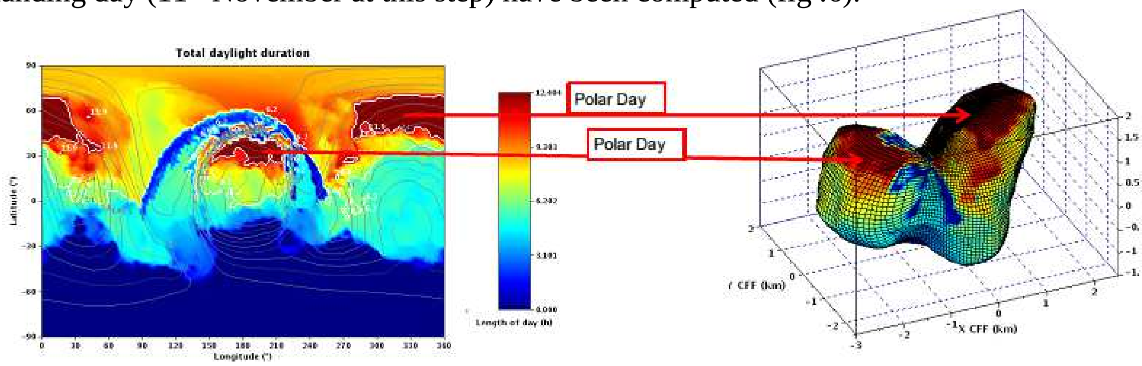


Figure 7 : Illumination conditions at comet surface (OSIRIS SHAP1).

An important constraint for the selection of the candidate landing sites were the illumination conditions. The landing site had to be sufficiently illuminated to enable correct recharging of the battery with the solar arrays. Moreover, some Lander instruments needed a minimum night period of at least 30 minutes. Taking into account the minimum day duration (6.2 hours) and the minimum night duration (30 minutes), the candidate landing sites had to be chosen in the North hemisphere, if possible excluding zones with polar day conditions.

For this first preliminary loop, no gravity model was available since Rosetta was still too far away and the gravitational force too weak to be estimated. The CNES-GRGS derived a gravity field from the shape model by assuming a constant density. As the real mass of the comet was unknown, it derived three different models with the following densities: 100 kg/m^3 (GM=135.4 $m^3.s^{-2}$), 370 kg/m^3 (GM = 501 $m^3.s^{-2}$) and 800 kg/m^3 (GM=1083 $m^3.s^{-2}$). This method is preferable to spherical harmonics expansion for small bodies whose shapes are far from being a sphere. For this kind of shape, Spherical Harmonics Expansion (SHE) may diverge inside the smallest sphere enclosing the whole body. Yet, constant density assumption may induce an offset of the center of mass position with respect to the actual one in case of heterogeneous small bodies.

These gravity fields were used to determine the area where the landing would be feasible. A search space was defined, taking into account the points at the comet surface where the illumination conditions were acceptable. For each of these points an exhaustive search was performed for acceptable landing trajectories (Orbiter delivery orbit and lander descent trajectory meeting technical constraints). Technically, the lander was considered impacting the comet surface at the targeted point with its +Z axis exactly aligned with the local normal. A scanning over different parameters inside pre-defined thresholds corresponding to the Lander and Orbiter constraints was performed. As soon as an acceptable trajectory was found, the landing point was considered to be “reachable”.

In this phase the goal was not to compute the actual delivery strategy but to ensure that RLGS would choose candidate landing sites inside the area where operational strategies exist. The complete search for a comet model took several days of CPU time. Different maps were produced, showing the impact of the comet mass.

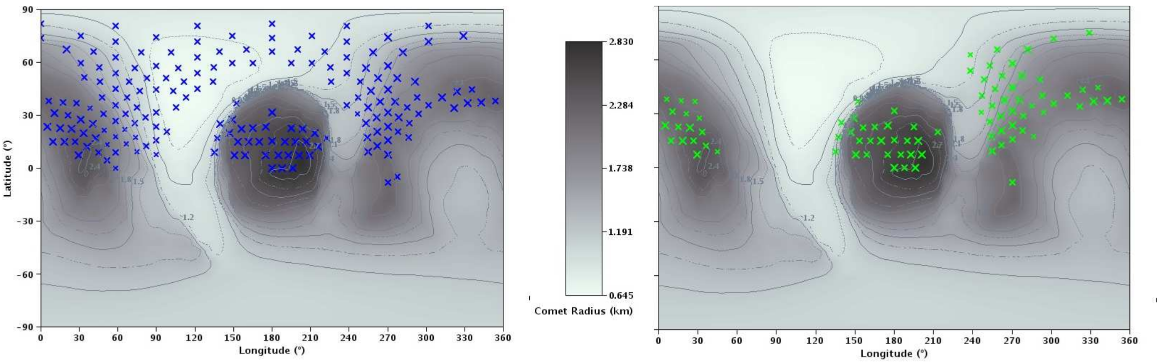


Figure 8 : Reachable areas for OSIRIS SHAP1 (density 100 kg.m-3 left, 800 kg.m-3 right).

“Heavy” comets were clearly less accessible for Philae. In case of a high density, the reachable areas would have reduced drastically, mainly due to the violation of the impact velocity.

5.2 Selection of 5 candidate landing sites

On 04th August 2014 began the first official LSSP loop with the delivery of the first comet model sets by RMOC and a refined comet model set by OSIRIS (SHAP2). At that time, the distance to the comet had been reduced significantly and the resolution of the comet models was greatly improved (about 20 meters horizontal resolution)

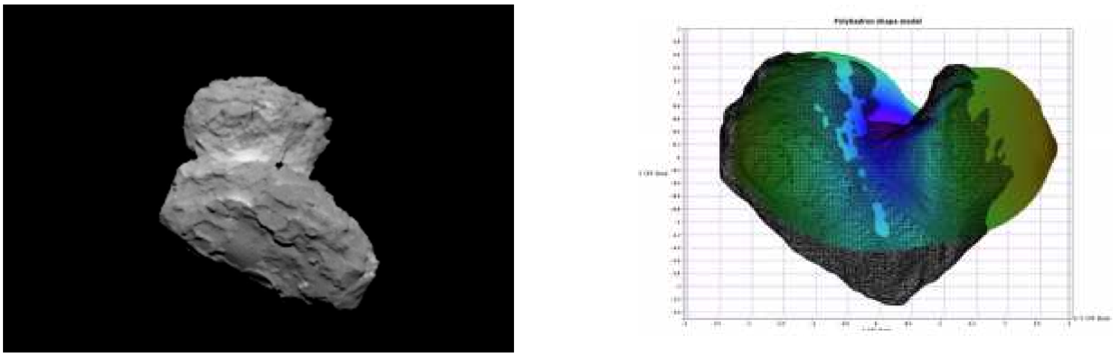


Figure 9 : Comet view OSIRIS 1000 km (left) and comparison of OSIRIS SHAP2 and RMOC global DTMs (right). OSIRIS DTM.

A comparison between the two comet models shows global consistency. A discrepancy could be observed in the South hemisphere, due to its very poor illumination of the zone. Reconstruction of the shape from images was not possible for this zone. The comet body-fixed frame defined by RMOC shape model was the reference frame for the navigation studies. In this context, the OSIRIS team tried to align as much as possible the axes of their shape model with the RMOC ones. The X-axis of the comet body-fixed frame (corresponding to the prime meridian) was then shifted about 180° w.r.t. OSIRIS SHAP1 reference frame. The prime meridian was then passing close to the middle of the great depression of the small lobe (the "head"). There was also a translation of about 285 m between RMOC and OSIRIS reference frames. Even if the reference frames were almost aligned (less than 0.1 deg rotation around Z), the translation of the origins implied a shift up to several degrees in latitude and longitude for a given point at the comet surface, in particular for high latitudes. This shift had to be taken into account when comparing specific topographic features on the RMOC and OSIRIS shape models.
The comet orientation parameters were also provided by both teams. They both showed a stable rotation with a period of about 12.404 hours, coherent with values computed with SHAP1 DTM (see Table 7). The following parameters were computed from the data provided by RMOC and OSIRIS teams.

Table 7 : Orientation parameters computed from OSIRIS and RMOC data.

Parameters	RMOC	OSIRIS
Right Ascension EME2000 (deg)	69.473	69.370
Declination EME2000 (deg)	64.011	64.132
Period (hours)	12.4038	12.4043

Using these input data the illumination conditions at comet surface were again computed for the targeted landing date (11th November) and one month later (to evaluate the evolution of these conditions at the candidate landing site). It showed that the zones where the illumination conditions were acceptable (more than 6.2 hours daylight duration and more than 30 minutes of night) represented only a rather small part of the comet surface as shown and the graphs here below. The acceptable zones were comparable to the ones determined using SHAP1 DTM.

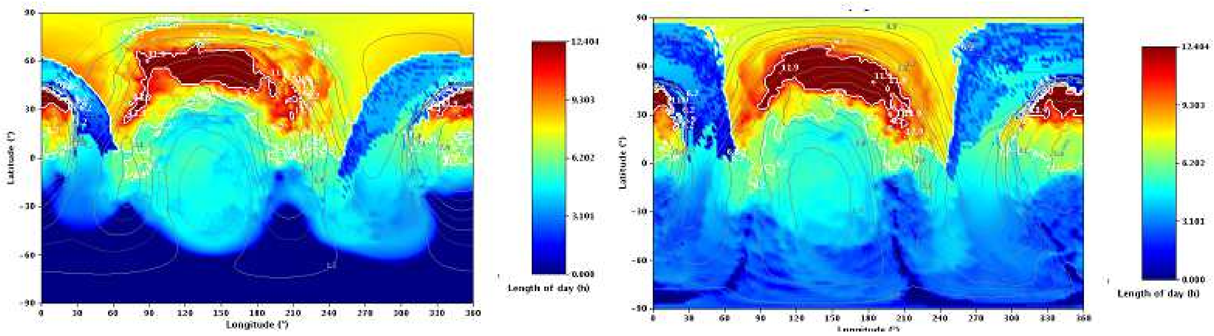


Figure 10 : illumination conditions from RMOC and OSIRIS shape models.

On the above plots the longitude 0 is shifted by 180 deg for the maps produced with OSIRIS SHAP1 DTM. Acceptable zones are similar, but low scale topographic features excludes additional zones (e.g. around the small lobe)

For each shape model, and for all points where illumination conditions are acceptable, an exhaustive search has been done to determine the reachable areas, as described above. To perform this analysis the gravitational field and outgassing forces have to be taken into account. RMOC delivered an estimation of the mass of the comet used for navigation. The corresponding gravitational field was then a simple mass point model, with the center of mass at center of the comet body-fixed frame. The GM estimated at this time from the navigation was 660 $m^3.s^{-2}$. The RMOC and OSIRIS shape models had different volumes (20.95 km^3 for OSIRIS, 23.17 km^3 for RMOC), corresponding to the respective density values: 427.1 $kg.m^{-3}$ (RMOC) and 471.2 $kg.m^{-3}$ (OSIRIS). Using the OSIRIS shape models, CNES-GRGS team generated a polyhedron gravity model using the constant density assumption. Comparison of the center of mass position resulting from the constant density assumption with the estimated position from the navigation data showed an offset of about 60 meters. This relatively small value confirmed that for this loop the polyhedron gravity field could be used.
In addition, SONC-FD used for the trajectory analyses an outgassing model provided by LATMOS team [3] using the first data from ROSINA measurement (see table below, production at 3 A.U.).

Table 8 :Parameters of LATMOS outgassing model

Molecule	H^2O	CO	CO^2
Q (molec/s)	$5e^{25}$	$1e^{25}$	$3e^{24}$

The ratio between the outgassing force and the gravitational force using this outgassing model is plotted on the graph below. The intensity of the outgassing force is higher for the illuminated part of the comet nucleus. Moreover, at this step, the outgassing effect was not really significant. Outgassing effect is more important around the sub-solar point (the white star on the left map), but at the comet surface, it is 3 to 50 times lower than gravitation force. For a few places is reaches 85% of the gravitation force. Due to the distance to the comet at that time, RMOC reported that, at this stage, it was impossible to estimate the drag force acting on the spacecraft from navigation data.

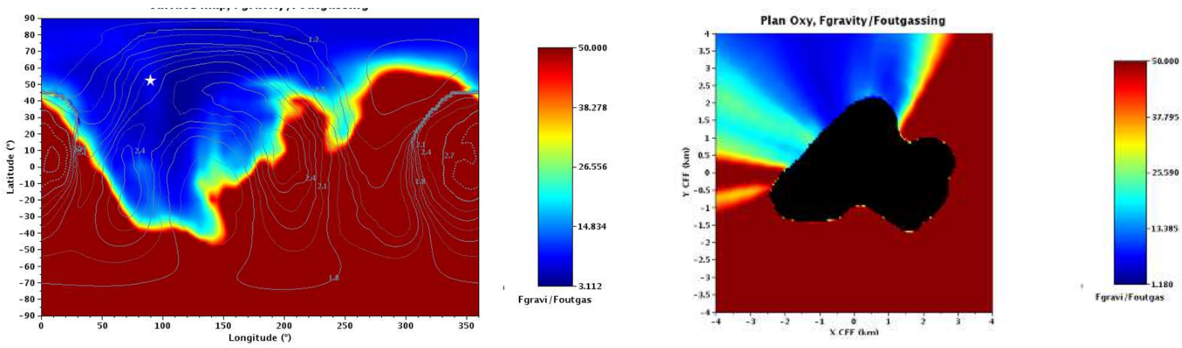


Figure 11 : Gravitation over outgassing ratio on 11th November 0h at 3 AU (from LATMOS outgassing model). Surface map (left) and Oxy plan (right).

Using these different models, the trajectory analysis showed that most of the points with acceptable illumination conditions could be reached with an O1 strategy, with descent durations lower than 12h. All the points correctly illuminated could be reached with an O2 strategy with descent durations lower than 4h30. The impact of the outgassing on the reachable area was not significant.

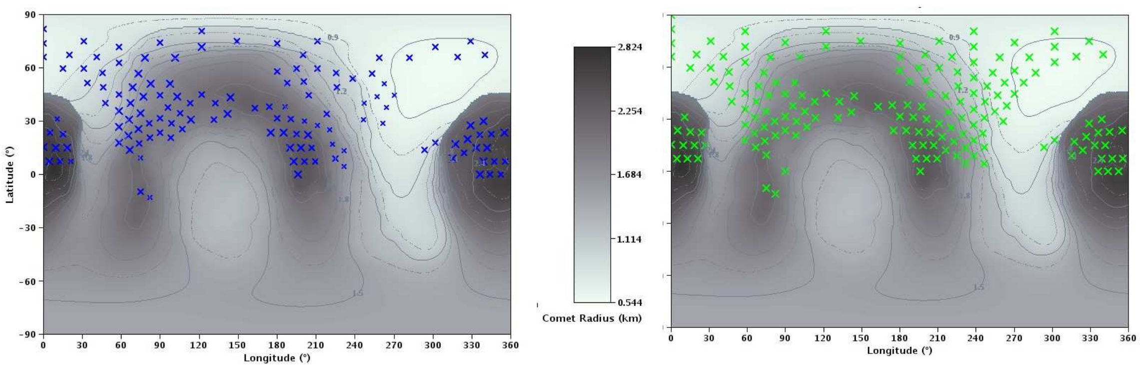
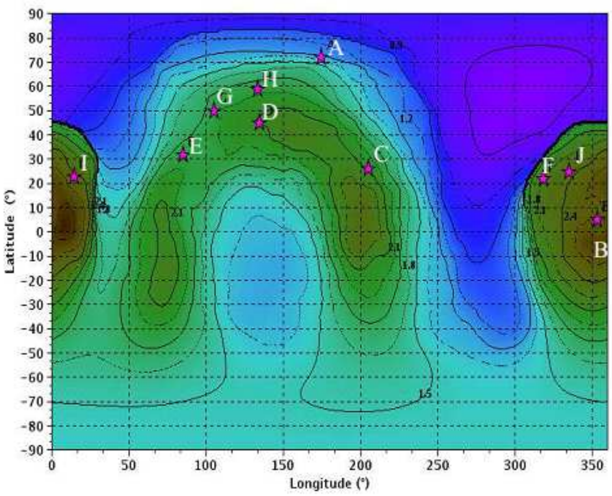


Figure 12 : reachable areas (OSIRIS SHAP2) for O1 strategy (left) and O2 strategy (right).

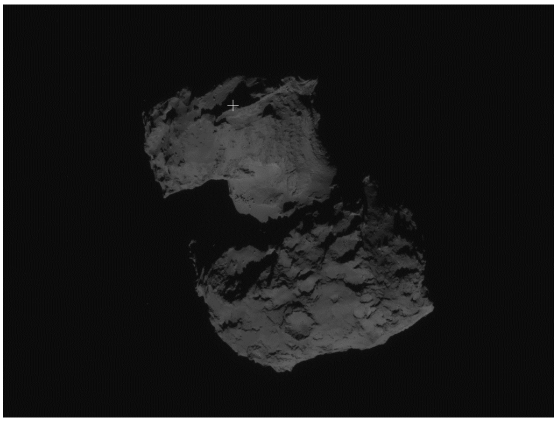
Taking into account these results, a restrained LSSP meeting has been held on August 20th 2014 to define 10 candidate landing sites inside the reachable area. The selection was made only on technical criteria, and without taking into account scientific interest of the landing site. Analyses done before the beginning of the operations had shown that the landing ellipse could reach 1 km^2, and so taking into account this uncertainty, almost all the reachable part of the comet was covered with these 10 sites that were named A to J.



Site	Latitude ; Longitude OSIRIS frame (deg)
A	72 ; 174
B	5.2 ; 353
C	26 ; 205
D	45 ; 134
E	32 ; 85
F	22 ; 318
G	50 ; 105
H	59 ; 133
I	23 ; 14
J	25 ; 335

Figure 13 : Pre selected candidate landing sites (A to J) on 20th August

Between 20th August and 24th August, a dedicated analysis was performed for each of the 10 landing sites. In particular, the flatness of the landing area was studied. OSIRIS images of the candidate landing sites were also produced. For example, the site F was clearly not a good candidate due to the position of the site on the ridge of the small lobe (see Figure). Opportunities of communication between Orbiter and Lander for the Long Term Science (LTS) phase (from 19th November to March 2015) were also studied. Since Rosetta orbit was already defined for this period, some of the chosen landing sites presented more opportunities of contact than others. They were thus scientifically more interesting since more opportunities of doing science were allowed.



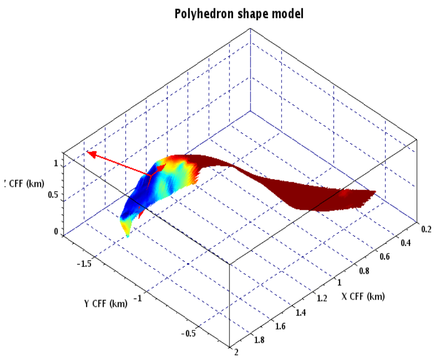


Figure 14 : OSIRIS images and local slopes for site F

A two-days meeting was organized in CNES Toulouse on 23rd and 24th August during which these technical criteria were presented. The scientific interest of the landing sites were also considered to choose the 5 candidate landing sites that were I, C, J, A and B. The coordinates have been fine tuned to be at the center of the targeted flat area.

The figure below present the 5 selected landing sites with their spherical coordinates

Landing Site	Coordinates lat ; long (deg)
I	20.2; 10.2
C	28.8; 201.4
J	14.3; 340.2
A	77.8; 127.45
B	5.2; 355.4

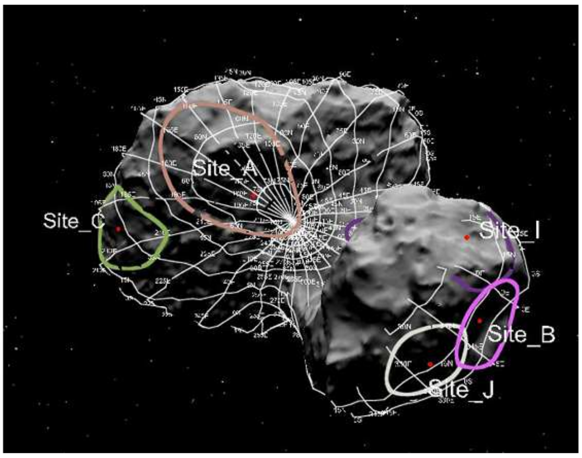


Figure 15 : Chosen candidate landing sites on 24th August.

5.3 Selection of nominal and back up sites

On the August 24th, RLGS provided to RMOC the list of the 5 candidate landing sites. 15 days later, RMOC provided back the operational feasibility analysis and the corresponding trajectory for the two pre-defined scenario O1 and O2. These strategies are illustrated below for site J. Left, for the O1 strategy, the emergency separation conducts to the same trajectory as the nominal separation since in both case the separation ΔV is 0.1874 m/s. Right for the O2 strategy, the nominal separation ΔV is tuned to 0.5 m/s and the emergency trajectory does not impact the nucleus.

Table 9 : Strategies characteristics

	Separation time	Distance to comet center	Touchdown time	Impact velocity
strategy O1	07h40m55s	22.6 km	14h43m33s	0.95 m/s
strategy O1	11h36m38s	8.6 km	14h28m15s	0.75 m/s

Figure 16 shows, in green, the nominal separation trajectory (using MSS) and, in red, the emergency separation trajectory (emergency spring fixed ΔV of 18.74 cm/s). For O1 strategy, the nominal and the emergency trajectories are the same. For O2 strategy, the emergency trajectory does not impact the comet nucleus.

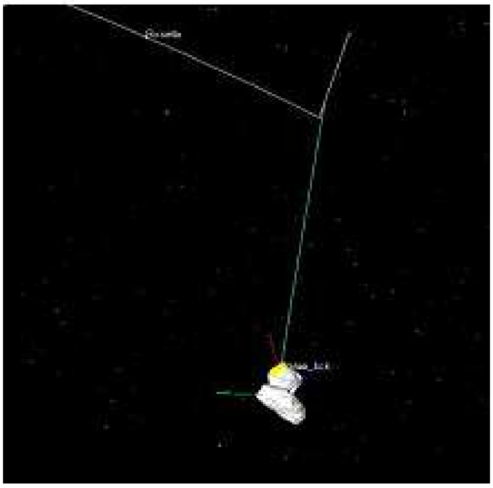
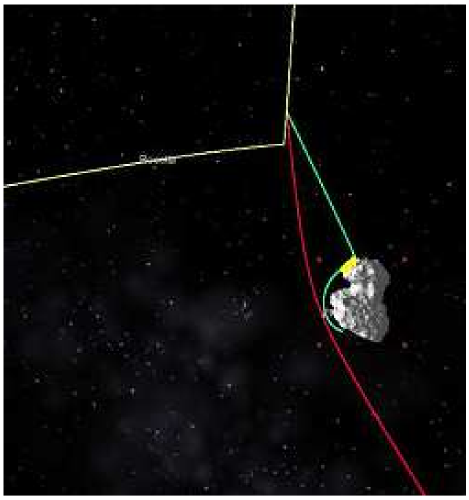
 

Figure 16 : O1 (left) and O2 (right) strategies for site J.

All sites were thus considered reachable, except site A for which trajectory would have crossed the transition area between the two lobes where gravity potential was poorly reconstructed, and where activity of the comet was higher. An attempt to land there was consequently considered very risky. Moreover, O1 strategies analyzed for site C would have led to a touchdown with low sun illumination (bad imaging conditions), and for this site O2 strategy was preferred. Even if this strategy was more risky, because not robust to a failure of the MSS, it allowed to land in good conditions for the scientific instruments.

Then, the Rosetta trajectory being at 30 km, new global DTM (with a resolution of about 10 m) was provided using latest NAVCAM and OSIRIS images. The updated volume was 21.18 km2. OSIRIS provided local DTM of the candidate landing area with a metric resolution. Both teams provided updated rotation parameters of the comet that were very close to the previous values (see Table 7). There was no change of the GM value estimated from navigation data (660 m3.s-2). This corresponded to an updated value of the density between 466.1 kg.m-3 (RMOC volume) and 471.2 kg.m-3 (OSIRIS SHAP2 volume).
LATMOS team also provided an updated coma model using latest ROSINA measurements with the following production estimation (at 3 A.U.)

Table 10.Parameters of LATMOS outgassing model

Molecule	**H^2O**	**CO**	**CO^2**
Q (molec/s)	$1.5e^{26}$-$2.4e^{26}$	$1e^{25}$	$3.2e^{24}$

The outgassing effect was still very small compared to the gravitational effect. The outgassing force was again generally 10 to 50 times lower than the gravitation, and RMOC reported it was still impossible to estimate outgassing effect from navigation data.
Taking into account these inputs, a dispersion analysis has been done for each of the trajectories by SONC-FD. The objective of this dispersion analysis was to check that all the Orbiter and

Lander constraints were respected. On Figure 17, graphs show some of the results for site J strategy O1. Dispersion ellipse and the statistical distribution of impact velocity have been computed for 10000 simulations. The landing area is almost 1 km^2 (500m over 400m ellipse) and the maximum limit of 1.1 m/s is never exceeded. Main contribution to the dispersion is the uncertainty on the Orbiter position at separation propagated over the 7 hours of descent. The contribution to the uncertainty of the Orbiter position was linked to the navigation errors and to the errors on the separation maneuver. Mis-modelling of the gravitation field, and of the drag caused by the outgassing are also injected in the computation of the dispersions. Dispersion on touchdown time have also been considered and was estimated around ±20 minutes. This uncertainty had to be taken into account in the Lander planning process.

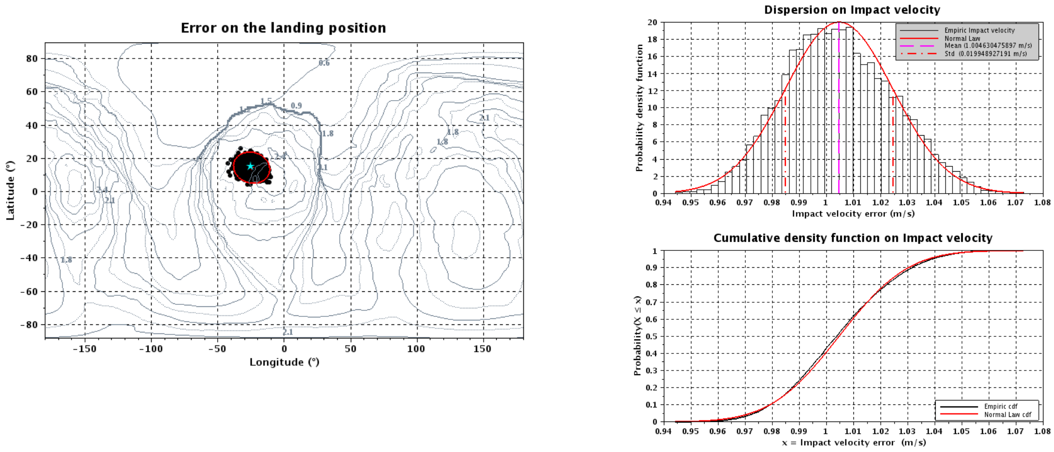


Figure 17 : Dispersion analysis site J (left dispersion ellipse, right dispersion on impact velocity)

To assess the uncertainty linked to modelling error, trajectories were extrapolated from the initial separation conditions provided by RMOC, using different models. They were compared to the reference trajectory generated with mass point gravity model and without outgassing. Maximal discrepancies were observed for site J, O1 strategy. They are listed in the table below, and considered acceptable.

Table 11.Effect of the models used for site J O1 trajectory.

	Polyhedron gravity model	Polyhedron gravity model + outgassing
Along track position	114 m	105 m
Cross-track position	29 m	30 m
Along track velocity	10.1 cm/s	9.7 cm/s
Cross-track velocity	1.7 cm/s	1.8 cm/s

As expected, the effect of the outgassing force is very small compared to the effect of the gravitational force. The 100 m difference between trajectories extrapolated with mass point

model and trajectories extrapolated with polyhedron gravity model is due to the mass repartition close to the targeted landing point, but also to the offset of the center of mass position.
The statistical distribution of the slopes in the landing area was also a criterion for the ranking. To ensure a safe landing, the angle between Lander Z axis and the local normal had to be lower than 30 degrees. Slopes (meaning deviation of the local normal w.r.t. the targeted normal) higher than 25 degrees were not desirable. No landing site was 100% safe from this point of view, even at this scale, but a few sites were clearly better than others.

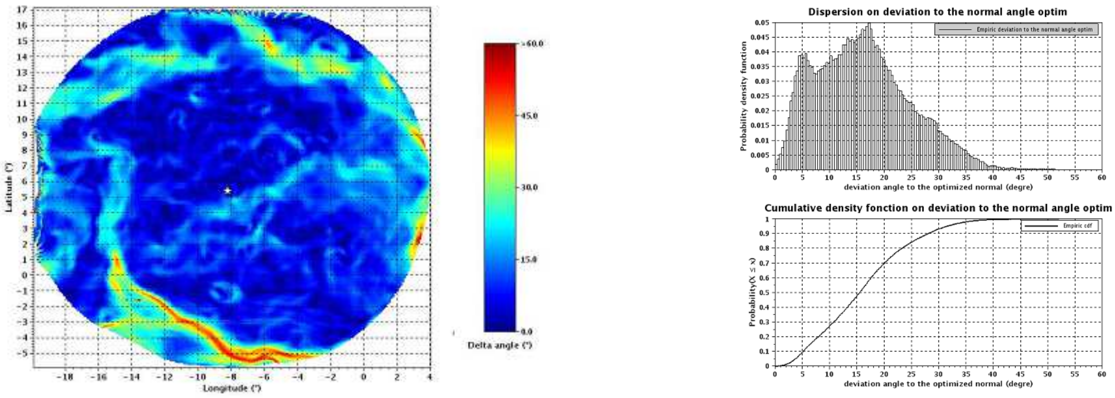


Figure 18 : Slopes around landing site B. Left color bar ranging from 0 deg (blue) to 60 deg (red). Right statistical distribution of the slopes inside landing area.

For example, for site B, which was the flattest, 85% of the area around targeted landing site had slopes lower than 25 deg with respect to the targeted normal direction. For site I, which was the roughest one, only 70% of the area had slopes lower than 25 deg. These data were cross-checked with the images provided by OSIRIS, as for example here below for site I. On this image, some very high slopes can be seen which confirms the statistical analysis results.

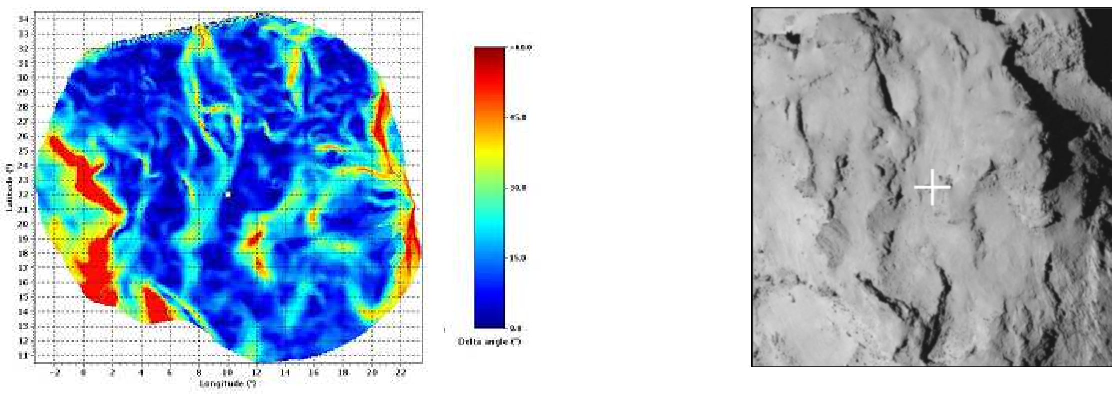


Figure 19 : Slopes computed from DTM (left) OSIRIS images for site I (right, distance 30 km)

The illumination conditions around landing sites were also studied in detail using the updated shape models provided by OSIRIS and RMOC teams. The illumination conditions in the 1 km2 around the targeted landing site have been plotted for site J and site B here below.

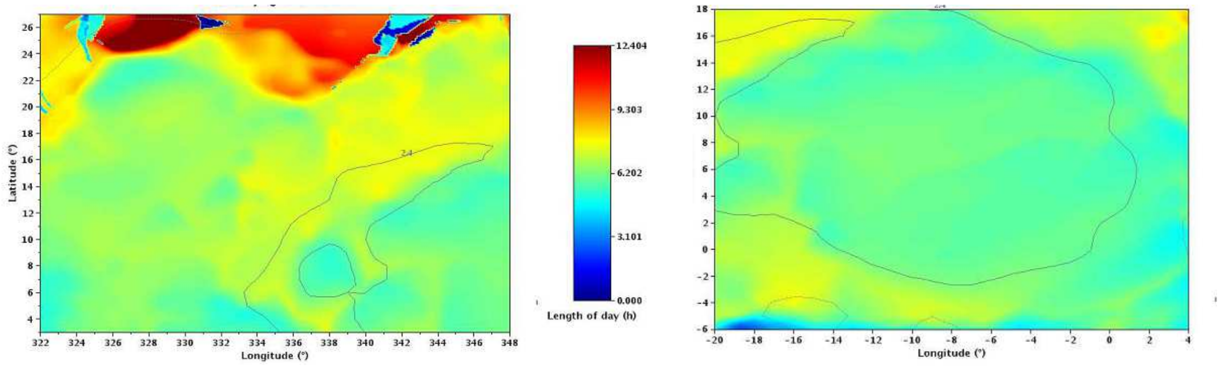


Figure 20 : Illumination conditions on 11th November in landing area around site J (left) and landing area B (right).

For site J the illumination conditions were globally acceptable in the whole area. 85% of the landing area was presenting more than 6.2 hours of daylight duration.The zones with non acceptable daylight conditions were mainly locate at the border of the landing area. For site B, the illumination conditions were less favourable. The daylight duration was very homogeneous in the whole area, around 6 hours. About 60% did not respect the 6.2 hours minimum duration, which was not sufficient for an efficient secondary battery recharging during LTS.

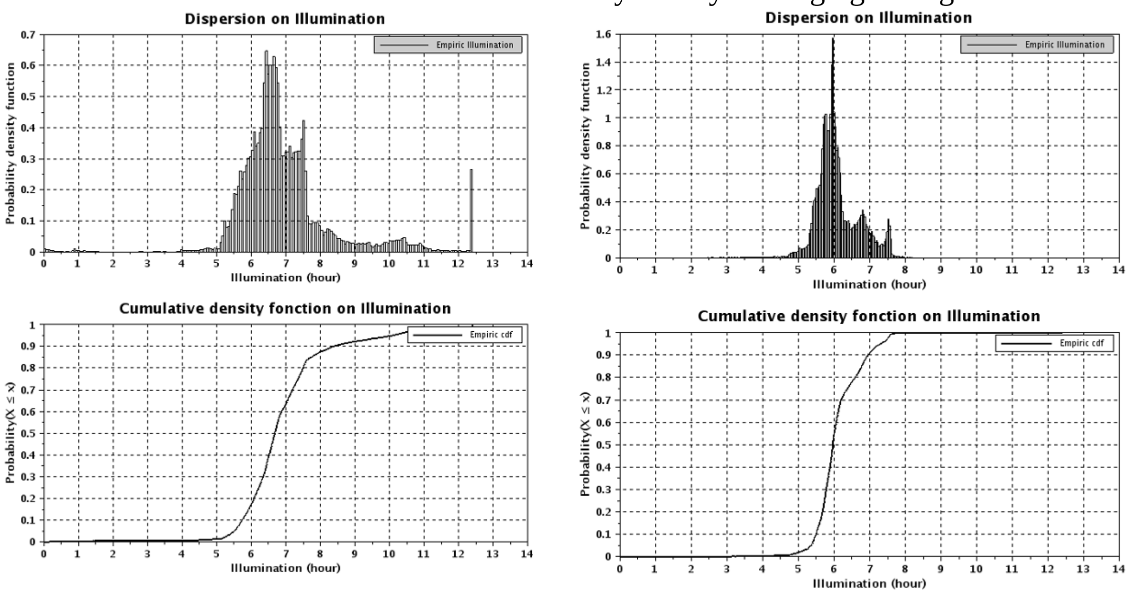


Figure 21 : statistical distribution of illumination conditions on 11th November for landing site J (left) and landing site B (right).

The opportunity of communication between Orbiter and Lander during the Long Term Science (LTS) phase, from December to March was also studied taking into account the LTS orbit for Rosetta and taken into account in the final ranking.
Finally, on 13th and 14th September a second two-day LSSP meeting was held in CNES Toulouse to decide for the final ranking. Technical results were presented, and the different sites were compared. Scientific interest of the different landing sites was also discussed. Site J was finally chosen as the nominal landing site (using O1 strategy) and site C as the backup landing site (using O2 strategy).

5.4 Confirmation of nominal landing site

On 14th September, site J, named "Agilkia" was chosen as the nominal landing site. End of September, in the scope of the preparations of the final operational trajectory for Rosetta, RMOC announced that Lander delivery will occurred on 12th November 2014 instead of 11th November as stated before.

Beginning of October, Rosetta came closer to the comet, up to 10 km from the center thanks to the low outgassing activity. New OSIRIS and NAVCAM images were taken and used to update the global and local DTMs (for site J and C).

A new gravity potential was provided by RMOC, with an updated GM of 667 $m^3.s^{-2}$ and spherical harmonic coefficients up to the degree 3. A polyhedron gravity model was also computed using the constant density assumption (471.8 $kg.m^{-3}$). The offset of the center of mass with respect to the spherical model was about 50 m, which indicated that the constant density estimation was still valid for trajectory extrapolation. Moreover, using either spherical harmonics degree 3 or polyhedron gravity potential modifies the touchdown position only by a few meters (about 20 m) and the touchdown time by about 50 s, which is not significant with respect to the expected dispersion ellipse.

The LATMOS provided an updated coma model using latest observations from Orbiter instruments. Using this model, the outgassing force was still about 50 times lower than the gravitational force. Thanks to the low distance to the comet, RMOC was able to discriminate between gravitational forces and outgassing. The estimation of outgassing effect by RMOC was coherent with LATMOS model and updated GM value took into account impact of the outgassing forces.

Final operational trajectory was provided by RMOC. Separation was planned on 12th November at 08h35m00s UT at 22.5 km from comet center and expected touchdown time was 15h34m55s UT with an impact velocity of 0.95 m/s.

At this step, thanks to the low altitude of Rosetta, OSIRIS was able to provide detailed statistics on the boulders inside the landing area (position, sizes and statistical distribution extrapolated up to 10 cm boulders).

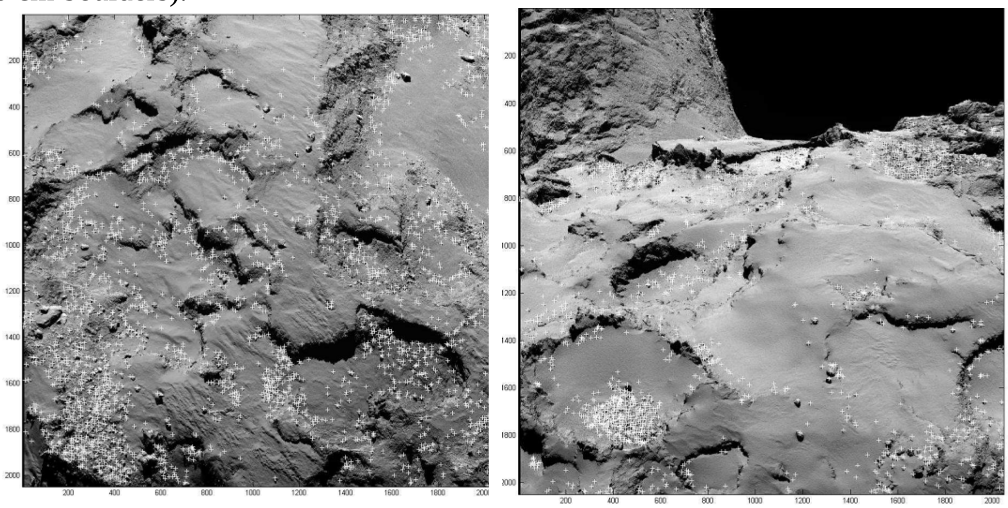


Figure 22 : Position of the boulders inside landing area J (left) and C (right) from OSIRIS.

The SONC-FD computed the risk of landing on a boulder taking into account the landing ellipse. The probability to land in a place free of boulders was estimated to be about 82% for site J and 90% for site C. The method was to model the boulders as a disk and Philae was taken into account through a safety radius of 2 m. Philae was considered to land on a boulder as soon as there is intersection of Philae safety radius with a boulder disk.

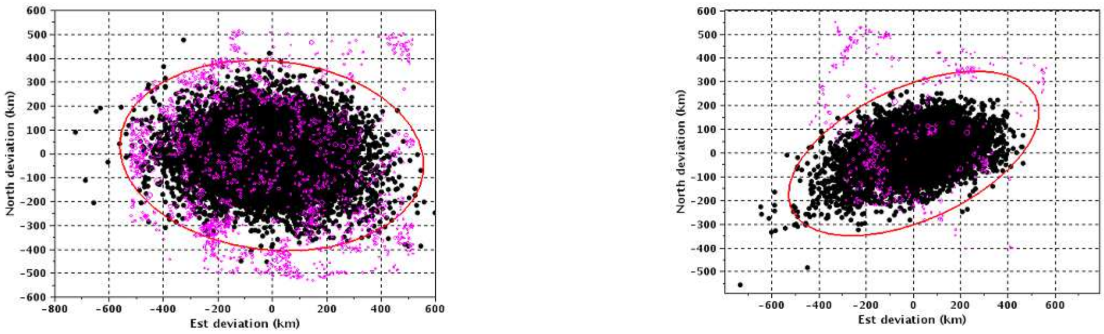


Figure 23 : Statistical distribution of boulders inside landing ellipse for site J (left) and C (right)

Even if the C area was slightly less risky than J area for what concerned the boulders, all the other data (slopes, illumination conditions, more risky O2 strategy…) were clearly indicating that site J was a better choice than site C. So on 10th October 2014, a final LSSP meeting decided to confirm the choice of site J as the nominal one. On 14th October 2014, the Lander Operational Readiness Review gave the final GO for the beginning of the landing operations. Preparation of the final operations then began, up to the delivery of the Lander on the 12th November 2014.

6. Conclusions

On 12th November 2014 at 08h35m UT, the Lander finally separated from Rosetta as planned. The pre-delivery maneuvers were executed perfectly and the MSS provided a very accurate separation ΔV, reporting a ΔV value of 18.76 cm/s instead of the expected 18.74 cm/s. Several images of the Lander during descent were delivered by OSIRIS and seemed to indicate that the trajectory was close to nominal. A farewell image of Rosetta by the CIVA camera of the Lander was taken several minutes after separation. The image was coherent with estimation during operations preparation, even Rosetta was in the border of CIVA field of view, which indicated a rather high rotation rate of the Lander around its Z axis. Estimation of the rotation rate during descent using solar arrays illumination and measurement of the magnetic field by the Lander instrument ROMAP indicated that the Lander was doing a complete rotation every 8.6 minutes.

From August to November 2014, several loops of Flight Dynamics analyses have been carried up to determine the best final landing site for Philae lander. The landing Site "Agilkia" was finally chosen as the one presenting less risk for the Lander delivery, and with good conditions for the Lander instruments. This site was reached with a very good accuracy on 12th November 2014 at 15h34m04s but due to the failure of the anchoring system, Philae bounced off from comet surface and came to a rest about 1 km away from the targeted point, in a poorly illuminated area. After 7 hours of descent and 57 hours of on-comet operations, the primary battery was finally completely depleted and due to the lack of solar illumination on the solar arrays, the Lander went in hibernation mode. Yet, Philae successfully performed the first-ever landing on a cometary surface. Outstanding results have been obtained at or nearby the surface by the Lander instruments.

7. References

[1] *Landing site and descent trajectory selection process*, Eric Jurado et al, RLGS-TNO-LTAN-TECH-9318-CN, v2.0, July 2014.
[2] *Philae Landing on Comet Churyumov-Gerasimenko: Understanding of Its Descent Trajectory, Attitude, Rebound and Final Landing Site*. Romain Garmier et al, submitted to the ISSFD 2015
[3] *Physical model of the coma of comet 67P/Churyumov-Gerasimenko, J.F. Crifo, G.A. Lukyanov, V.V. Zakharov, A.V. Rodionov in: Colangeli, L., Elena Mazzotta Epifani, E.M., Pasquale Palumbo, P. (Eds.), The new Rosetta targets - observation, simulations and instrument performances. Kluwer Academic Publishers, Dordrecht, NL, pp. 119-130, 2004.*

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