Philae Landing on Comet Churyumov-Gerasimenko: Understanding of Its Descent Trajectory, Attitude, Rebound and Final Landing Site

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Abstract:
The 12th of November 2014, Rosetta released Philae. The small lander, after 7h descent, finally touched softly the ground of comet Churuymov-Gerasimenko. Unfortunately its anchoring system failed and Philae experienced a 2h bouncing trajectory. It landed 1 km away from its target site. Nevertheless it was operated during 57h performing its First Science Sequence (FSS). The FSS, made possible with the two batteries, should have been followed by the Long Term Science Sequence (LTS) but Philae was not well illuminated and fell "asleep". The 13th of June Philae contacted Rosetta again. The lander was still not properly illuminated. The final position and attitude of Philae were key data to forecast an eventual wake-up. But as Philae was not equipped with system dedicated to position and attitude monitoring, the only way to determine missing data was to examine all collected measurements, housekeeping as well as scientific data. The Science Operation Navigation Center was responsible to coordinate and to realize activities necessary to determine the Philae attitude and position. Thanks to a collective effort, a possible landing area and an attitude were successfully estimated. Equivalent work was also realized to achieve the reconstruction, both of trajectory and attitude, of the descent and bouncing on the surface.

Keywords: *Philae, landing, trajectory, attitude, comet.*

1. Introduction

The 12th November 2014, at 16:03 UTC, Philae became the first spacecraft to "softly" land on a comet. It was released by Rosetta around 8:35 UTC and gently descended to the comet. After 7 hours, it touched down on the ground 122 m away from its targeted landing point and 51s later than scheduled. Its impact velocity was around 1m/s. This was already great news as the landing dispersion ellipse was 1 km long and the touchdown window, 40 minutes large.

To prevent any rebound, Philae was equipped with two harpoons and a thruster supposed to push the spacecraft to the ground. Unfortunately the anchoring system and thruster system failed and Philae experienced a two hour long bouncing trajectory, including two more touchdowns. Philae finished its ballistic flight more than 1 km from its targeted landing site.

During its descent, called Separation Descent Landing phase (SDL), Philae was stabilized around its Z axis (Figure 1) by a flywheel. At the first touchdown, the flywheel was nominally switch off but continued to rotate 32 min before complete immobility [2]. As the lander was flying, the deceleration of the flywheel transferred its momentum to Philae providing stabilization during the rebound.

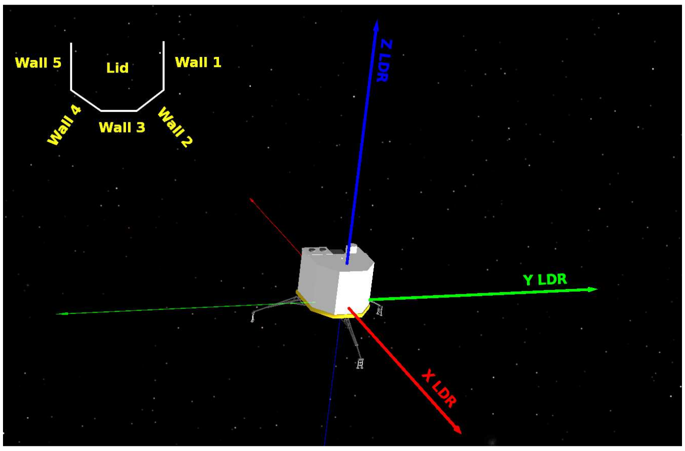

Figure 1: Philae and its LDR frame axis. Philae is stabilized and spinning around its Z axis

During the First Science Sequence (FSS) of 57 hours, Philae realized in situ analysis. The FSS was designed to work only with the two Philae batteries. As soon as the batteries run out of energy, Philae was supposed to recharge one of them with the help of its 6 solar arrays and resume its science activities for the so called Long Term Science sequence (LTS). Unfortunately, as the final site was poorly illuminated, the lander failed to recharge its battery and it was switched into a hibernation mode waiting for more sunny days. One of the last Philae actions was to rotate its head slightly (+22° around Z axis) to improve solar arrays illumination.
The wake-up occurred the 13th of June 2015. A very short and unstable RF link was established between Philae and Rosetta. During the next weeks, Rosetta and Philae teams tried to assess the Philae's status and to improve the RF links. Unfortunately, due to comet outgassing, it was not possible to reduce the distance between the two spacecrafts significantly. The last telecommunication occurred on the 9th of July.

Table 1: landing sequence [2]

Event	**Time (UTC)**
Release of Philae	2014/11/12 - 08:35:00
Unfolding of the landing gear	2014/11/12 – 09:05:00
First Touchdown (TD1)	2014/11/12 - 15:34:03
Second Touchdown (TD2)	2014/11/12 - 16:20:00
Third Touchdown (TD3)	2014/11/12 - 17:25:26
Final landing (FL)	2014/11/12 - 17:31:17

The landing operations were accomplished thanks to the joint work of the ESA, DLR, CNES and the scientific teams. The Science Operation and Navigation Center (SONC) located in CNES was in charge of:

- Supporting the Landing Site Selection Process (LSSP): the objective of LSSP was to find a nominal site and a backup that comply with the numerous missions constraints [10].
- Planning science operations of the Philae instruments and distributes the data among the instruments teams.
- Determining, after landing, the precise location and attitude of Philae
- Computation of orbital events as the communication opportunities and lander illumination.

The SONC-Flight Dynamics (SONC-FD) team was in charge of point 1 and 4. Point 1 is presented in [10].

The paper deals with point 3 and more precisely presents the effort realized by SONC-FD in close collaboration with other teams:

- To determine Philae last landing site and attitude (section 2).
- The forecast of illumination and RF communication for Philae wake-up (section 3).
- The reconstruction of the landing trajectories and attitude during SDL (section 4)
- The reconstruction of the rebound trajectories and attitude (section 5).

The two first activities were high priority tasks, on one hand to realize the FSS and to plan instrument activities, on the other hand to determine if Philae will be able to wake-up.

Philae was not equipped with instruments dedicated to position and attitude monitoring. But, during the landing preparation, several key contributors were identified to help determining these data:

The first five are Philae scientific instruments or Philae subsystems:

- Images provided by ROLIS [12]. This camera is located beneath Philae (along its – Z axis) and realized pictures of the ground during SDL and FSS.
- Images provided by CIVA system [1]. CIVA system is able to realize a panoramic picture (360°x60° field of view). A picture was realized during the FSS.
- The ROMAP magnetometer [3,11]. This scientific instrument was used as a compass to determine the Philae attitude.
- The CONSERT sounder [4]. CONSERT is a radar sounder located on Rosetta and Philae. It is used to probe the internal structure of the comet but may be used to determine the landing area through ranging measurements.
- The HK of currents and voltages produced by the Philae solar arrays. They help to determine the lander attitude.

The last one is a scientific camera on board Rosetta:

- Images provided by OSIRIS [6]. This scientific camera is on board Rosetta and is used first to determine Digital Terrain Model (DTM) but also to determine the landing position (on flight pictures, lander foot prints and final position…)

ROLIS and CIVA images were analyzed by a CNES team specialized in image processing for robotics. They also used OSIRIS images. CONSERT, ROMAP and OISIRIS teams provided to SONC-FD their own analysis. SONC-FD realized the attitude determination from the currents HK.

SONC-FD was then responsible to collect all the identified data or measurements and cross validate them.

SONC-FD used the comets models (ephemeris, shape, rotations, gravity field...) as well as Rosetta trajectories and attitude provided by RMOC.

2. Position and attitude of Philae on its final landing site

2.1. Introduction

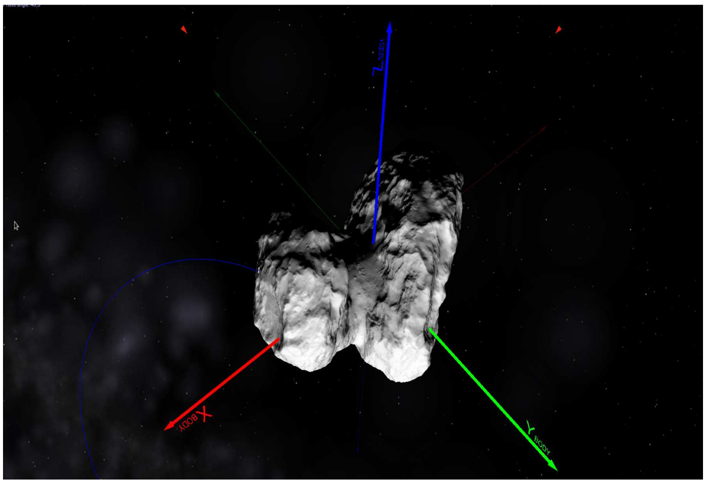

Figure 2: shape model of comet Churymov-Gerasimenko and its CFF axes. Comet is rotating around the Z axis (blue) in 12.4h

Several teams worked simultaneously on the determination of the position and attitude of Philae on its final landing site.

ROMAP and CONSERT teams provided respectively an attitude estimation and a most likely area where Philae may be located, quiet early in the process. Later, other teams (CNES, OSIRIS…) provided new positions or possible areas. ROMAP also refined its attitude.

As SONC-FD was responsible of the validation and the merge of the data, it was decided to develop a methodology to cross-validate all proposed data.

For the flight dynamics team, the available validation data are:

- The HK data for the currents and voltages produced by the Philae solar arrays.
- The windows of communication between Rosetta and Philae during FSS
- A few additional data such as the sun direction in the lander frame at the epoch of the CIVA pictures.

The HK data about currents and voltages had to be used carefully. The behavior of a solar array is complex. Philae has 5 lateral solar arrays and one lid (cf. Figure 1). There is around 250 solar cells per panel (wall 1 and 5 are larger than wall 2, 3, 4, themselves larger than the lid). Each panel is divided into two strings of solar cells.

The complexity comes from the fact that a shaded cell consumes voltage. It is estimated that 8 shaded cells consume the whole voltage of the string. To counteract this, an electrical subsystem automatically disconnects a string in such situation. It means that a solar array is producing current either at or near 50% of its capacity or at 100%.

A second problem comes from wall 1 and 5. As they are located on opposite sides (never illuminated at the same time), they share the same HK channel. Only a good knowledge of the

lander attitude and a time series measurement may help to disentangle currents from walls 1 and 5.
The shadows on the solar arrays may come either from the surrounding environment (rocks) either from the lander itself. For example, the upper part of the drill tower may shadow the lid. The landing gear may also produce self-shadowing if the sun is illuminating Philae from bellow.

2.2. Attitude determination

SONC-FD and ROMAP teams worked on the attitude determination of Philae. Both methods do not require knowing the Philae position to determine the attitude of Philae. It means that this work may be realized independently from the search of the landing site.
These methods provide the orientation of the lander frame (LDR, cf. Figure 1) with respect to the Comet Fixed Frame (CFF, cf. Figure 2). CFF origin is located at the center of mass of the comet and its Z axis is aligned with the comet rotation axis. This frame is rotated with the comet (period circa 12.4 h).

ROMAP was the first to be able to determine the attitude (method is described in [3]).
SONC-FD teams used the currents generated by the solar arrays.
At first order, the current produced by a solar array is proportional to the cosine of the incidence angle (angle between the normal to a solar array and the direction of the sun).
Some basic algebraic manipulations show that:
- The sun azimuth expressed in the LDR frame is determined from the currents output from two lateral walls.
- The sun declination is determined from currents output from the lid and a lateral wall.

One then compute the sun direction for several dates, and as the comet rotation is well characterized, one can determine the attitude of the lander with respect to the comet fixed frame.
As explained, it is not necessary to know the Philae position. The attitude estimation is performed using a least square approach tailored to quaternion.
The estimation quality depends on:

- The shadowing of the solar array. As explained earlier, a few shaded cells may lead to switch off a string, half of the solar array. This is of course impacting the quality of attitude determination.
- The width of the time span used for the attitude determination: if this time span is too short, the sun direction is not changing a lot in the lander frame and the determined attitude will not be very accurate.
- The dust accumulation of the solar arrays: it modifies the efficiency of each solar array and introduces systematic bias.

During FSS, the wall 2, 3 and the lid were poorly illuminated. The estimated attitude was not consistent with the one derived from ROMAP measurements.
CNES robotic team analyzed the pictures taken by CIVA cameras and they were able to derive from the self-shadowing of two of Philae feet the sun direction at date of picture. This was also confirmed using the shadow created by CONSERT antenna on the rocks, and analyzing the solar flare present on two pictures.
The ROMAP prediction of the sun direction at the date of CIVA picture was coherent with the CNES robotic estimation. So it was decided to consider ROMAP attitude [3] as correct.

After the Philae wake-up, SONC-FD was able to determine the attitude from the new transmitted HK data but only with data of the 13th of June (cf. Figure 3). Actually, each time Philae falls “asleep”, it loses its internal clocks but increments a reboot counter. Therefore the dating of recording HK data is wrong. Nevertheless, assuming one increment per comet rotation leads to a rough estimate for the day of the recording. Of course if for any reasons, the lander falls “asleep” several times per rotation, this date will be wrong. Moreover, this date is approximate as the day is known but not the period of the day. On the contrary, live HK data is well dated because Rosetta is dating received HK data.

HK data of the 13th of June is well dated and Philae is correctly illuminated (wall 1, 2, 3 and lid producing currents). Wall 1 current is discarded as the current generation reaches the saturation. As seen, the current produced by this wall is almost constant for 3h. This means that, this current is not proportional anymore to the cosine of the incidence angle.

The attitude was determined using 70 min of HK with currents from wall 2, 3 and the lid.

As seen on Figure 3, Wall 2 and wall 3 present some strong variations. There are probably caused by shadow of surrounding rocks. This is of course impacting the quality of the attitude determination.

ROMAP and SONC-FD attitude are rather close: The angle between the two Z LDR axes is 5.5°. The Euler angle (X, Y, Z) between ROMAP attitude and SONC-FD attitude are [1.9° 2.6° -14.2°].

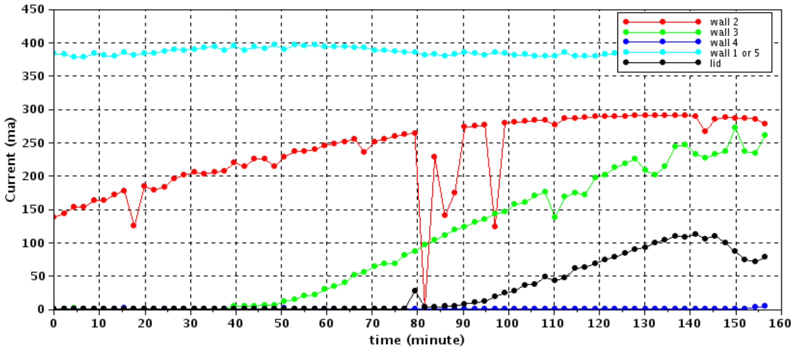

Figure 3: Currents produced by solar arrays (Time=0 is 2015/06/13 21:34:46).

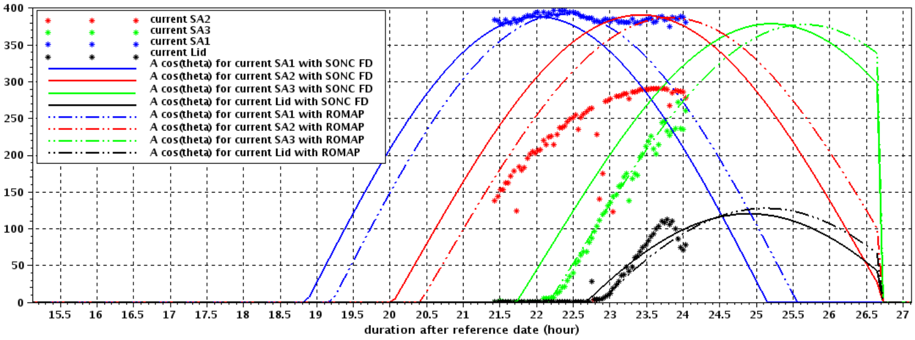

Figure 4: current output of the solar arrays. HK, ROMAP, SONC-FD for the 2015/06/13

Figure 4 presents a comparison between the HK currents and a rough estimate of the current determined from ROMAP attitude and PADI attitude. By rough estimate, we mean that we just compute the cosine of the incidence angle multiply by a constant. LCC is doing more accurate current estimation but SONC FD does not use their model. Nevertheless Figure 4 clearly shows that, for the 13th of June both predictions are correct. ROMAP seems more accurate than SONC-FD. SONC-FD is prognosticating sunrise on wall 3 half an hour earlier.

2.3 Position determination

During FSS, CONSERT, based on the analysis of ranging measurement between Rosetta and Philae [4], proposed a first landing area with size of 350 m x 30 m. Later, the team reduced the area to a box 22.5 x 106.5 m with a most probable area of 22.6 m x 41.5 m [13].
At the same time, SONC-FD was searching landing areas complying with the estimated sun set and sun rise date estimated from HK data and the acquisition and loss dates of RF links (FSS data).
OSIRIS and CNES analyzed pictures of the comet performed on board of Rosetta. The process was to compare pictures of the same area taken before and after the landing, if possible with equivalent illumination conditions. Most of the pictures used for the comparison were taken at 40 km altitude. As the lander has a metric size, it should be only a few pixels on these images. In this way, the involved teams discovered a few tens of “bright area” that were absent in earlier pictures.
The comet surface is active and due to its outgassing activities, its surface is changing with time with fresh ice, very bright, when exposed to the Sun light.
So SONC-FD developed a process to try to eliminate candidate landing sites.

The idea was to produce exclusion zones. It is obviously hard to know where is Philae but it is quiet easy to map places where it cannot be.
The realization of such map is possible thanks to:

- The illumination period of the lander. The HK voltages and currents indicate when Philae’s solar arrays are illuminated.
- The communication windows period between Rosetta/Philae.

The process is the following:

1. We extract an area to analyze from a Digital Terrain Model (DTM). The DTM consists of polyhedron with triangular faces (typical ridge is 5 m long). We extract triangles located in a 200 m radius circle around the candidate site from the DTM.
2. For each center of triangle, we determine if the triangle is illumined during the daytime observed during FSS. If not, the candidate landing site may not be located on the triangle. This triangle is excluded as the landing site may not be located here.
3. For the remaining triangles, considering Philae’s attitude proposed by ROMAP, we check whether any of the individual solar arrays is illuminated as observed during FSS. If not, the triangle is excluded.
4. For the remaining triangles, we compute if the communication between Philae and Rosetta are possible during the real communication period of FSS.

This process is very easy to implement and has a lot of advantages. At each level of the process, one produces an exclusion map based on a given data.

Map of step 2 are considered very reliable and the largest error sources are the Digital Terrain Models. Maps of step 3, 4 required to trust the Philae attitude provided by ROMAP. Nevertheless, they are rather close to the map of step 2, so results are convergent.

Figure 5 represents a typical exclusion map. The landing site may be located only in a place without a gray or black dot (north of the map). The yellow, respectively orange, stars delimit the CONSERT possible zone and most likely zone [13].
The red star (longitude, latitude)=(-1.8, -8.1) is the position chosen by SONC-FD to perform the communication opportunities.

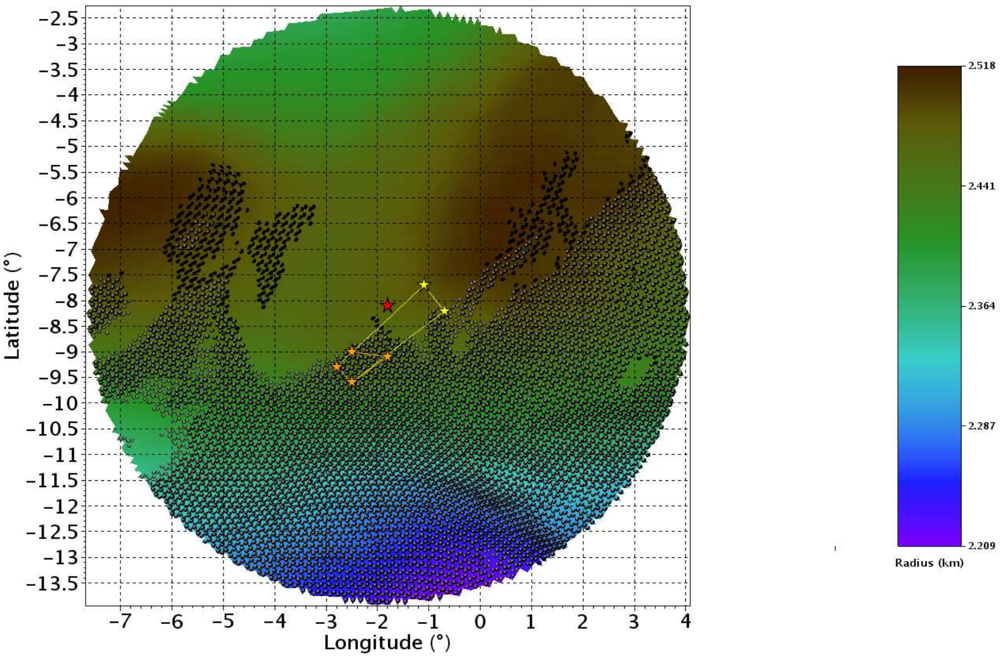

Figure 5: exclusion map. (black dots are not compatible with illumination and gray dot with RF links of the FSS. Yellow and orange stars are the CONSERT possible and most like area, blue star is the SONC-FD position).

The SONC-FD site is 8 m away from the possible CONSERT zone (yellow stars) and 46 m from the most likely zone (orange stars). The most likely zone seems to be not compatible with illumination and RF link but it is close to an admissible zone. So maybe a DTM with a higher resolution may change the results.
The SONC-FD site was chosen in March 2015 and since that choice a better DTM was released by OSIRIS and delivered in July 2015. With the previous DTM (October 2014), the exclusion map was excluded a large part of CONSERT zone. CONSERT team also continued to refine its analysis. It could why SONC-FD site is not within the possible CONSERT zones.
With this site, the prediction of sunrise/sunset and RF links were rather coherent with the observations. Table 2 presents the dates of acquisition and loss of signal during FSS. It also contains the error (real date – prediction date) realized when computing the RF link with the ROMAP attitude and considering a 60° half lobe. Real acquisition occurred between 1h and 2h earlier than predicted. SONC-FD tools does not compute signal outside the 60° half lobe antenna. Of course communications may be possible a larger angles. It seems that we received

signal up to 80° from the Z lander direction. The attitude error of Philae is also responsible of the observed discrepancy.

On the other hand, the predicted loss of signal is rather accurate. Effective loss occurred between 0 and 17 minutes later than scheduled. This error is created mainly by local masking created by the surrounding environment (not well represented by the DTM) and in a less important way by the inaccuracy on the Philae attitude and position.

Table 2: Dates of acquisition and loss of signal during FSS

Date of Acquisition of signal (UTC)	Error in the prediction (min)	Date of Loss of signal (UTC)	Error in the prediction (min)
2014/11/13–05h32	-129min	2014/11/13–09h30	17min
2014/11/13–19h27	-148 min	2014/11/13–23h09	11 min
2014/11/14-09h00	-100 min	2014/11/14 11h48	9 min
2014/11/14-21h47	-65 min	2014/11/15 00h09	0min

Among the candidate sites obtained by means of the image analysis, only one was consistent with the exclusion zone. It was discovered by the LAM [5], (Laboratoire d’astrophysique de Marseille France). This candidate was only a tens of meters away from the site proposed by SONC-FD based on CONSERT zone.

Later, this laboratory also realized a high resolution local DTM. Using the SONC tools, DTM, position and attitude of Philae, simulation of pictures taken by CIVA camera were realized. The result is rather consistent with real pictures. Such a simulation is not an absolute proof, but it brings confidence in the location.

This landing site is within the CONSERT zone and it is compliant with the illumination conditions and communication windows. Analysis of the pictures and derived DTM match the CIVA pictures. Maybe in the future, Rosetta will perform a close flyby of this site and will take pictures with a resolution high enough to see if Philae is really located here.

The SONC-FD landing site was chosen before consolidated data of ([5,13]) were achieved and better DTM available. According to [5, 13], it is clearly not the best site but it is close enough to all proposed area and sites. Moreover as the DTM used to realize the analyses is locally very smooth and the estimated attitude of Philae is correct up to a tens of degree, to move the position of Philae by a tens of meters would not change too much the prediction.

3. Prediction and wake-up of Philae

3.1 Prediction

Once the position and the attitude had been estimated, the situation and future of Philae was better understood with some good and bad news…

The bad news was that the lander is almost lying on its side and its antenna is pointing toward the comet making communication difficult. More than 60% of the antenna half lobe is obstructed by the ground. The area is extremely rocky and our local DTM is too smooth to properly model the shadowing. Figure 6 presents a view showing Philae (size magnified by 25) on its final landing site. The good news was that the lander was more to the South than its original landing site. It means that the local illumination will improve in such a way that Philae may have enough power to wake up. The improvement has two origins: first the distance Sun/comet is decreasing. The comet reached its perihelion (1.2 AU) the 13th of August 2015. As during FSS the distance was 3AU, the photon flux reaching Philae will be multiplied by a factor 6. Secondly, the sun elevation with respect to the landing site was increasing. Its maximum was expected for the beginning of June.

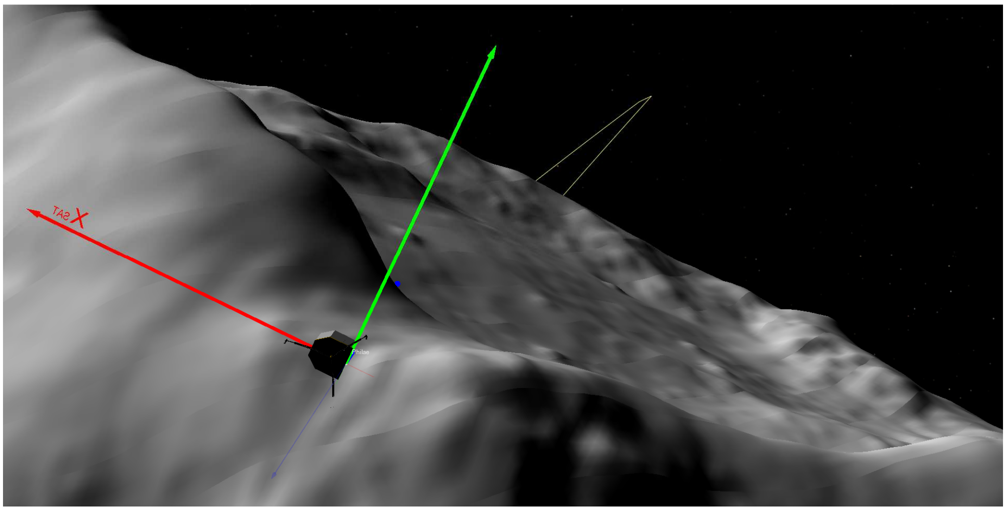

Figure 6: Philae on its final landing site (Philae size is magnified 25 times).

Figure 7 represents the distance Sun/comet with respect to the latitude of the subsolar points from February 2015 to February 2016. For a given date, the subsolar point represents the intersection between the comet surface and the direction from the comet center to the sun. The green dashed line represents the latitude of Philae. This plot indicates that at local noon the first of June, the sun reach its maximum elevation.

LCC analyzed the SONC-FD illumination prediction and concluded that Philae, if still working, could wake-up around April/May 2015.

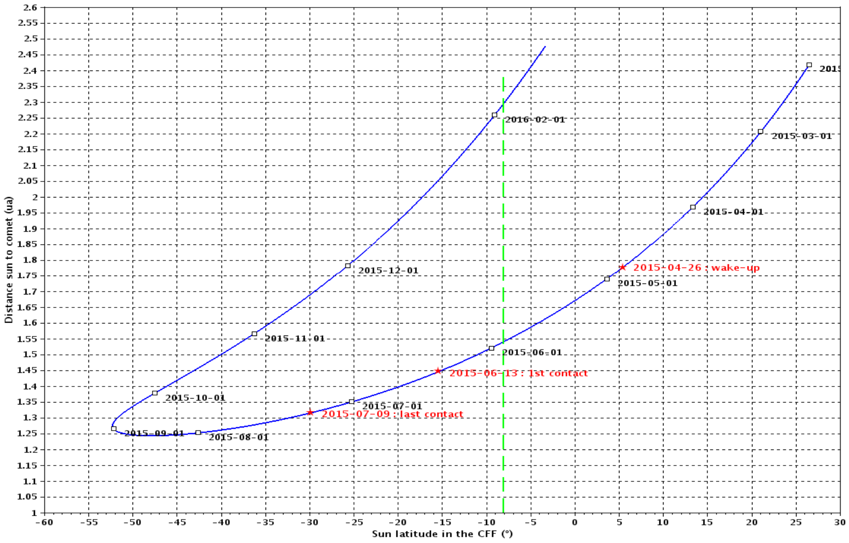

Figure 7: distance Sun/comet with respect to the sun subsolar latitude in CFF. The green dashed line represents Philae latitude in the CFF.

3.2 Wake-up

A wake-up of Philae is possible only if the solar arrays produce at least 5.5 W and if the internal temperature exceeds -45°C. If this happens, Philae is able to receive the signal from Rosetta and to charge its battery. To communicate with Rosetta, Philae should at least have 19W available and receive a signal from Rosetta (i.e. the hibernation mode allows only to answer to Rosetta). Philae does not use its battery unless commanded to do so.

Since February 2015, several communication campaigns were realized by Rosetta. Rosetta sent blind commands to the lander. The purpose of these commands is to optimize the use of energy on board Philae. If Philae received them, it would have been able to execute even if it was unable to answer to Rosetta.

A communication between Rosetta and Philae is possible only if:

- The distance between the two spacecrafts is not too large. The antennas were designed for communications within the 60° half lobe up to 80 km but may be possible up to 150 km most probably with 40/50° half lobe.
- Rosetta and Philae antennas should face each other.
- The lander should have been illuminated for at least 15 minutes (time necessary to awake) before the communication. Most of the time (for security reasons), Rosetta is moving along terminator orbits. It may fly over the lander either in the morning, or the evening. As Philae is not using its battery, the lander had to be illuminated for as long as possible and the morning path was chosen.

The 13th of June, Philae briefly contacted Rosetta… The contact was very short, only 85 s, and unstable but 300 data packet were transmitted to Earth through Rosetta.

After an analysis of the transmitted HK, it appears that the lander started to awake the 26th of April (as explain earlier this date is quiet approximate as it is computed thanks to the reboot increment).

Between the 13th of June and 9th of July, 8 others contacts occurred. The best one, almost 20 minutes long, was the last one (obtained with an orbit altitude of 150km). To improve the contact, ESA tried to decrease the Rosetta altitude (cf. Figure 8) but as the outgassing was increasing, orbits lower than 150 km altitude cannot be reached. After this date, the outgassing increased even more, creating problems with the star trackers, so Rosetta had to increase its attitude again.

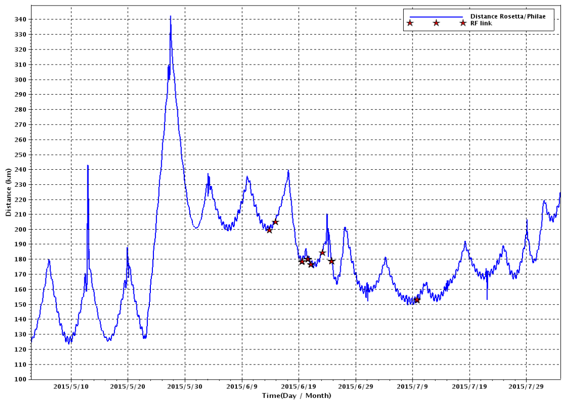

Figure 8: distance between Rosetta and Philae from May 2015 to august 2015. The red star indicated the moments were Philae contacted Rosetta.

If the lander started to awake at the end of April, why did we have to wait one month to have the first contact? Beginning of May, the altitude was low but unfortunately the Rosetta pointing and/or the trajectory phasing was not correct (fly over the site too early in local time).

After the wake-up, ESA dedicated Rosetta orbits to the communication with Philae. Rosetta was flying orbits through a zone of latitude defined by SONC-FD (taking into account the lander position and the antenna field of view). The orbit was crossing the latitude band between 5° and 55°. Rosetta was flying over Philae the morning on a terminator orbit. Based on the Rosetta ephemeris and attitude provided by RMOC, SONC-FD computed twice a week the communication opportunities. Figure 9 is a typical output of these predictions. It is a topographic map (longitude, latitude, radius of the comet).

The signification of the colored lines and symbol are:

- The red star is the Philae position.
- The gray lines are the comet topography (i.e. radius).
- The yellow lines are the portion of the Rosetta ground tracks when Philae is illuminated.
- The dark blue lines are the portion of Rosetta orbits where communications are possible considering a 60° half lobe for the antenna of Philae and Rosetta.
- The light blue lines are the portion of Rosetta orbits where communication are possible but with a 40° half lobe.
- The green squares represent the Rosetta ground tracks for real communication opportunities.
- The pink lines represent the Rosetta ground tracks for communications that occurred during the FSS.

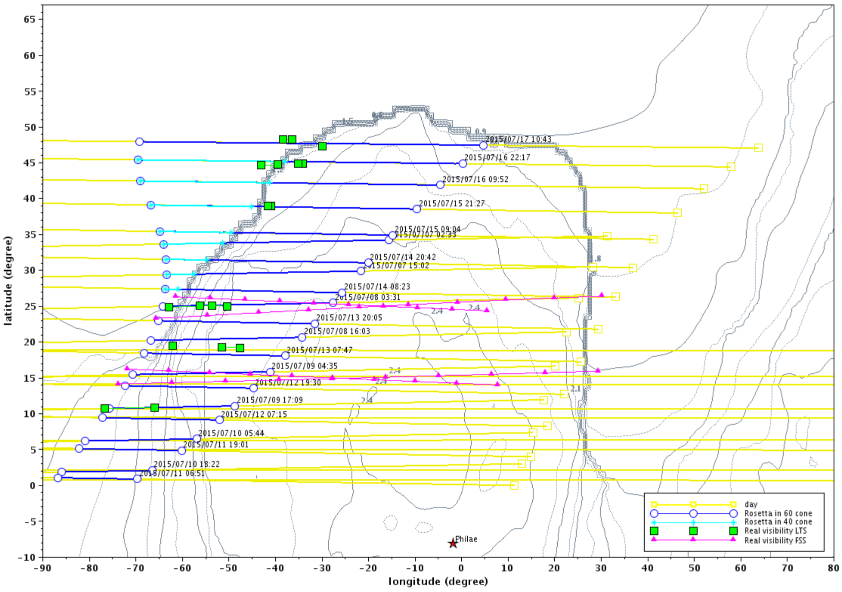

Figure 9: prediction of communication opportunities between Rosetta and Philae from 7th of July 2015 to 17 of July 2015.

We experienced less communication slots than expected. Rosetta was sometime flying almost the same orbit than the one where Philae communicated some days ago, but no link was established. This behavior was not explained but we suspect several origins:

- Some problems with the platform. One of the two Philae receivers does not work and one of the two transmitters works erratically. The mass memory seems also to have some problems.
- The distance Rosetta/Philae is too large and received signals are very weak and close to the detection limits.
- Some rocks may obstruct portions of the Philae antenna field of view preventing some communications.

We hope that in the next weeks, we will have new communications Rosetta/Philae. When Philae woke-up, the distance sun to comet was 1.8 AU. According to Figure 7, after the first of December 2015, the distance Rosetta/sun will be larger than 1.8 UA and it means that the amount of photons reaching Philae will be lower too.

4. Landing Phase

4.1. Descent trajectory

The descent trajectory may only be computed from simulation. CONSERT radar was active during the descent and performed ranging measurements but its accuracy is not sufficient enough to constrain the descent trajectory. It only shows that Philae descent was very close to the targeted trajectory.

Based on ROLIS and CIVA images, the CNES robotic team was able to derive the touchdown position [2,9] and attitude [9].

Table 3: comet models used and effect on the landing site date and position

Model set	**Shape Model**	**Gravity Filed**	**Outgassing**	**Time delay for the touchdown dates (s)**	**Distance to real touchdown site (m)**
1	OSIRIS	RMOC spherical harmonic expansion	No	10.1	7
2	RMOC	RMOC, spherical harmonic expansion	Yes	-2.37	12
3	OSIRIS	Gravity field derived from the constant density polyhedron	No	5.1	11

We then estimate the trajectory by using a classical propagation and taking into account:

- The epoch, position and velocity at the date of release (available from RMOC data)
- A shape model provided by OSIRIS. The shape model is a triangular faces polyhedron with 5 m resolution.
- A gravity field model. RMOC provided a classical spherical harmonics expansion (up to degree 3) derived from the navigation data. SONC-FD also used a gravity model derived from the shape model assuming a constant density [7].
- The comet ephemeris and rotation parameters provided by RMOC

- A comet outgassing provided by RMOC. The outgassing was very small at the date of landing so we did not use it all the time.

We also have neglected the solar radiation pressure for such a small duration.

According to Table 3, the largest distance of real landing site is 12 m and largest time delay is 10s.

The main contributors to the propagation error are the inaccuracies of the point of release and the DTM errors around the landing site. For all models set, the impact velocity expressed in CFF is close to 1.01 m/s (one notice that a 10 m error on the release point is around a 10s delay in the landing date).

4.2 Attitude during the descent

ROMAP team derived Philae attitude for some portion of the descent trajectory (ROMAP was sometimes switched off for the first 2h of descent). This work is still on-going and preliminary results are presented here.

During descent, Philae is rotating around its Z axis with a rotation rate slowly increasing from 8 to 9 minutes ROMAP method requires assuming a constant period of rotation and Z lander direction for a 20 minutes time span. The origin of the tumbling is mechanical (lander separation mechanism, landing gear and instrument deployment) and environmental (effect of the outgassing).

Figure 10 represents the Z lander axis direction (right ascension and declination) with respect to the Z direction of an inertial frame centered on the comet nucleus.

On the plot, the obtained directions (red and blue lines) are compared to:

- The targeted attitude at release (red or blue dashed line). This attitude was chosen to ensure that the lander will touch the ground along the local normal of the landing site. ROMAP solution is close to this attitude at the beginning of descent and slowly diverges.
- The lander attitude at moment of landing (light blue and magenta square): thanks to the ROLIS images taken in last portion of descent, CNES estimated an attitude. ROMAP direction is not too far from CNES direction. It is difficult to establish the error bound of each method.

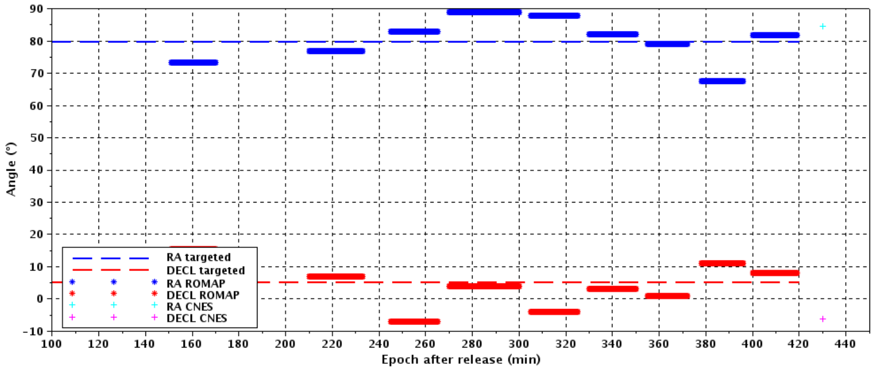

Figure 10: Z lander direction expressed in J2000 inertial frame according to ROMAP attitude with respect to the time after release

The validation of the full attitude during the whole descent is trickier. Again the ROMAP attitude is cross-checked with the illumination of the solar arrays.

Unfortunately as each current output is recorded each 4 minutes and as the rotation period is 9 minutes, the validation may only be very approximate. Nevertheless, ROMAP attitude is rather coherent with HK data (no results presented here). For the lander X axis, the results are less good and the error on the pointing is probably several tens of degree.

It should be mentioned that CONSERT measurement may also be used to estimate the attitude during the descent. As a matter of fact, CONSERT team was the first to measure the rotation rate evolution. ROMAP team is currently working with CONSERT team to cross validate the proposed attitude.

5. Rebounds

The results presented here are preliminary and need to be confirmed by more detailed analyses.

The available data to rebuild the rebound trajectories are not numerous:

- The dates of touchdowns and final landing (cf. tab. 1),
- An estimation of the position of the first touchdown and final landing position,
- Two estimations of Philae position during the flight between touchdown 1 and 2. OSIRIS camera took some pictures of the landing zone. Philae and its shadows were observed on one picture and the CNES robotic team was able to compute an estimate of the position.
- NAVCAM also observed Philae during second and third touchdown but we did not have the position estimation.

The comets models used for the analysis are:

- The comet ephemeris and rotation parameters provided by RMOC,
- The shape model provided by OSIRIS (the same than section 4),
- The gravitational potential is computed by considering a constant density polyhedron. This method seems preferable than using the RMOC spherical harmonics expansion because it is better represent close vicinity comet gravity field (Spherical harmonics expansion is limited to degree 3) and is valid everywhere outside the comet surface (Spherical harmonic expansion may present divergence properties inside the smallest sphere enclosing the shape model).
- The outgassing and solar radiation pressure are considered negligible.

The construction of a rebound trajectory was realized by optimizing a trajectory taken into account the available data. The optimization was based on the well-known “Nelder-Mead” algorithm.

The trajectory is optimized according to the following constraints:

- The flight duration of each rebound (plus or minus one minutes)
- At the date where the second OSIRIS picture was realized, the lander should be at 75 m from the position determined by the CNES robotic team
- The final landing site should be at less than 20 m from the determined ones.

We decided to not model the last rebound as its flying time was less than 6 minutes. In other word, we consider that the touchdown 3 is close enough to the real final landing site.

Among all trajectories that the optimizer may find, we extract 6 trajectories that are represented on Figure 11. Touchdown 1 is identical for all cases and touchdown 2 is located on various part of the crater rim. The largest distance between two touchdown 2 site is 275 m.

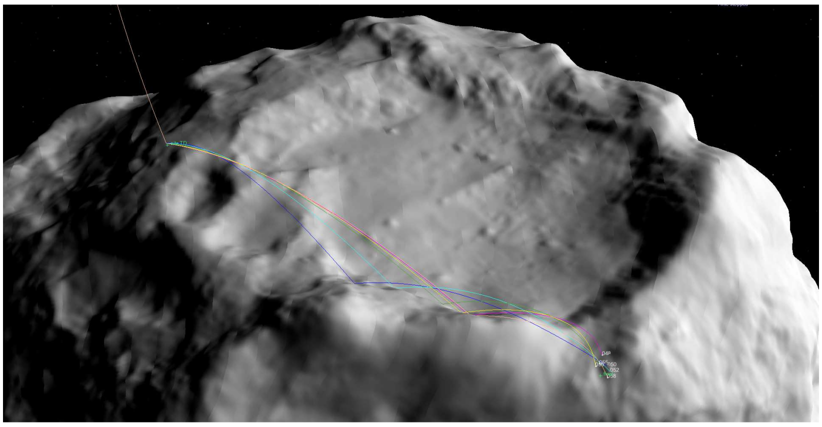

Figure 11: 6 rebound trajectories obtained through optimization.

For each obtained trajectory, we characterize the rebound geometry with use the following coefficients:

$$C_n = \frac{\|\vec{V}_{reb} - \vec{V}_{reb} \times \vec{n}\|}{\|\vec{V}_{in} - \vec{V}_{in} \times \vec{n}\|} \text{ and } C_t = \frac{\|\vec{V}_{reb} \times \vec{n}\|}{\|\vec{V}_{in} \times \vec{n}\|} \qquad (1)$$

Where

- C_n and C_t are the normal and tangential restitution coefficients,
- $\vec{n}$ is the surface normal at touchdown,
- $\overrightarrow{V_{in}}$ is the incoming velocity at touchdown point,
- $\overrightarrow{V_{reb}}$ is the rebound velocity at touchdown point.

We also computed the rebound angle (angle between -$\overrightarrow{V_{in}}$, $\overrightarrow{V_{reb}}$) and the absorption coefficient : $\frac{\|\vec{V}_{reb}\|}{\|\vec{V}_{in}\|}$

Figure 12 represents for each rebound the tangential coefficient with respect to the normal coefficient (left plot) and the absorption coefficient with respect to rebound angle (right plot).

Whatever is the trajectory, the two rebounds are different: for first rebound the incoming velocity is almost along the normal to the touchdown (this angle is 4°) but the rebound velocity is nearly orthogonal to the incoming velocity. At moment of touchdown, the lander was rotating around its Z axis and the three feet of the landing gear touch the ground one after the other [2]. As a consequence, it transforms a vertical velocity (relative to the local normal) to a tangential velocity. Two third of the incoming velocity (Vin=1.01 m/s) is dissipated by the landing gear dumping mechanics and by the contact with the ground. This is clearly not an elastic collision.

Second touchdown exhibits a different behavior. The angle between the incoming and rebound velocity is more 120°. The contact seems to be hard with low velocity absorption (absorption coefficient between 0.7 and 1). The tangential coefficients are between 1 and 2 and between 0.5 and 1 for the normal coefficient. The collision is almost elastic.

Concerning the attitude determination, this task is still on-going. The work to realize is equivalent to the one realized with ROMAP for the descent. As results are very preliminary, there are not presented here.

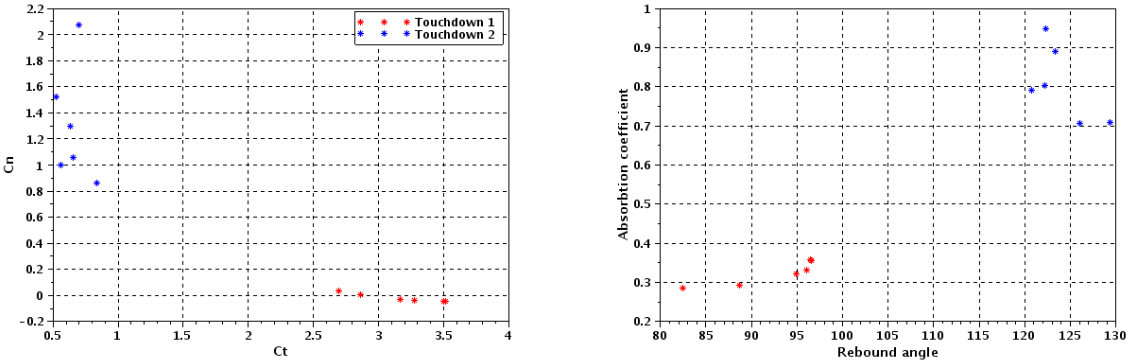

Figure 12: characterization of the rebound geometry for touchdown 1 and 2

6. Conclusion

Thanks to a collaborative effort involving various teams (CONSERT, OSIRIS,…), a highly possible landing area was identified. There is still some unknown in the exact localization of Philae but we hope that in a nearby future, Rosetta will fly by the proposed landing area bringing a conclusion to this activity.

Attitude on the final landing site was determined thanks to ROMAP team and later confirmed by a determination of attitude from the currents outputs produces by the solar arrays. The two solutions are coherent up to a ten of degrees.

A course analysis of Sun illumination evolution indicates that Philae may stop to be well illuminated at the beginning of December. As winter is coming very soon, one can only wish that in November, RMOC will be able to decrease Rosetta/Philae distance to less than 150 km. Of course, this is highly depending on the comet outgassing level.

The reconstruction of the descent trajectory is achieved. Depending on the comet model chosen, the obtained landing site is less than 13 m away from the observed one. Concerning the rebound trajectories, the lack of observation made the work uneasy. One may only obtain trajectories that do not violate the observations but there are just considered as plausible.

The attitude determination during descent and rebound may be partially (ROMAP was sometimes switched off) rebuilt with ROMAP data. For the descent, the rotation rate and Z lander axis direction seems in agreement with the HK current. This work is still under progress and better results may be expected soon.

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