PHILAE DESCENT TRAJECTORY COMPUTATION AND LANDING SITE SELECTION ON COMET CHURYUMOV-GERASIMENKO

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Abstract: *Rosetta, the European space probe that will orbit the comet Churyumov-Gerasimenko while it is heading to the inner Solar System, has been on its way for more than 8 years. After successful fly-by's of the asteroids Steins and Lutetia, another extremely challenging objective of this mission is to be fulfilled in November 2014: the first controlled touchdown on a comet nucleus. The work presented in this paper deals with the development of strategies for the optimization of descent trajectories to the comet and for the computation of ancillary quantities aimed at supporting the operational Landing Site Selection process. This process has to take into account the orbiter and lander operational constraints, harmonize these technical aspects with the landing site preferences of the scientific teams, as well as ensure the safety and back-up conditions that such a mission requires. Furthermore, the large amount of unknowns concerning the comet itself imposes the need for the strategies to be flexible. A well justified selection of candidate landing sites is essential from an operational point of view, because the planning of the operations of the last phases of Rosetta mission, as well as the global success of the landing is strongly dependent on this choice.*

Keywords: *lander delivery, optimization, landing scenario, flight dynamics products*

Glossary

ADS	Active Descent Subsystem
CNES	Centre National d'Etudes Spatiales
ESA	European Space Agency
FSS	First Scientific Sequence
LTS	Long Term Science
MSS	Mechanical Support System
PI	Principal Investigator
RLGS	Rosetta Lander Ground Segment
SDL	Separation, Descent and Landing
TBC	To be confirmed
TM	Telemetry

1. Introduction

Rosetta ESA mission was launched on the 2nd of March 2004. Its final target is the comet Churyumov-Gerasimenko (67P/G-C), that will be reached by the probe in 2014. One of the main mission objectives is to study this comet on its way around the Sun, both from orbit and in-situ. In order to do so, Rosetta's payload includes a 100 kg lander. The lander is called Philae and it can be seen as a small space probe in itself ([1]). In addition to its own scientific instruments, it carries several sub-systems such as solar panels, a fly-wheel for attitude control and an active descent system (ADS) with the capability to perform a pre-commanded ΔV during the descent, aimed at improving the landing conditions (speed, touchdown angles…). Rosetta will bring Philae close to the comet nucleus and release it. Then, the lander will perform a controlled landing on the comet surface, where it will carry on various scientific activities. At the same time, the orbiter will continue to orbit around the nucleus performing science operations with its instruments and relaying Philae's science data back to Earth.

Both Rosetta and Philae are now in hibernation mode, waiting for the arrival to the comet. After the spacecraft wake-up in January 2014, the following mission phases can be identified:

While Philae is still attached to the orbiter:

- Post-hibernation commissioning phase: after S/C wake up, the lander subsystem good health will be checked. This phase should last about 60 days.
- Pre-delivery calibration and science: during the Comet Approach phase, lasting about 150 days. Precise comet models will be elaborated by the scientific teams during this phase.
- In parallel to the pre-delivery calibration and science process, the Landing Site Selection will be performed.
- Lander delivery preparation phase: Once the landing site has been chosen, the final landing trajectory will be computed and the different operational products will have to be generated.

After the delivery of the lander:

- Separation, Descent and Landing (SDL): this is a short but crucial phase, lasting for less than one day, during which the lander will separate from the orbiter and land on the comet.
- First Science Sequence (FSS): consists of the first scientific operations just after landing and has a duration of up to 5 days, related to the lifetime of the non-rechargeable batteries.
- Long Term Science phase (LTS): having an approximate duration of 120 days during which scientific experiments will be conducted.

The flight dynamics team in charge of the lander (part of RLGS) is responsible for providing the technical elements that will help to choose the landing site. Besides, once the landing site has been chosen ESOC's orbiter flight dynamics team will compute the separation conditions and the operational descent trajectory. Both teams will provide the required flight dynamics products to the operational and scientific teams. Finally, after the landing is complete, they will continue to deliver orbital data and operational products.

The selection of the landing site is an extremely critical task that will take place during the mapping and observation phases that precede the lander delivery. Not only will it condition the operations until after landing but it will also play a key role in the global success of the mission. The final choice will certainly take into account a lot of scientific criteria. However, these criteria are under Philae PIs responsibility and consequently beyond the scope of the present work.

The Rosetta Lander Ground Segment(RLGS) is concerned by the following aspects related to the selection of the landing site (see [2]):

- the feasibility of the lander descent trajectory fulfilling the constraints coming from both

orbiter and lander sides,
- the solar illumination of the landing site (related to the available power for the lander's scientific activities).
- the relay orbit coverage.

The objective of the present paper is to give an insight into the on-going studies of landing feasibility as they are being developed at CNES, as well as the foreseen flight dynamics operational products. The methodology for the optimization of descent trajectories and the different operational scenarios currently under investigation are explained in more detail in section 2. Moreover, an example of the flight dynamics products produced by the RLGS is given in section 3. Finally, a summary and some conclusions of the work can be found in section 4.

2. Methodology

The goal of the methodology explained in this section is to assess the feasibility of Philae's landing on the comet 67P/Churyumov-Gerasimenko. In order to do so, trajectory optimization strategies have to be chosen and implemented, the operational scenarios have to be defined and several ancillary tools need also to be developed (such as event calculation based on ephemeris, solar illumination and energy production charts).

Moreover, Philae is expected to land and perform science activities on a celestial body whose characteristics are unknown. Therefore, modelling of the comet based on observations, as well as assumptions and accumulated knowledge from other missions, is strictly necessary. In particular, the shape and associated gravitational potential of Churyumov-Gerasimenko as well as the predicted out-gassing forces at the moment of Rosetta arrival and Philae deployment are inputs that have to be available before any trajectory computation starts. It is not the aim of this paper to describe the scientific activities related to the comet characterisation. Nevertheless, the reader has to be aware of the importance of this process. Descent trajectory analysis will use updated models as soon as they are established as reference models.

2.1. Daylight duration

Given a separation date, the landing in some regions of the comet surface becomes straightaway impossible due to the daylight duration requirements. This constraint currently establishes that a point on the surface needs to be illuminated for more than half the rotation period in order to be considered as possible landing site, both for scientific and energy generation purposes. In addition, at least 30 minutes of night at the landing site are required, to ensure shadow conditions for the FSS experiments that cannot work under illumination conditions, as well as to allow for the cooling down of the subsystems.

A quick analysis combining the comet shape model with the comet kinematics and solar ephemeris yields a preliminary filtering of possible landing sites, as shown in figure 1. Eliminating regions of the comet where the landing is not possible is helpful when exhaustive calculations are performed, as in this way the computational time can be significantly reduced.

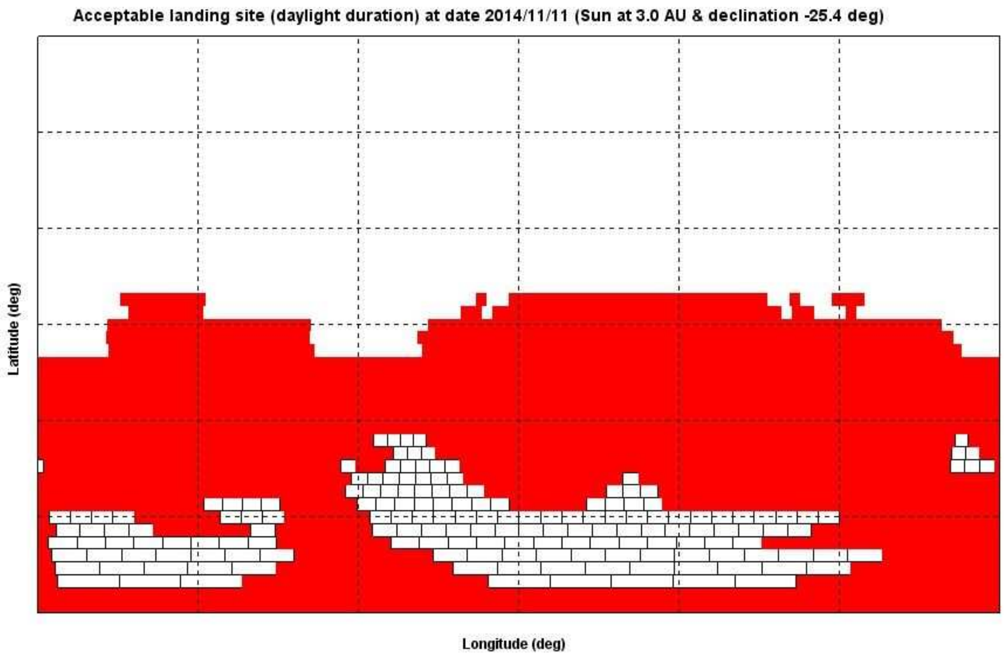


Figure 1. Example of comet cartography. In red, sites satisfying the daylight duration constraints on the landing date 11/11/2014. The division in hemispheres is due to the inclination of the rotation axis, while the *white islands* appearing for negative latitudes are a consequence of the relief.

2.2. Computation of descent trajectories

Andromac is the name of the software tool developed at CNES for the computation of descent trajectories and the assessment of landing feasibility on the comet Churyumov-Gerasimenko. In a first layer, it contains basic routines which handle the cometary models provided as input, make geometrical and algebraic calculations (reference frame transformations, vector operations. . .) as well as numerical integration according to a dynamical model. On top of this, optimization methods have been implemented, allowing to take into account the constraints on the descent trajectories coming from both the orbiter and the lander (see subsection 2.2.1.).

The following parameters characterize the descent trajectories and are used as variables in the search for solutions:

- the magnitude of the separation maneuver: ΔV_{sep},
- the angle of Philae X-axis with respect to a predefined North direction in the plane tangent to the landing site: ϕ (this angle defines the orientation of the ΔV_{sep}),
- the time from separation to impact: t_{imp},
- the impact velocity: v_{imp},
- the magnitude, ΔV_{ADS}, and time of the ADS maneuver, t_{ADS}.

A very simplified overview of the optimization process is given in what follows. Computations are done in a loop of latitude and longitude on the comet, excluding the points which have already been discarded due to daylight duration issues. Backwards propagation is performed, assuming that the nominal landing velocity is perpendicular to the surface impact point, as given by the shape model. For the trajectories which propagated backwards reach a sufficient altitude within the allowed bounds in duration, the orbital parameters of Rosetta at the moment of separation are computed. Further checks of the constraints lists are then performed and feasible solutions are stored.

Two different approaches are used:

1. Nelder optimization: given the list of constraints and the allowed ranges for the search parameters, a Nelder-Mead type algorithm is started (see [3]). The cost function to be minimized can be set to the descent duration, the impact velocity or a combination of both. The advantage of this method is that it penalizes the violation of any constraint and includes them in the function to be optimized. Thus, the best possible solution is given as an output even if it doesn't correspond to a feasible solution (that is to say, even if one or several of the constraints have to be violated). Furthermore, the penalty associated to each constraint can be modified, for instance to take into account the fact that a limit can be technically rigid (due to operational or safety reasons, such as the maximum deviation of the solar arrays on the orbiter from the Sun direction) or soft (scientific or project decisions). In this way, the mission designers realise which are the constraints that kill a higher number of solutions and get a hint on the bounds that should be negotiated if one wants to increase the probability of success and/or the number of reachable sites.
2. Exhaustive exploration, consisting of a discreetisation of the optimization parameters inside the allowed ranges and the exploration of the solutions resulting from all possible combinations of these parameters. Among the advantages of this method we find the variety of different solutions that can be computed for a single landing site, which yield the possibility to perform quantitative studies of the suitability of landing in a given comet region. The drawbacks with respect to the previous method are principally the increase in computational time and the lack of insight into the problem when no solutions are found for a given set of constraints.

Both methods are combined in order to take advantage of their different performances and to make up for their weak points.

2.2.1. Constraints

As mentioned above, the landing trajectories are subject and strongly conditioned by a list of constraints coming from the orbiter and the lander. The constraint concerning the daylight duration of the landing site depends only on the ephemeris and the comet geometry (axis and relief of the shape model), so the study is performed independently before the trajectory optimization starts (see section 2.1.)

The other constraints are listed below ([4]):

Lander side

- Impact velocity between 0.2 and 1.2 m/s (detection of landing and structural resistance).
- Descent duration between 30 minutes and 360 minutes. This constraint is related to the autonomy of the secondary batteries.
- Instantaneous touchdown angles, in case of a non-perpendicular landing (see figure 2):
  - Angle θ between lander Z axis and the surface normal should be less than 30 deg (related to the attitude at the moment of separation).
  - Angle γ between the velocity vector and the plane tangent to the impact point should be between -90 deg and -60 deg.
  - Angle α between the -Z axis and the touchdown velocity vector should be less than 30 deg.
- Magnitude of the ADS maneuver smaller than 1 m/s. The total maneuvering capacity of the ADS system is 1.85 m/s but a portion of it is kept as hold down, during touchdown.

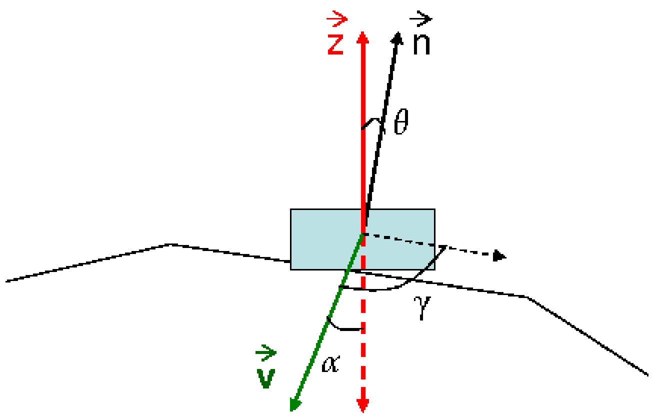


Figure 2. Schematic representation of Philae's touchdown angles.

Orbiter side

- The range of separation ΔV provided by the nominal separation mechanism is between 0.05 and 0.5 m/s. The back-up separation resort provides a ΔV fixed to 0.17 m/s.
- The orbiter will never descend to a pericentre radius of less than 5 km, neither for comet characterisation, nor for the delivery phase.
- For navigation accuracy, the angle between the delivery orbit plane and the terminator (i.e. plane perpendicular to the Sun direction) is restricted to a maximum of 20 deg. This angle is referred to as β-angle (even if sometimes in literature the β angle is defined as the complementary to the one used in the present work).
- The angular deviation of the Y axis of Rosetta from the Sun direction must be less than 30

deg (Solar Array deviation).

- The orbit of Rosetta is eclipse-free at all times.
- The period of the pre-delivery orbit should be commensurable with the comet rotation (for better comet characterisation and delivery rehearsal relevance) and ensure that the apocentre distance is approximately 10 km.

These two sets of constraints are very difficult to satisfy simultaneously. Therefore, different delivery strategies will be studied. To start with, the *direct deliveries* in which the last close observation orbit corresponds to the delivery orbit. Secondly, delivery trajectories including an orbiter *blind maneuver* performed 2 hours before separation. In the case of an orbiter maneuver, the orbital constraints listed above have to be satisfied only by the close observation or *pre-delivery orbit* (before the ΔV). So the advantage is that the actual delivery arc has more degrees of freedom, specially concerning the constraints on the β-angle and the period of the orbit.

2.2.2. Landing scenarios

Three baseline scenarios for the descent trajectories have been designed, characterized by the value of the separation ΔV as well as their use of the ADS (see table below). As a preliminary consideration, note that the nominal separation mechanism can provide a variable magnitude of ΔV, while the back-up spring will separate Philae at 0.17 m/s. Therefore, if a landing trajectory is computed for this particular value of the separation maneuver it will be robust to MSS failure, as the back-up trajectory and the nominal trajectory are the same. Furthermore, the probability of failure of the ADS system is estimated to be higher than the one for the MSS system. Consequently, a descent scenario making no use of the ADS is currently seen as less prone to failure.

Scenario	Optimization parameters	Advantages	Drawbacks
Preferred	h_{sep}, v_{imp}, ϕ ΔV_{sep}= 0.17 m/s, ΔV_{ADS}=0	Robust: MSS back-up case coincides with nominal trajectory	Solutions rarely found, restrained accessibility to comet surface.
Alternative	h_{sep}, v_{imp}, ϕ $\Delta V_{sep} \in [0.17, 0.5]$ m/s, ΔV_{ADS}=0	More solutions found, moderate failure risk.	Back-up trajectory has to be computed and constraints checked on it.
Last Chance	h_{sep}, v_{imp}, ϕ $\Delta V_{sep} \in [0.17, 0.5]$ m/s, $\Delta V_{ADS} \in [0, 1]$ m/s $t_{ADS} > 2$ min after separation	High number of accessible sites.	Higher probability of failure and larger ground dispersion ellipse.

Table 1. Main features of the analysed landing scenarios.

Computations for these basic scenarios are then combined with two other features of the trajectory: the satisfaction of the constraints for a safe landing in case of a back-up separation (and/or the failure to perform the ADS maneuver in the case of the Last Chance strategy) and the possibility of executing an orbiter maneuver 2 hours before the separation time. For the sake of simplicity, only the main characteristics of each scenario are explained here, but the reader should be aware of the large amount of possibilities that have been studied (i.e. last chance with/without orbiter maneuver, back-up trajectory satisfying/not satisfying the safe landing conditions. . .).

In case a landing site is accessible by means of trajectories corresponding to different operational scenarios, the risks associated to each descent trajectory are evaluated. In general, priority will be given to the scenario considered as the most robust among the feasible ones. For instance, if a *preferred scenario* trajectory is found, it would always be recommended for SDL, because of its operational simplicity and robustness from a flight dynamics point of view. Furthermore, trajectories with a safe back-up landing option in case of failure of the MSS are preferred to the ones having unsafe touchdown conditions. However, the landing trajectories have to be studied in a case per case basis and an exhaustive list of the criteria used to sort them out would exceed the objectives of the present work.

On the other hand, note that even if the MSS mechanism may be able to provide lower values of the separation maneuver than the ones shown in the table, values below the back-up spring ΔV_{sep} are never considered in the optimization. The reason for this is that situations leading to a back-up touchdown time earlier than the nominal one have to be avoided. The ADS reservoirs will be emptied for anchoring purposes when touchdown is detected or, at the latest, after the nominal landing time (including uncertainties) if no touchdown signal has been received by then. Therefore, commanding a separation maneuver smaller than the one provided by the back-up spring could result in longer descent durations, leading to an emptying of the ADS reservoirs while still in the descent trajectory. That is to say, it can produce an involuntary ADS trajectory correction with unpredictable consequence.

2.2.3. Dispersion analysis

Finally, for the study of the landing trajectories to be complete, a dispersion analysis has to be performed after the nominal trajectory computations explained in the previous sections. This analysis accounts for the effect of the uncertainties in the assumptions. As a result of the dispersion analysis, the risk associated to a given descent solution can be quantified in terms of dispersed landing conditions, such as impact velocity and touchdown angles, as well as distance from the nominal landing site and spatial distribution of the dispersed impact points. It is essential for a mission like Rosetta, implying the landing of Philae on an unknown body, to be able to predict the maximum deviation from the targeted landing site with a sufficient level of confidence. Then, this information can be combined with the knowledge of the comet provided by the available terrain models. In this way, the suitability for landing of the area that is covered by the dispersed touchdown points can be checked and the corresponding descent trajectory can, in turn, be accepted or rejected.

In particular, the dispersions applied to the nominal trajectories come from:

- Uncertainties in the comet models: the shape and gravity models are expected to be updated during the mapping phases, leading to models with low error margin. However, current models still have a significant level of incertitude and therefore results have to be dispersed to account for it. As for the out-gassing force, it will be very difficult to predict in an accurate way until short before landing.
- Orbiter related errors: in the separation attitude, position and velocity, as well as the execu-

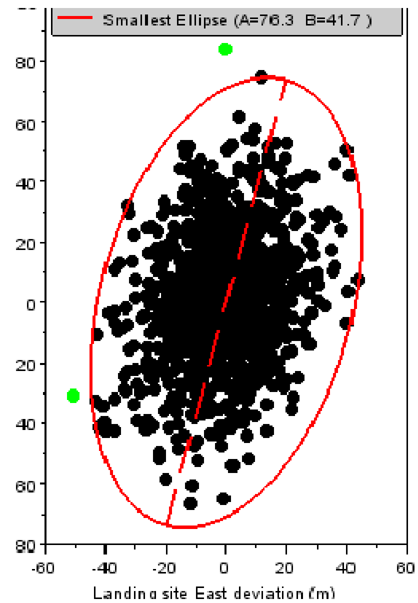


Figure 3. 3-σ dispersion ellipse: latitudinal and longitudinal deviations from a target site.

tion of the separation maneuver and the maneuver to go from pre-delivery orbit to delivery arc, in case an orbiter maneuver before separation is performed.

- Errors related to the ADS maneuver (when used): errors in the time of execution, in the direction and in the magnitude of the ADS maneuver can also have a dramatic effect on the landing conditions.

A Monte Carlo simulator has been included in Andromac. A large amount of simulations are performed using the information of a given descent trajectory, combined with the dispersed quantities. The ranges of variation of the parameters to be dispersed as well as the probability law that they are assumed to follow have to be provided as an input. Then, forwards propagation is used and the resulting descent trajectory characteristics and impact conditions are stored. At the end of the simulation, statistical quantities are computed. As mentioned above, one of the quantities derived from the dispersion analysis that may have a significant effect on the suitability of a given landing trajectory is the size and the orientation of the 3-σ dispersion ellipse. That is to say, the area on the surface of the comet around the target site, in which Philae will land with a probability of 99.73% (an example of the dispersion ellipse derived from the dispersed impact points is shown in figure 3). For a more detailed analysis of the uncertainties and the quantities that can qualitatively modify the descent trajectory calculations, see [5].

3. Flight Dynamics products

In this section, an overview of the flight dynamics products related to the lander delivery, touch-down and scientific phases on the comet is given. They are organised in three subsections, following a chronological order: landing preparation and landing site selection, products to be delivered during SDL and finally, products to be delivered after landing.

3.1. Landing preparation and LSSP

The method for the computation of landing trajectories explained in section 2. can be applied to all the landing sites. When the calculations are finished, a large amount of information concerning feasible descent trajectories will be available. All this information should then be post-processed and presented in a way that can be usable during the landing site selection process.

3.1.1. Global cartographies

Some of the results will be presented in the form of global cartographies (planar projections on latitude-longitude maps). The aim of these representations is to get a global idea of the variation of a given quantity over the whole comet surface, in order to be able to identify the most convenient areas. Examples of such cartographies are (see figure 4):

- Feasibility cartographies showing the latitude/longitude of the reachable landing sites. They can present results for a single scenario or combinations of landing scenarios.
- Daylight duration on the comet.
- Presentation of results from the exhaustive explorations: number of different landing trajectories, minimum descent duration trajectory. . .

3.1.2. Specific products for a landing site

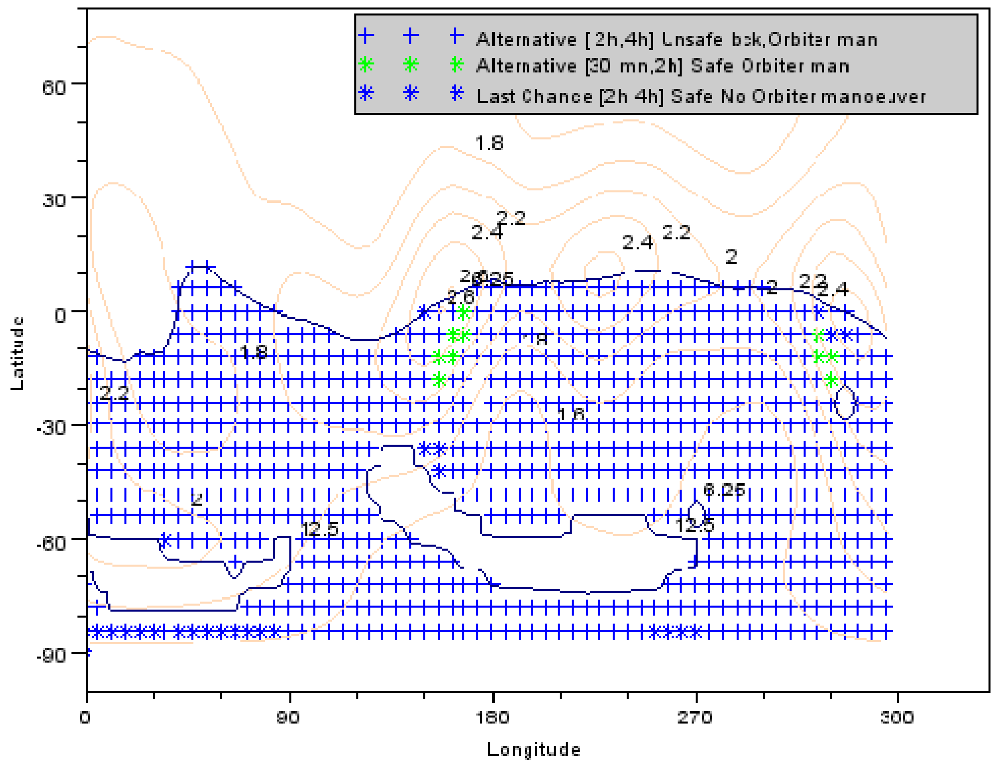
When a given site wants to be studied with a higher level of detail, different kinds of products can be generated. This will actually be done only for a short list of sites, for instance after some appropriate zones for the landing have been identified by means of the global cartographies presented above. Typical FD products for a specific site include:

- Local terrain model: Showing the specific local relief and horizon mask for a given landing site.
- Illumination and solar elevation (including the masking caused by the relief), that will be used by the lander system team to compute the available level of energy received by Philae's panels.

3.2. SDL phase

During the SDL phase products coming from the Flight dynamics team will be required mainly by the teams in charge of the instruments on the orbiter and the ones responsible for the lander platform science and safety. The list of the products to be delivered during this phase may include (TBC):

- Distance between the orbiter and the lander as a function of time (during descent).
- Minimum length trajectory going from the orbiter to the lander, with one rebound on the comet surface as a function of time.
- Altitude and velocity of the lander over the surface perpendicular given by the terrain model.



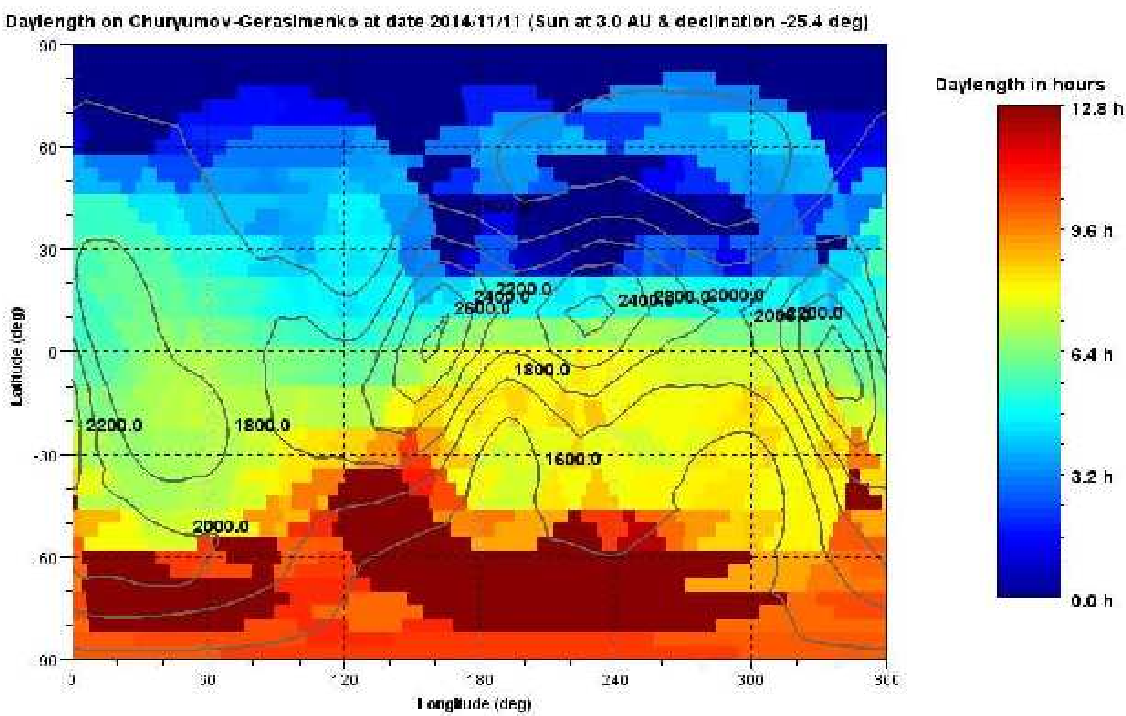


Figure 4. (top) Representation of the reachable landing sites, combining several descent scenarios. (bottom) Daylight duration on the comet, on 11/11/2014.

3.3. After landing

Shortly after touchdown, the exact position and orientation of Philae will have to be determined. Then, the degrees of freedom of Philae's platform (where payload is stored) with respect to the landing gear will be used in order to bring it to an optimized orientation. The flight dynamics products to be delivered afterwards are based on the knowledge of Rosetta and Philae position and related to the two sub-systems which are essential for the scientific activities: energy and data link. These products include:

- Tables of visibility windows from orbiter to lander, for TM transmission.
- Calculation of events based on the Solar ephemeris and the knowledge of lander position and orientation (such as local sunrise and sunset times).
- The illumination profile of Philae for the dates following the landing, in order to estimate the electrical power available.

4. Conclusions

A methodology for the computation of descent trajectories, as well as ancillary quantities to support the operational activities during the landing site selection process and Philae's descent and landing on the comet 67P/Churyumov-Gerasimenko, has been presented. An overview of the constraints and strategies that are currently being considered has also been given. On should bear in mind that this is a continuously evolving process: every time new information on the comet is received and established as reference model, the flight dynamics teams concerned by the landing operations preparation adapt their strategies accordingly.

Moreover, the choice of the landing site, together with the accomplishment of the descent and touchdown phases, are challenging activities both from a theoretical and from operational point of view. Besides, they are also rather delicate activities, mainly because of their relevance in the global success of Rosetta's mission, the restrictive technical constraints imposed by the lander and orbiter, together with the large amount of teams involved (belonging to several spatial agencies and scientific institutions). Consequently, an intensive preparation of these critical phases is required.

5. Acknowledgments

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6. References

[1] Bibring, J.-P., Rosenbauer, H., Boehnhardt, H., Ulamec, S., Biele, J., Espinasse, S., Feuerbacher, B., Gaudon, P., Hemmerich, P., Kletzkine, P., Moura, D., Mugnuolo, R., Nietner, G., Pätz, B., Roll, R., Sheuerle, H., Szegö, K., and Wittmann, K. "The Rosetta lander (Philae) investigations." Space Science Rev., Vol. 128, pp. 205–220, 2007.

[2] Blázquez, A., Jurado, E., and Canalias, E. “Philae Flight Dynamics Mission Analysis document.” RLGS-TNO-SONC-OPER-9306-CNES, 2011.

[3] Nelder, J. and Mead, R. “A simplex method for function minimization.” The computer journal, Vol. 7, No. 4, pp. 308–313, 1965.

[4] Biele, J. “Lander model for descent navigation and sensitivity analysis.” RO-LAN-RD-2000, 2012.

[5] SONC Flight Dynamics team. ”Descent trajectories on comet 67P/Churyumov-Gerasimenko using complex nucleus shape model”. ROS-TNO-LTAN-1869-CN, 2012.