ROSETTA LANDER DESCENDING PHASE ON THE COMET 67P/CHURYUMOV-GERASIMENKO

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ABSTRACT

On the 2nd of March 2004, Ariane 5 successfully launched the ROSETTA spacecraft of the Planetary Cornerstone Mission in ESA's long-term space science program. The probe began a 10-year heliocentric cruise which allows the encounter in May 2014 with the comet 67P/Churyumov-Gerasimenko. The main goal of the mission is the characterization of the comet environment in terms of dynamic and chemical properties. The ROSETTA spacecraft is made of two main parts: the orbiter (prime component) and the lander named PHILAE. This latter one with its own experiments is planned to land on the comet in order to perform various measurements and pictures. The French Space Agency (CNES) is in charge of the computation and the operational implementation of the lander descent trajectory. Thus, this paper concerns the design and optimization of the descent trajectory. Many issues appear when solving this problem because of the high number of unknown parameters characterizing the comet environment: shape, bulk density, outgassing, spin period... The computation of the descent trajectory is a very difficult task which drives to different assumptions and calculations: numerical model of the shape, computation of the gravitational acceleration and complex computation of the acceleration due to the outgassing. For these new mission analysis results, we will use the shape model described in [1] and the relevant results concerning the comet outgassing proposed in [2].

1. INTRODUCTION

Two important mission analyses of the ROSETTA mission landing phase have been already achieved. The first one, see [3] for example, carried out before the launch delay in January 2003, concerned descent trajectories on comet 46P/Wirtanen. The design of the spacecraft was partly based on the relevant results. Afterwards, the mission target changed and became comet 67P/Churyumov-Gerasimenko (67P/CG). The main difference between 46P/Wirtanen and 67P/CG is the size of the comet nucleus. This largely influences the landing conditions (see [4]): secure landing sites, impact velocity, and descent duration... This paper proposes new results on descent trajectories on comet 67P/CG. The originality of this study comes from a non-regular comet nucleus deriving from recent astronomical observations [1], and from an outgassing force caused by two predominant gases mixture [2].

After the description of the landing phase, i.e. the definition of the operational sequence, the comet environment is characterized in terms of shape, gravitational force, gas production and spin period. Thus, numerical computations carried out by means of ANDROMAC (internal CNES tool), allow to find optimal trajectories leading to secure landing sites.

2. LANDING PHASE STATUS

2.1 Phase Description

With respect to the nominal ROSETTA scenario, several operational phases are planned during the year 2014: the comet approach, the second rendezvous maneuver, the global mapping and close observation phases and finally the lander delivery. At that time, the comet will be located at 3 AU from the Sun and from the Earth. In this section, we will detail the landing phase, which may be split into five steps:

- After the close observation phase, the spacecraft is transferred on a delivery orbit.
- Then, PHILAE is released by means of the Mechanical Separation System (MSS) which provides a separation maneuver (MSS maneuver) whose direction is located in the plane orthogonal to the lander Z-axis. This axis has to remain in the same direction as the local normal at the landing site. The separation maneuver makes the ROSETTA orbiter move on a post-delivery orbit.
- An additional maneuver (ADS maneuver), performed by the Active Descent System (ADS), may be planned during the descent in order to reach the comet surface under conditions as favorable as possible. Magnitude of this maneuver and execution date are uploaded before release. Its direction is also collinear to the local Z-axis.

- After a ballistic phase, PHILAE lands on the comet surface under restrictive conditions on the impact velocity (magnitude and direction).
- Finally, other operations are planned to secure the touchdown, but they will not be detailed in this paper.

2.2 Descent Trajectories Optimization

This paper is focussed on the computation of the separation and descent maneuvers. A lot of constraints are expressed and included into the definition of a descent trajectory: minimum altitude for separation, maximum allowable magnitude of the impact velocity, impact avoidance between the orbiter and the comet nucleus, minimum duration between the separation and the descent maneuvers…

All descent trajectories are computed through an optimization procedure. The objective function, which has to be minimized, is generally the descent duration or the magnitude of the impact velocity. The constraints, described above, are then taken into account into the cost function by means of penalty coefficients. Finally, direct optimization methods allow to obtain optimal solutions avoiding the violation of constraints. Once the optimal trajectories are obtained for various landing sites, we have to study their robustness. The most critical parameters defining the trajectories, like the maneuvers or initial position and velocity on the delivery orbit, are affected by noises. The robustness is then characterized by the dispersions of the landing location and values of the impact velocity. In this way, some very interesting optimal solutions can be excluded because of their sensitivity to noise and only secure trajectories are kept.

3. COMET ENVIRONMENT

The computation of a descent trajectory requires the knowledge of the comet environment. Even if it will be well specified by the scientific teams at the end of the global mapping and close observation phases in 2014, some dimensional assumptions (on the shape, the bulk density, the gravitational force, the gas production…) have to be expressed for the needs of mission analysis.

3.1 Nucleus Shape

The shape model used in this paper is derived from the numerical model proposed in [1] and based on Hubble Space Telescope (HST) observations. This “starfish” shape can be closely approximated by the analytical and concise formulation given by equation (1), where f denotes the longitude, q the latitude and r the radius of a point located on the surface of the comet nucleus. Constant a is chosen in order to obtain a volume equivalent to that of a 2 km radius sphere.

$$\begin{cases} f = 1.3 + (0.3 + 0.09\cos f)\cos^2 f \\ u = \operatorname{atan}\left(\dfrac{\tan(q + p/2)}{f}\right) \\ r = a\sqrt{f^2 \sin^2 u + \cos^2 u} \end{cases} \qquad (1)$$

The proposed nucleus shape is shown in Fig. 1, where (X, Y, Z) is the frame of inertia.

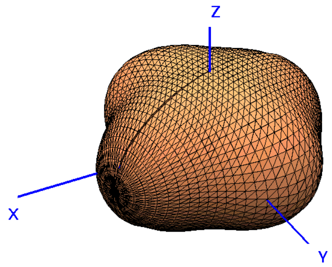

Figure 1: Comet 67P/CG nucleus shape

For the (X, Z) or (Y, Z) plane, the cross section of this shape is extremely regular, i.e. ellipsoidal, but the main characteristic comes from humps and hollows appearing for the (X, Y) plane. Thereby, this model is clearly not a convex one. The maximum radius reaches 2.64 km whereas the minimum one is 1.56 km.

3.2 Bulk Density and Gravitational Force

As mentioned in the previous studies, c.f. [3] and [4], the comet nucleus is assumed to be completely homogeneous inducing a constant bulk density. It is obvious that this hypothesis is not realistic but only dimensional. In this study, the nominal value of the nucleus density is taken equal to 1g/cm^3 but cases with variations between 0.5 g/cm^3 and 1.5 g/cm^3 will also be considered for future mission analyses.

The computation of the gravitational force may be done by means of several numerical methods. Let us quote for example: the spherical harmonic expansion approach, the ellipsoidal harmonic expansion approach and the polyhedron potential method. The two first approaches require restrictive topological assumptions on the shape of the considered body. These hypotheses are not fulfilled by the nucleus shape presented in the previous section. In this way, the polyhedron potential method only allows the computation of the gravitational force anywhere in the neighborhood of the comet. The shape of the nucleus is approximated by a polyhedron and the potential is equal to the sum of the contributions from each facet, using the method of Werner [5]. The precision obtained increases with the number of facets considered. Then, a direct consequence is the important increase of the computing time required. Another important remark has to be formulated: if the nucleus is not homogeneous then the method can not be applied. For the moment, this remains an open point for a future operational use considering that the probability to encounter a real heterogeneous nucleus is high.

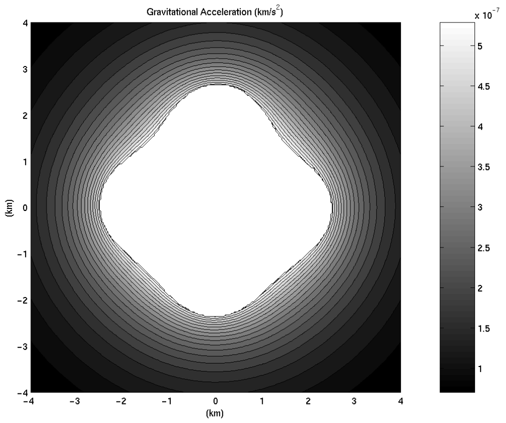

Figure 2: Iso-level curves of gravitational acceleration in the equatorial plane.

The gravitational acceleration (computed from the gravitational force) in the equatorial plane is represented in Fig. 2. This acceleration reaches its maximum value, i.e. 5.5e-7 km/s^2, at the surface of the nucleus and more precisely where the corresponding radius is minimum. Furthermore, the gravitational force vanishes for points far from the comet nucleus where the solar gravitational force becomes predominant.

3.3 Spin Period and Rotational State

It is assumed that the comet nucleus is animated by a continuous rotation rate around the Z-axis (see Fig. 1). This spin period is taken to 12.6 hours, which is the result of light curves analyses based on HST observations [1]. Compared with the previous studies on the landing on comet 46P/Wirtanen, where the rotation period varied from 7 hours to 24 hours, this value may be viewed as an average.

Today, as specified in [6], the rotational state is unknown. The pole is considered as fixed in these simulations since anyway the descent duration is short, typically less than 1 hour. The real rotational state will be identified during the global mapping phase by means of extensive measurements. This will lead to build and to update the rotational state model.

3.4 Gas Production

This point is probably the most interesting one because the gas production is specific to comets. Furthermore, the modeling of the gas production is a quite difficult task because close observations are not yet available.

All inputs presented in this paper are given by Crifo and al. (see [2]). In the framework of previous studies with target 46P/Wirtanen, similar outgassing results had been already included into the landing simulations [7]. Here, two different gases are taken into account for the outgassing computations: H_2O and CO. The combined gas production rate Q is equal to 1e+27 molecules/s. Moreover, the outgassing is only considered in an established and steady rate (the transitory phase is neglected). The force due to the gas production can then be derived (see Fig. 3 for the corresponding acceleration).

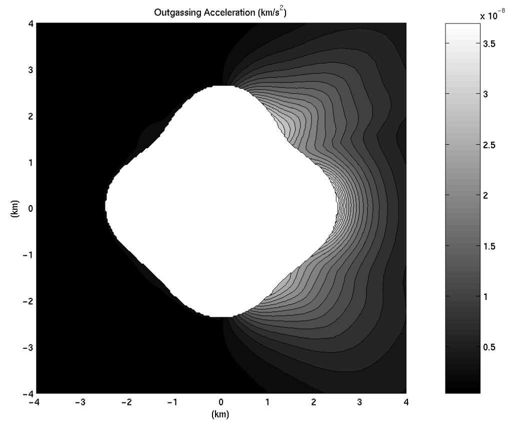

Figure 3: Iso-level curves of the outgassing acceleration in the equatorial plane.

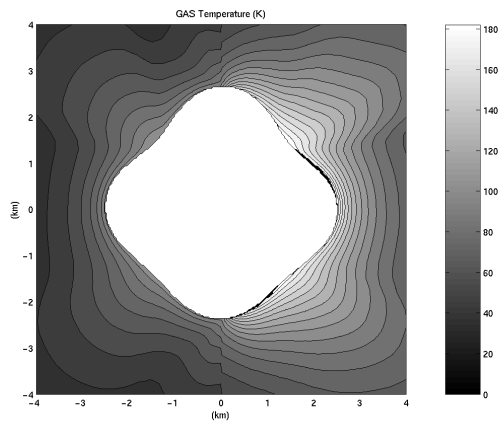

Figure 4: Iso-level curves of the gas temperature in the equatorial plane.

The outgassing acceleration reaches its maximum value at the surface of the nucleus and more precisely at locations for which the local normal is collinear to the sun direction. Thus, the most gas-productive locations can be clearly identified in Fig. 3. The maximum ratio between the outgassing and the gravitational accelerations is close to 8 %. That means that the gravitational force remains predominant adopting the assumptions formulated in section 3.2.

Figure 4 shows the gas temperature in the vicinity of the nucleus. One can notice the important variation between the day side and the dark side though the landing occurs at 3 AU from the sun. Thereby, the temperature climbs to 180 K and tends to 0 K at the dark side. For the understanding of Fig. 3 and Fig. 4, we have to precise that the Sun is located in the equatorial plane and in the East direction.

In this mission analysis, the dust production, (c.f. [2] and [8]) has not been considered. It would be preferable in the future to introduce the corresponding force in the simulations in order to obtain more realistic landing conditions.

4. RESULTS

4.1 State of the Analysis

Since the landing site will be determined at the end of the global mapping phase, the entire nucleus surface has to be inspected for the needs of mission analysis. The topography of the surface and the landing location, i.e. latitude and longitude coordinates, determine the normal vector with respect to the site and also the rotational velocity. Thereby, important disparities may appear. Furthermore, multiple sun directions are considered in order to include all the critical cases mainly due to the outgassing force.

4.2 Optimal Trajectories

Concerning the descent trajectories, two different strategies are offered. The passive strategy means that after separation the trajectory is purely ballistic. The active descent strategy allows to introduce one ADS maneuver during the descending phase. The choice of the strategy will be determined by the optimization procedure.

The descent strategy is directly defined through the optimization criterion adopted. The impact velocity is a critical parameter because the safety of the lander depends on it. A high impact velocity leads immediately to a crash. So all the decisions and conclusions will be determined by the value of this parameter. Nevertheless, the descent duration may be also considered in order to minimize the duration of the ballistic phases. During these phases, perturbing forces (gravitational force, outgassing, and dust…), which are known only roughly, influence the motion of the lander. Thereby, the shorter the duration is, the greater the robustness with respect to model uncertainties. We propose to compare the optimal trajectories obtained with either criterion. The optimization procedure has to take into account some other technological and operational constraints. The main dimensional constraints are described as follows:

- The modulus of the impact velocity is limited to 1.2 m/s since beyond this threshold the lander integrity is not guaranteed.
- The duration of the descent phase has to be greater than 30 minutes for operational reasons (deployment of the landing gear, measurements…).
- The magnitude of the separation maneuver, respectively the descent maneuver, is limited to 0.529 m/s, respectively 1 m/s.
- The directions of the maneuvers and the lander attitude are constrained as described in section 2.1.
- The release altitude must be greater than 1 km/s.

In a first step, we will inspect the entire nucleus surface by considering the impact velocity criterion. A number of 286 cases are analyzed. 158 cases (55 %), respectively 128 cases (45 %), present an impact velocity less, respectively greater, than 1.2 m/s. The minimal impact velocity is obtained for *configuration 1* (i.e. landing site located at 0 deg. of latitude and 0 deg. of longitude and the sun direction points at 0 deg. of latitude and 0 deg. of longitude) and its value is equal to 0.718 m/s. On the other hand, the maximal impact velocity appears for *configuration 2* (i.e. location 0 deg. of latitude and 45 deg. of longitude and the sub-solar point is located at 0 deg. of latitude and 180 deg. of longitude) and the corresponding value is 1.325 m/s. The characteristics of these extremal trajectories are summarized in tables 1 and 2.

Table 1. Results for configuration 1

Criterion ®	**Impact velocity**	**Duration**
impact velocity	0.718 m/s	1.159 m/s
descent duration	55 mn	30 mn
separation *DV*	0.529 m/s	0.489 m/s
descent *DV*	0.164 m/s	0.675 m/s
release altitude	1 km	1.5 km

Table 2. Results for configuration 2

Criterion ®	**Impact velocity**	**Duration**
impact velocity	1.325 m/s	1.5 m/s
descent duration	102 mn	52 mn
separation *DV*	0.529 m/s	0.529 m/s
descent *DV*	0.754 m/s	0.974 m/s
release altitude	3.1 km	2.9 km

For each trajectory, the strategy consists in using the maximum capability of the separation system, i.e. the magnitude of the separation maneuver is equal to the upper bound (0.529 m/s). This leads us to think that the constraint on the magnitude of the MSS maneuver is the most restrictive one. For a greater upper bound, we would obtain a lower impact velocity. In both cases, the strategy employed falls into the active category, see values of descent *DV*s in tables 1 and 2. Concerning the release altitude, one can notice that the optimization procedure set it to the lower bound (i.e. 1 km) for configuration 1.

When the duration criterion is considered, the previous better case (in terms on impact velocity) becomes critical. Even if the duration is equal to the lower bound (30 minutes), the impact velocity becomes quite high, close to 1.16 m/s. We notice that the ADS maneuver is used to speed up the lander. The magnitude of this ADS maneuver is increasing indeed from 0.164 m/s (minimum impact velocity criterion) to 0.675 m/s (minimum duration criterion). On the other hand, the magnitude of the MSS maneuver is decreasing from the upper bound 0.529 m/s to 0.489 m/s. This is due to the direction of the separation maneuver which is constrained to be in the plane orthogonal to the lander Z-axis and then not favorable to a diminution of the descent duration. Similar results with higher impact velocity and longer duration are obtained for configuration 2. We can conclude that trajectories generated for configuration 2 must be categorically rejected.

At this point of the study, it is very important to analyze the effect of the gas production on the value of the impact velocity. The inspection of the entire nucleus shows that this effect can not be neglected. Depending on the sun direction and so on the outgassing, the part of the nucleus reachable by the lander varies from 46 % to 62 %. Configuration 1, for which the best value in terms of impact velocity is obtained, is defined by a landing site located at the sub-solar point. This proves that the gas production, which reaches its maximum at the sub-solar point, influences notably the lander motion during the descending phase. Furthermore, one can obviously deduce that the outgassing force is opposite (in terms of direction) to the gravitational one.

Concerning the effect of nucleus shape disparities, the conclusions of this present analysis is that the part of the nucleus reachable by PHILAE is located near humps and close to the equator. As the magnitude of the separation maneuver is constrained, the strategy minimizing the impact velocity consists in using the rotational velocity of the comet nucleus. Indeed, the impact velocity is the result of the difference between the lander velocity and the rotational velocity. This last one reaches its maximum near the equator (low latitudes) and where the radius is highest (humps). On the other hand, landing sites close to poles and/or located in hollows (such as configuration 2) present the lowest rotational velocity and thereby the highest impact velocity.

Optimal trajectories, with respect to duration or impact velocity, for configuration 1 are proposed in Fig. 5.

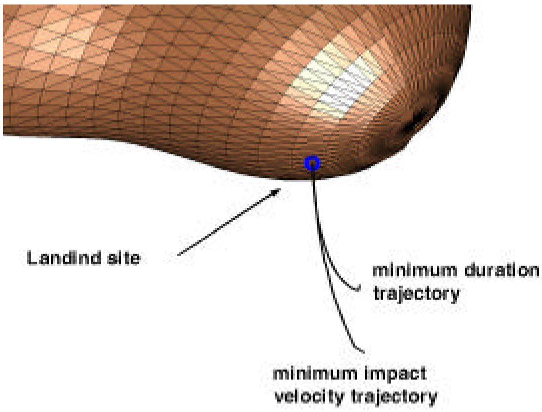

Figure 5: Lander trajectories – for configuration 1 - minimizing the impact velocity and the descent duration.

4.3 Robustness

In the previous section, optimal trajectories have been obtained. It is important to analyze their robustness with respect to errors on control parameters. A robust trajectory is defined as follows: whatever the dispersions may be, PHILAE is ensured to land 50 m around the nominal landing site with an acceptable impact velocity. An optimal trajectory presenting very high dispersions must not be implemented for an operational point of view. Here, the parameters affected by disturbances are:

- The initial orbit parameters, i.e. position and velocity of the orbiter/lander system at the separation date.
- The MSS maneuver: magnitude and direction.
- The ADS maneuver: magnitude and direction.

This list is clearly not exhaustive and other dimensional parameters (like the lander attitude, the comet density…) must be added in the future. The nominal values of the deviations are defined as follows (see [9]): 20 m on the orbiter/lander position, 1 mm/s on the orbiter/lander velocity, 1 % on the magnitude of the separation and the descent maneuvers, and 0.5 deg. on the separation maneuver direction. The deviation of the ADS maneuver direction is equal to 0.33 deg. if $DV <$ 0.1 m/s, 0.6 deg. if 0.1 m/s $\leq DV <$ 0.5 m/s, and 1 deg. if $DV \geq$ 0.5m/s. A Monte-Carlo procedure with 5000 tries is applied in order to simulate these perturbed cases. Results for configurations 1 are summarized in table 3 (results for configuration 2 are not detailed in this paper). There are presented the values of maximum, minimum, mean and standard deviation of the following parameters: impact velocity, distance to the landing site, latitude, longitude, difference between the landing date and the nominal one.

Table 3. Dispersions for configuration 1, trajectory minimizing the impact velocity

	Max.	**Min.**	**Mean**	**Std**
impact velocity	0.754 m/s	0.716 m/s	0.734 m/s	5e-03 m/s
distance	71 m	0.15 m	22 m	12 m
latitude	1.38 deg.	-1.44 deg.	9e-03 deg.	0.34 deg.
longitude	1.61 deg.	-1.22 deg.	0.24 deg.	0.41 deg.
date	289 s	-188 s	39 s	62 s

The mean value of the impact velocity is naturally greater than the nominal value since the landing sites are systematically different than the nominal one which is set to be the optimal location for landing. We can compute the 3-σ-error on the distance to the nominal landing site. This means that 99.7 % of the cases presents a distance less than the 3-σ-error. Here, this last one is equal to 60 m. This value is not in accordance with the landing results proposed in [9]. Nevertheless, the probability to obtain distances greater than the expected 50 m is 2 %. Moreover, the maximum value of the impact velocity is only 5 % greater than the nominal value and so largely less than the upper bound (1.2 m/s).

5. CONCLUSIONS

In this paper, landing scenarios on comet 67P/CG have been described. The present mission analysis has taken into account a numerical complex nucleus shape, the effect of the gravitational force (which has been computed for a non spherical and non ellipsoidal shape), the effect of the force due to the gas production (computed by means of complex fluid mechanics and thermodynamics tools) and the spin period of the comet nucleus. The results are quite different than the previous ones obtained for comet 46P/Wirtanen essentially because of the size of the comet nucleus (and so bulk density, spin period…). Compared with the previous study on the comet 67P/CG, the main differences come from the non-regularity of the shape and the production of two different gases. Influence of humps and hollows is clearly shown. So, the best landing conditions are obtained for the configurations defined as follows:

- Proximity between the landing site and the sub-solar point to take advantage of the outgassing force.
- Near equator location and humps vicinity to have high rotational velocity.

The robustness analysis shows that optimal scenarios (like configuration 1) remain achievable for an operational point of view. Finally, in case of a lack of knowledge on the perturbing forces, short descent trajectories have to be envisaged in order to minimize the duration of ballistic phases. Further developments on the CNES mission analysis tool (ANDROMAC) will concern the complexity of the dynamical model. The rotational state of the nucleus and some other significant forces, like that coming from the dust production, will be introduced to make the model more realistic.

6. AKNOWLEDGEMENT

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