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Rosetta Lander – Philae: Landing preparations ☆

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ABSTRACTS

Rosetta is a Cornerstone Mission of the ESA Horizon 2000 program. After rendezvousing with comet 67P/Churyumov–Gerasimenko in August 2014 and a 10 year cruise it started to study both its nucleus and coma with an orbiting spacecraft. The Lander, Philae, will land on November 12th and perform in-situ studies of the cometary material with a payload consisting of 10 scientific instruments.

Rosetta and Philae have been in hibernation until January 20, 2014. After the successful wakeup they underwent a post-hibernation commissioning. The orbiter instruments (like e.g. the OSIRIS cameras, VIRTIS, MIRO, Alice and ROSINA) characterized the target comet and its environment to allow landing site selection and the definition of a separation, descent and landing (SDL) strategy for the Lander.

By September 2014 our previously poor knowledge of the characteristics of the nucleus of the comet has increased drastically and the nominal and backup landing could be selected. The nominal site, as well as the corresponding descent strategy have been confirmed in mid-October, one month before the landing. The paper summarizes the selection process for a landing site and the planning for Separation-Descent-Landing (SDL).

1. Introduction

Rosetta is an ESA mission to an active comet, 67P/Churyumov–Gerasimenko. It has been launched in March 2004 and reached its target in August 2014 after 10 years of cruise [1,2]. After a careful investigation during the first months near the comet, with spectacular results from the Orbiter instruments, it is planned to deliver Philae, the Rosetta Lander, to the surface of the comet in mid-November 2014 [3].

The lander and its payload have been described in some detail e.g. by Biele and Ulamec [4]. Philae will be ejected

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from the Rosetta Orbiter at a pre-calculated point of a dedicated delivery trajectory and descend ballistically to the surface of the comet. The delivery orbit allows targeting for a particular landing site, which has been selected, following a selection process, as described in Section 4.

Philae is operated from the LCC (Lander Control Centre) at DLR, Cologne, and the SONC (Science Operations and Navigation Centre) at CNES, Toulouse [5]. Both centers are directly connected to the Rosetta Mission Operations Center (RMOC) at ESOC, Darmstadt. Rosetta science operations planning is performed at the RSGS (Rosetta Science Ground Segment) at ESAC, near Madrid [6]. The responsibility for Lander delivery lies with ESA. However, close cooperation between the partners is envisaged, to reach the challenging task of the first successful landing on a comet.

2. Flight activities of Philae since end of hibernation

After successful wakeup of Rosetta, January 20, 2014, spacecraft and payload have been re-commissioned. Also the Lander went through this post-hibernation commissioning (PHC) process. The first switch-on after more than three years took place on March 28, when an updated software for the central data management system (CDMS) was uploaded.

This activity was followed by three commissioning blocks, where all lander subsystems and instruments were activated, EEPROMs have been refreshed and in some cases new software was uploaded. No major degradation has been observed, the lander was found to be in a state very similar as during the checkouts before entering hibernation.

The lander has been switched on for several further occasions, before the actual separation-descent-landing (SDL) sequence will be initiated in November (see Table 1). The so called Pre-Delivery Calibration and Science (PDCS) phase includes background measurements and “sniffing” of the mass spectrometers (Ptolemy and COSAC), calibration of the CIVA cameras as well as imaging of the comet nucleus, parallel operations of ROMAP with RPC (magnetic field, ion environment) and activation of CONSERT. The solar generator performance has been verified (in PST-2, power system test) and the secondary batteries were cycled for capacity degradation measurement.

3. Preparations for landing and on-comet operations

Several aspects of landing as well as operations at the comet have been prepared and tested in great detail during cruise and hibernation, over the past years.

The operations of the lander have been (and are still) tested e.g. with the Philae Ground Reference Model (GRM), consisting mainly of flight spares and qualification models of the various instruments and subsystems and with the Lander Simulator (LS, a dedicated software) at DLR while the definition of timelines of operations on comet has been supported with MOST (a planning tool, developed at CNES).

Various scenarios have been exercised with the models on ground to ensure fast reaction time and flexibility to any given situation in the vicinity or on the surface of the comet in 2014/2015. The GRM was also used to prepare operations during cruise (see e.g. Ulamec et al. [5]).

The tight resources in terms of power, energy and data relay opportunities require intelligent planning of the science sequence (timeline, optimum use of battery capacity, thermal aspects, and definition of decision points) [6].

Moreover, a procedure for the selection of the most appropriate landing site, making maximum use of products from the Rosetta Orbiter instruments (in particular OSIRIS, VIRTIS, MIRO, ROSINA and ALICE) has been developed and tested.

The Landing site selection process, as well as the preselected landing sites are described in the following chapters. In order to test the actual landing dynamics the Landing and Mobility Test Facility (LAMA) at DLR in Bremen has been used [7]. A robot (Kuka KR500 [8]) was

Table 1
Philae flight activities between end of hibernation and separation.

Activity	Start	End	Duration (h)	Comments
PHC-0	28.03.2014 06:02:15	28.03.2014 13:52:39	07:50:24	Status check after hibernation, CDMS S/W upload
PHC-1	08.04.2014 10:02:15	10.04.2014 17:52:39	55:50:24	Verification of status of all Lander units
PHC-CNT	12.04.2014 00:02:47	12.04.2014 01:47:19	01:44:32	Contingency activities
PHC-2	14.04.2014 05:02:31	17.04.2014 17:52:40	84:50:09	Subsystem, payload commissioning activities
PHC-3	20.04.2014 21:02:32	23.04.2014 15:53:12	66:50:40	Finalization of commissioning and payload interference tests
PDCS-1	13.07.2014 14:37:30	14.07.2014 20:23:06	29:45:36	Ptolemy, CIVA and APX calibration, ROMAP/RPC measurements; distance to comet about 10,000 km
PST-2	23.07.2014 00:51:54	23.07.2014 06:17:14	05:25:20	Power system test
BattChar-TxRx	04.09.2014 02:02:20	05.09.2014 18:17:16	40:14:56	Battery characterization and test of RF communications system
PDCS-Block 4-1	07.09.2014 15:31:56	08.09.2014 06:22:36	14:50:40	CIVA imaging, ROMAP/RPC measurement; distance to comet about 50 km
PDCS-Block 2B	15.09.2014 02:02:20	17.09.2014 01:52:44	47:50:24	Ptolemy “sniffing” measurements; distance to comet about 30 km
PDCS-Block 4-2	24.09.2014 20:32:44	25.09.2014 11:22:20	14:49:36	CIVA imaging, ROMAP/RPC measurement; distance to comet about 30 km
PDCS-Block 3	06.10.2014 08:01:49	08.10.2014 00:57:17	40:55:28	Ptolemy and COSAC “sniffing”, ROMAP/RPC measurement; distance to comet about 20 km
PDCS-Block 6	16.10.2014 04:01:49	17.10.2014 20:38:05	40:36:16	Ptolemy and COSAC “sniffing”; SESAME measurement, CONSERT pingpong test.
LDP	27.10.2014 02:41:49	28.10.2014 07:47:57	29:06:08	Lander delivery preparation
	28.10.2014 08:01:49	28.10.2014 20:38:05	12:36:16	

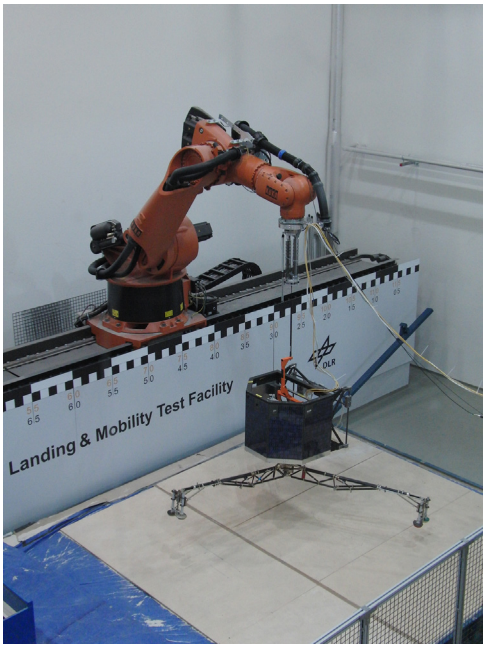

Fig. 1. Landing Tests with LAMA facility at DLR.

supporting a mass dummy of the lander together with the qualification model of the landing gear (see Fig. 1).

This way the dynamics of the touch-down under low gravity conditions could be simulated better than during the original pendulum tests, as performed during qualification at the Max Planck Institute in Lindau, MPS [8]. A detailed SIMPACK model of the lander has been established [9] and was calibrated and verified with the data from the LAMA tests. For any given touchdown condition (attitude and velocity vector angles, velocity – for two soil compressive strengths, soft/7 kPa and hard /2 MPa) the landing can now be simulated.

4. The landing site selection process

The selection of the landing site was driven by the observations necessary to characterize the comet in the various mission phases [10]. A number of decision points have been defined to first lead to the selection of five potential landing areas. Those have been announced on August 24 and are briefly described in the following chapter. Out of the five the nominal and backup sites have been defined on September 14. Since there was no technical reason against, the top priority landing site, as proposed by the Lander Project representative has been confirmed in a Lander Operations Readiness Review (LORR) and is now implemented into the operational timeline by RMOC. Decision points (as described in more detail in Rosetta internal documents [11]) as part of the Landing Site Selection Process have been the following:

a. August 24, about 80 days prior to landing, the Lander Project has proposed five potential landing areas to ESA/RMOC.
b. RMOC confirmed that these sites were acceptable according to Rosetta spacecraft requirements and made first trajectory analyses. Note that one site (A) turned out not to be acceptable and for another site (C) no solution allowing full redundancy of the separation mechanism could be found.
c. September 14, about two months before landing the landing areas have been ranked. The top ranked site (J) is the selected landing site.
d. Thirty days prior to landing, the Lander Project has confirmed the nominal landing site. No final tuning of the landing sites coordinates was required. This was originally foreseen to consider more detailed risk analyses, including bolder distribution, slope and illumination statistics. This decision was based on high resolution OSIRIS images and detailed trajectory calculations by both, RMOC and SONC.

An ESA-led Landing Operations Readiness Review (LORR) has given the formal go ahead for landing operations.

e. Five days before landing the LCC will provide RMOC with the final products for Lander commanding.
f. The final GO from Lander side for SDL operations is planned to be given seven hours before separation. Note that another GO/NOGO decision point has been introduced by ESA, two hours prior to separation, after confirmation of the integrity of the last trajectory correction maneuver, bringing Rosetta into delivery orbit. This is the latest time to (actively) abort Lander separation.

A number of requirements have been defined for choosing the final landing scenario [12]. Examples are:

- The angle between the Sun direction and the surface normal shall be $<60^\circ$ at and during ≥ 40 min after

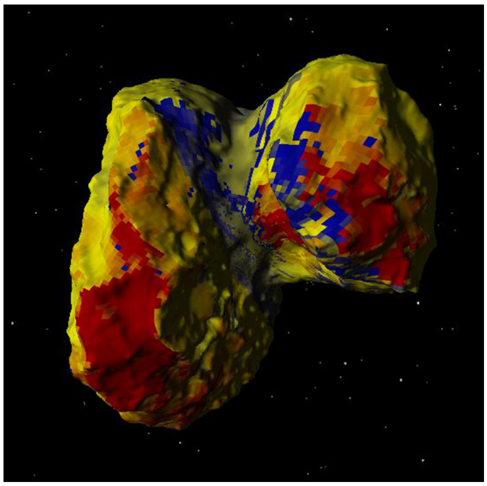

Fig. 2. Illumination map, projected onto the comet shape model. The illustration shows the conditions in mid-November, 2014. The colors refer to the hours of sun illumination per comet rotation. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

landing. This means, there should be daylight just before and during the early activities after landing.

- The impact velocity shall be between 0.3 m/s and 1.2 m/s. The landing gear was originally designed for a mission to comet Wirtanen [3], where low impact velocities were to be expected.
- The vertical axis of the lander shall be within 30° of the surface normal at landing (including an assumption for local roughness).
- The angle between the velocity vector and the lander Z axis angle shall be less than 30° at landing.
- The angle between the velocity vector and the surface normal shall be less than 30° at landing. (including an assumption for local roughness)
- The nominal separation velocity from the orbiter is commandable between 5 cm/s and 0.5 m/s. A backup (emergency) release mechanism would eject the lander with a separation velocity of ~18 cm/s. It was desired that, if possible, the nominal separation velocity should be set to 18 cm/s or close to it, such that even in case of a failure of the nominal separation the backup puts the lander in the nominal descend trajectory or close to

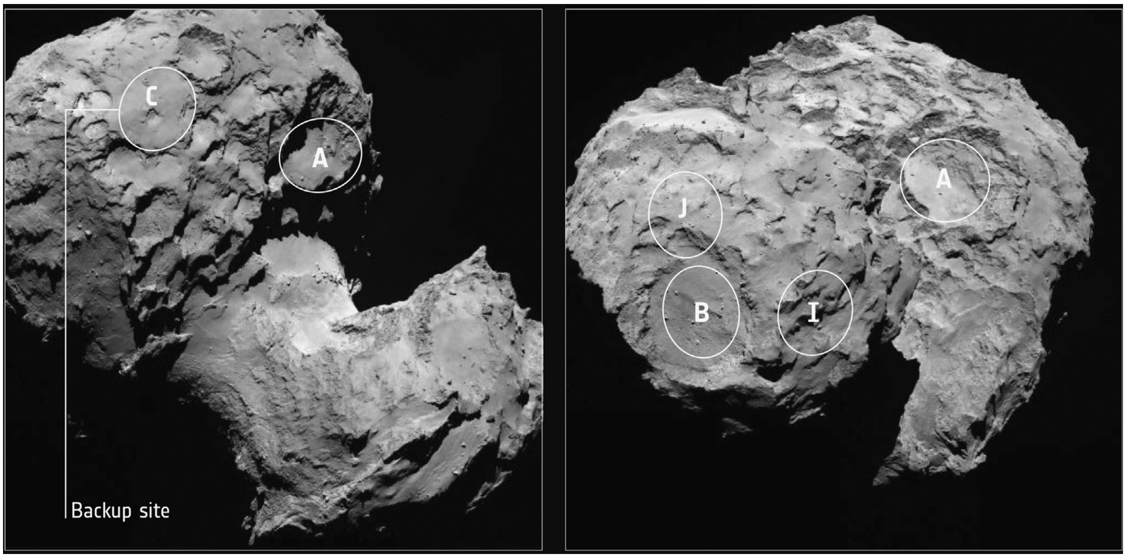

Fig. 3. (a,b): Potential landing sites (image: ESA, NAVCAM) [12].

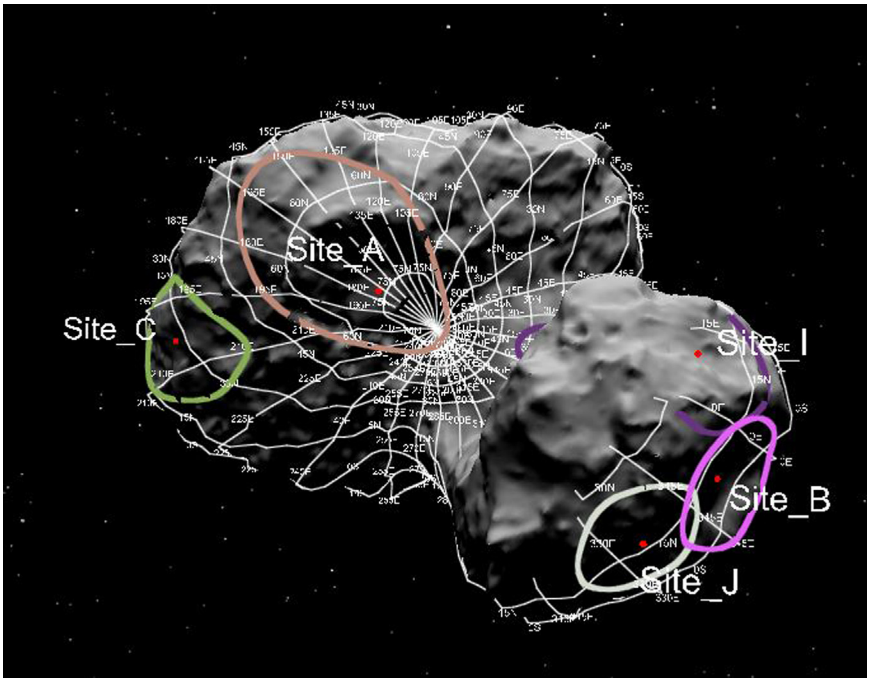

Fig. 4. Potential landing sites, including error ellipses projected on comet nucleus DTM.

it. Such a scenario is referred to as "Option 1 (O1)" and has been preferred even at the expense of a longer descent time.

A very important aspect in selecting the landing site was the sun illumination. After a first scientific sequence, Philae will rely on the power generated by the solar generator and on sufficiently high internal temperatures to allow operations and to discharge and charge the battery. It is required to have at least 6 h per comet rotation (12.4 h) to keep the lander "alive" and not enter hibernation. Longer illumination is preferable, since more science activities during the Long Term Science (LTS) phase will be possible. However, areas of permanent illumination are not desired either, since one of the Lander scientific objectives includes the observation of the day–night cycle. Permanent illumination may also lead to an early end of LTS due to overheating when the comet approaches the Sun. Estimated and propagated comet surface temperatures are another key ingredient to judge the operational mode sequencing at a particular landing site.

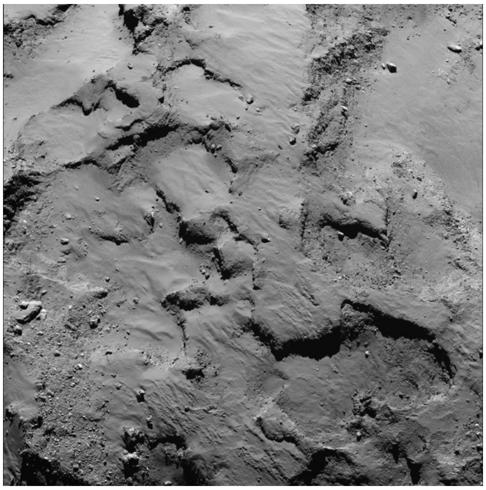

Fig. 5. Detail of selected landing site J (from OSIRIS camera).

Fig. 2 shows the illumination map for November 12, 2014, projected onto the comet DTM. Red areas are permanently illuminated; blue areas receive very little sunlight. All candidate landing sites (with the exception of "B" that has been chosen for dynamic reachability and its apparent flatness) target for "orange areas" and illumination periods between 7 and 10 h per comet day. Note that within the landing error ellipse of about 500 m radius, the insolation may be very variable.

In the months after landing, the situation will change from northern summer to autumn (equinox is on May 12, 2015).

5. The candidate landing sites

Five sites have been selected as candidates, following the process as described above. According to an internal numbering scheme they are referred to as sites A, B, C, I and J. All of them appeared to be reachable with an acceptable descent time, had good or acceptable illumination, the topography looked relatively flat (using NAVCAM and OSIRIS images as a reference) and they were scientifically valid. Fig. 3 (a) and (b) show NAVCAM images with the sites indicated (see ESA press release), Fig. 4 indicates the same areas on the comet nucleus DTM, indicating the expected landing uncertainties (radius 500 m, 3σ).

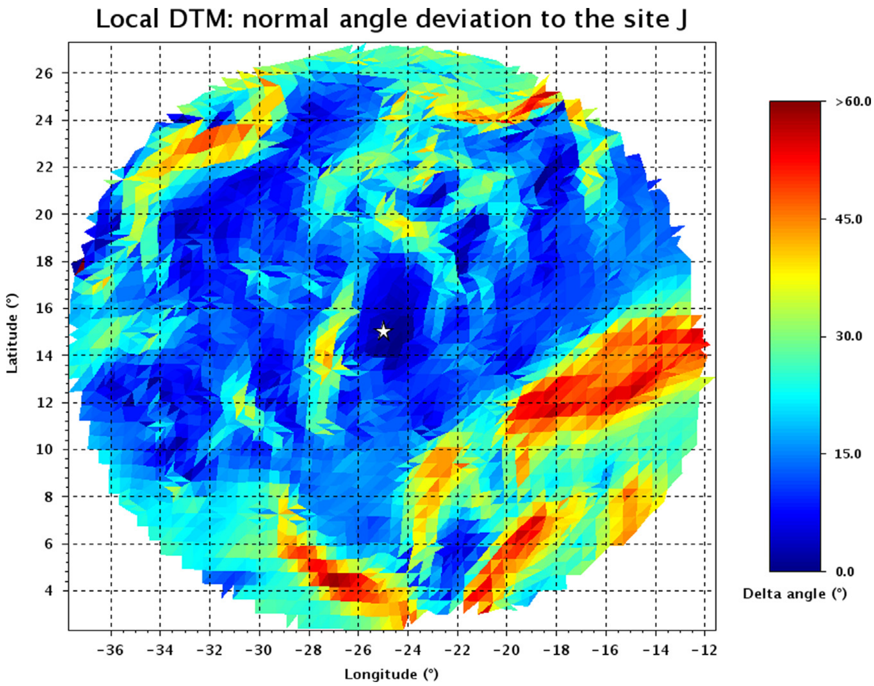

Fig. 6. Slopes deviation in landing area J (based on RMOC/NAVCAM DTM).

Site A was considered scientifically very interesting, on the main lobe of the nucleus, close to the transition area between the lobes and near the pole. There is a 200 m wide, 180 m deep pit nearby that has been shown to be active. The site, however, would have been very challenging to reach (high dispersion) and the illumination variability within the landing uncertainty is high.

Site B is within the large crater like structure on the smaller lobe. The size of this structure is comparable with the landing ellipse, thus there is a relatively low variability in terms of local slopes. The size does have disadvantages regarding its illumination (about 6 h per comet day, leading to compromises for LTS) and was scientifically ranked relatively low (material in crater may have undergone modifications, also indicated by a significantly higher thermal inertia than found elsewhere on the surface).

Site C is a relatively flat area on the larger lobe with good illumination conditions. Unfortunately, site C could not have been reached with an O1 scenario (see above) and the analyzed trajectories would have led to a touch-down with very low sun illumination angles (bad for imaging).

Sites I and J are both on the smaller lobe, scientifically interesting and reachable with acceptable descent times. The illumination for site I appeared more favorable as compared to J. Detailed analysis of the respective terrains showed, that site J has less slopes than I. The chosen O1 trajectory to site J leads to a descent time of about 7 h (as compared to about 10 h for site I). Consequently, site J got priority.

Fig. 4 shows the sites projected on top of a nucleus digital terrain model. Fig. 5 shows a high resolution image of site J, taken with the OSIRIS camera from a distance of about 20 km.

After taking into account all the considerations, listed as criteria in the selection process, site J was finally chosen.

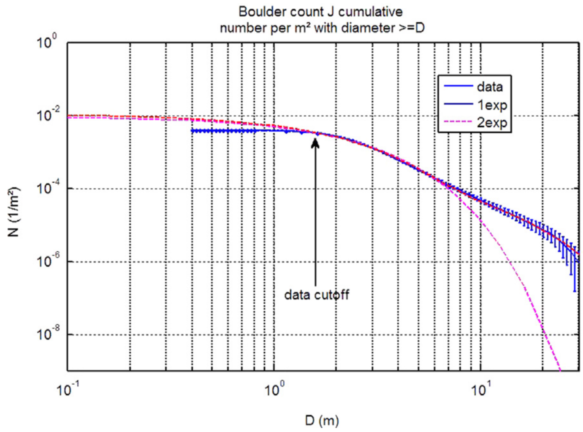

Fig. 8. Boulder statistics for site "J" (number of boulders per m²).

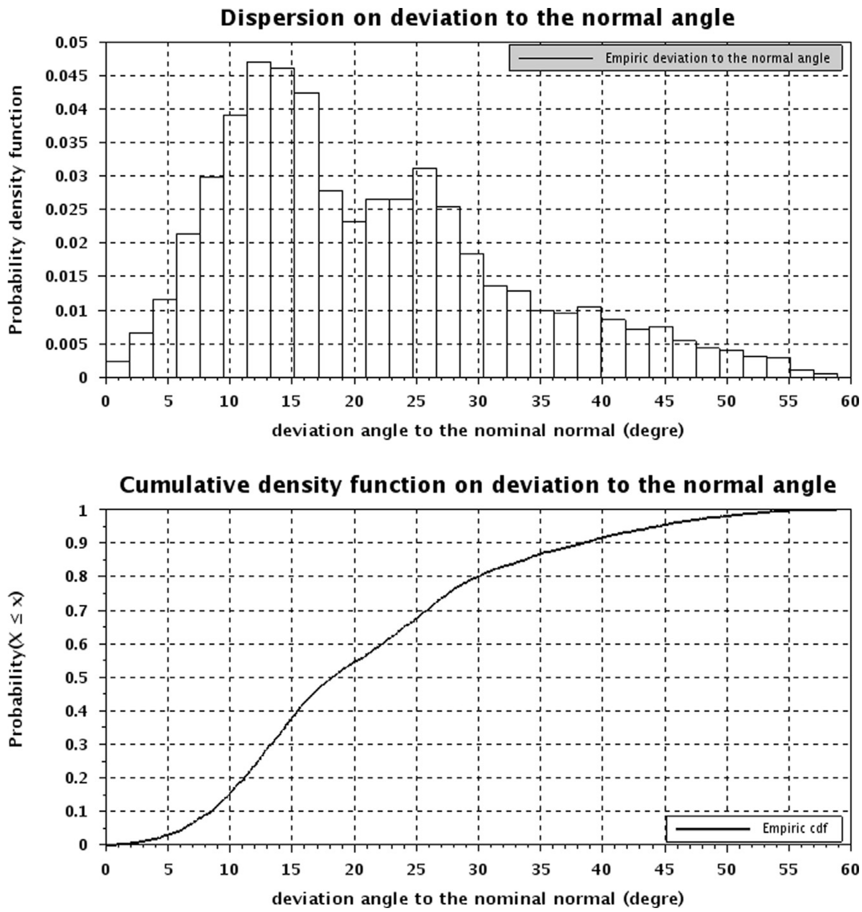

Fig. 7. Slope statistics for landing site J.

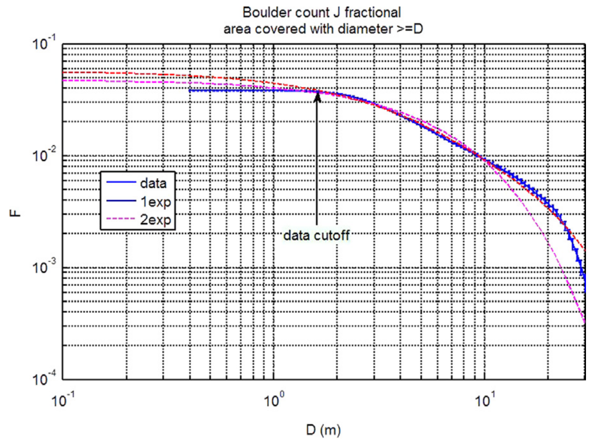

Fig. 9. Boulder statistics for site "J" (area covered by boulders per m²).

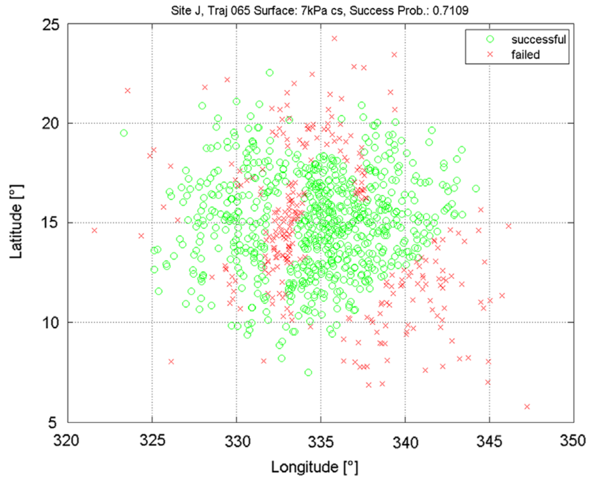

Fig. 10. Landing success, using SIMPACK and Monte Carlo landing distribution.

Following a competition (initiated by DLR, ESA, CNES and ASI) the site was named "Agilkia", after the island in the Nile where the ancient temples of Philae have been moved to be rescued after the construction of the Aswan dam. The statistics of slopes for site J is depicted in Figs. 6 and 7.

Boulder counts by OSIRIS have been evaluated as input to fine adjustment of the nominal landing coordinates (not applied) and for estimate of the risk to hit a boulder. For the latter purpose, the boulder cumulative size and area fraction distribution has been tentatively extrapolated to sizes (> 0.1 m diameter) not resolved by OSIRIS (lower limit 1.5 m). Figs. 8 and 9 show the data and extrapolations. We find that

- Power-law fits are not a good fit.
- Exponential fits fare much better and are physically more realistic; double exponential are almost perfect, and are plotted for comparison of extrapolation with simple exponential
- Site J has about 1 boulder per 100 m² of "any size" (D > 0.1 m for sure), surface fraction covered with boulders of "any size" is ~6%
- Site C has about 1 boulder per 300 m² of "any size" (D > 0.1 m for sure), surface fraction covered with boulders of "any size" is ~3%

The SIMAPACK simulations, applied to site J with a soft (7 kPa compressive strength) soil and based on the trajectory endpoint Monte Carlo dispersions in touchdown velocities, attitude and flight path angles, predict (Fig. 10) a landing success probability of ~71%.

6. Philae landing scenario

Philae will be separated from the Rosetta Orbiter with an adjustable ejection device and descend ballistically,

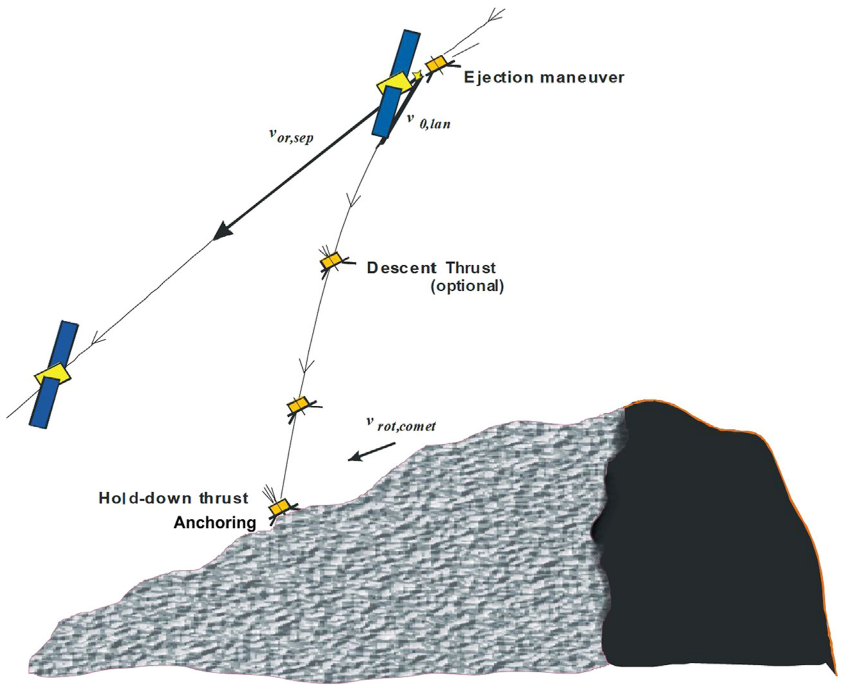

Fig. 11. Philae landing scenario [3].

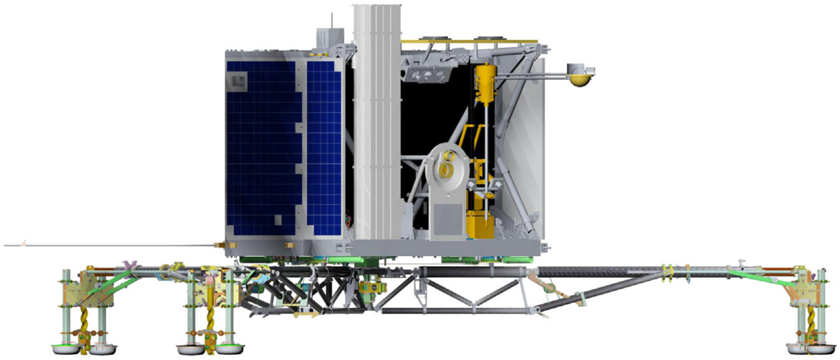

Fig. 12. Philae Lander in on-comet configuration.

stabilized by an internal fly-wheel, on a pre-calculated trajectory to the surface of the comet.

The chosen scenario implies a separation velocity of 18.7 cm/s, which is identical to the one provided by a spring based backup mechanism, that will come in place autonomously, in case the nominal device would fail. An active descent system (ADS, cold gas system) could have been used during descent, but will not be required, given actual comet properties. Separation takes place at a distance of 22.5 km from the comet, the descent lasts about 7 h. At touch-down, two harpoons will be fired simultaneously and anchor Philae to ground. The ADS will be fired to push the Lander towards the comet surface and minimize any possible re-bouncing. The landing strategy is described in further detail e.g. by Ulamec and Biele [13]. Fig. 11 shows a sketch of the landing scenario and its geometry. Fig. 12 shows a CAD model of the Lander.

7. Conclusions

The preparations for the first landing on a cometary nucleus are in their final stage. Despite of the challenging task to find an appropriate landing area on the surface of 67P Churyumov–Gerasimenko, sites implying a minimum mission risk have been identified. The time for characterization of the nucleus was extremely limited. We are all looking forward to the first ever comet landing in November 2014.

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References

[1] K.-H. Glaßmeier, H. Böhnhardt, D. Koschny, E. Kührt, I. Richter, The Rosetta mission: flying towards the origins of the solar system, Space Sci. Rev. 128 (2007) 1–21.

[2] ⟨http://www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_arrives_at_comet_destination⟩ [retrieved Sep. 2014].

[3] S. Ulamec, S. Espinasse, B. Feuerbacher, M. Hilchenbach, D. Moura, H. Rosenbauer, H. Scheuerle, R. Willnecker, Rosetta Lander – Implications of alternative mission scenarios, Acta Astronaut. 58 (2006) 435–441.

[4] J. Biele, S. Ulamec, Capabilities of Philae, the Rosetta Lander, Space Sci. Rev. 138 (2008) 275–289.

[5] S. Ulamec, J. Biele, C. Fantinati, J.-F. Fronton, P. Gaudon, K. Geurts, C. Krause, O. Küchemann, M. Maibaum, B. Pätz, R. Roll, R. Willnecker, the Philae team, Rosetta Lander – after seven years of cruise, prepared for hibernation, Acta Astronaut. 81 (2012) 151–159.

[6] K. Geurts, C. Fantinati, S. Ulamec and R. Willnecker, Rosetta Lander: On-comet operations preparation and planning, in: Proceedings of the 13th International Conference on Space Operations, Pasadena, California, 5–9 May 2014, ID#: 1829333.

[7] S. Schröder, J. Biele, J. Block, R. Roll, S. Ulamec, and L. Witte, Philae Landing Test at the Landing and Mobility Test Facility (LAMA), in: Proceedings of the 64th International Astronautical Congress, IAC-13, A3,4,3, 2013.

[8] Technical Data KR500 and KL1500-2, [online database], www.kukarobotics.com, [retrieved Sep 2014].

[9] L. Witte, S. Schroeder, H. Kempe, T. van Zoest, R. Roll, S. Ulamec, J Biele, J. Block, Experimental investigations of the comet Lander Philae touchdown dynamics, J. Spacecr. Rockets (2014), http://dx.doi.org/10.2514/1.A32906.

[10] S. Ulamec, J. Biele E. Jurado and K. Geurts, Landing preparations for the Rosetta Comet Lander, Philae, in: Proceedings of the 64th International Astronautical Congress, Beijing, September 2013.

[11] A. Accomazzo and J. Biele, Rosetta – Mission Level Decision Process for Landing Operations, RO-ESC-TN-5054, 2014.

[12] ⟨http://www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_Landing_site_search_narrows⟩ [retrieved Sep. 2014].

[13] S. Ulamec, J. Biele, Surface elements and landing strategies for small bodies missions – Philae and beyond, Adv. Space Res. 47 (2009) 847–858.