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ROSETTA lander Philae: Touch-down reconstruction

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ABSTRACT

The landing of the ROSETTA-mission lander Philae on November 12th 2014 on Comet 67 P/Churyumov-Gerasimenko was planned as a descent with passive landing and anchoring by harpoons at touch-down. Actually the lander was not fixed at touch-down to the ground due to failing harpoons. The lander internal damper was actuated at touch-down for 42.6 mm with a speed of 0.08 m/s while the lander touch-down speed was 1 m/s. The kinetic energy before touch-down was 50 J, 45 J were dissipated by the lander internal damper and by ground penetration at touch-down, and 5 J kinetic energy are left after touch-down (0.325 m/s speed). Most kinetic energy was dissipated by ground penetration (41 J) while only 4 J are dissipated by the lander internal damper. Based on these data, a value for a constant compressive soil-strength of between 1.55 kPa and 1.8 kPa is calculated.

This paper focuses on the reconstruction of the touch-down at Agilkia over a period of around 20 s from first ground contact to lift-off again. After rebound Philae left a strange pattern on ground documented by the OSIRIS Narrow Angle Camera (NAC). The analysis shows, that the touch-down was not just a simple damped reflection on the surface. Instead the lander had repeated contacts with the surface over a period of about 20 s $\pm$ 10 s.

This paper discusses scenarios for the reconstruction of the landing sequence based on the data available and on computer simulations. Simulations are performed with a dedicated mechanical multibody model of the lander, which was validated previously in numerous ground tests. The SIMPACK simulation software was used, including the option to set forces at the feet to the ground. The outgoing velocity vector is mostly influenced by the timing of the ground contact of the different feet. It turns out that ground friction during damping has strong impact on the lander outgoing velocity, on its rotation, and on its nutation. After the end of damping, the attitude of the lander can be strongly changed by the additional ground contacts even with the flywheel still running inside the lander.

The simulation shows that the outbound velocity vector and the lander rotation were formed immediately at touch-down during the first 1.5 s. The outbound velocity vector is found to be formed by the ground slope and the lander damping characteristic, especially the nearly horizontal flight out.

1. The Philae landing data

The reconstruction of the Philae landing should show that all information available on the first touch-down is reflected properly. A good overview on the Philae landing and related information data is described in Biele (2015). The first Philae touch-down at the comet can be separated into three phases; (a) Inbound to the touch-down area; (b) Ground contact at Agilkia, and (c) Outbound after ground contact at Agilkia. The landing reconstruction tries to get a synoptic picture of the lander ground contact taking the flight to and out as constraining conditions.

1.1. Inbound to the touch-down area

The inbound velocity vector (components and amplitude) of the lander is listed in Table 1. The velocity vector in Biele (2015) is defined with respect to local geographic coordinate system, which means that the ground is tilted by 11.8° to the South and 1° to the East in respect to the incoming velocity vector.

The velocity vector is close to the lander $-z$ direction, which means the velocity vector is nearly perfect aligned with the lander damper direction. An angle between the lander z-axis and the velocity path at touch-down of 4° to the West is used for touch-down simulation, based on the assumption that probably the rotation axis of the lander was 4° tilted against the velocity vector during descent. During descent the lander rotated counter-clockwise as seen in $-z$ direction with a rotation period of about

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500 s. This slow rotation turns out to be unimportant for the touch-down dynamics.

The image series of the ROLIS camera during descent allows to calculate the lander tilt with respect to the velocity vector and the lander leg orientation at touch-down: Lander leg 2 (also called *X*-leg) is rotated by 115° (yaw) out of South direction to North-East (Fig. 4 in Biele (2015)), see also Fig. 3.

1.2. Ground contact at Agilkia

The ROLIS descent photos show the local surface structure at the touch-down site in great detail (Fig. 4 in Biele (2015)). Images of the touch-down area before and after touch-down are also available from the OSIRIS NAC camera (Biele, 2015; Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA). Fig. 2 shows that the footprint at touch-down is much larger as the lander foot-soles and even the lander dimensions.

Four separated and significant changes of the surface terrain can be identified in the OSIRIS images, despite that the lander has only three feet. Two of the surface changes are identified as holes with a diameter of 2 m each and with an estimated depth of 0.1 m and 0.2 m, respectively (Fig. 5 in Biele (2015)). Two of the surface changes show some inner structure. The complex pattern left on the surface after touch-down indicates that the lander had more than one contact with the surface over an area of around 8 m linear size and a time range of 10–30 s. The ROLIS and OSIRIS images can be combined, leading to additional restrictions for landing reconstruction. From the images it is concluded, that at touch-down foot 1 did not penetrate into the ground significantly, while the other two feet sank in deeply. Hence, in the following we assume that feet 2 and 3 or at least one of the two sinks into the ground significantly while the ground penetration of foot 1 at first contact is comparably small.

As mentioned above, the average ground slope in the touch-down area is 11.8° to the South and 1° to the East with respect to the lander inbound velocity vector. The ground slope as seen by the lander feet may deviate due to local ground structure in a 3 m diameter footprint area of the lander. In addition a tilt of the lander 4° to the West is assumed. The timing of the ground contact of the different feet can be calculated from ground slope and lander attitude at touch-down. This model results in ground contact of foot 1 first, followed by foot 2, and finally foot 3. Ground contact of leg 1 instead of foot 1 or contact of the central landing gear structure instead of foot 2 cannot be excluded. The model is supporting the interpretation of the lander damper potentiometer reading (Fig. 1 in Biele (2015)). The time frame from the first ground contact until foot 3 reaches finally the ground is 0.55 s ± 0.1 s. This model is free of conflict with the SESAME-CASSE instrument signals of ground contacts of all three feet (not

Table 1
Inbound and outbound velocity of the lander for the first touch-down at site Agilkia. The components and the amplitude are based on the ESOC data with respect to the geographic coordinate system (Biele, 2015). The velocity vectors are given in addition in the lander reference frame. The lander reference frame is used for the simulation calculations. All velocities are given in cm/s.

Geographic coordinate system	*East*	*North*	*Zenith (up)*	*Amplitude*
Inbound velocity	2.0	−20.7	−99.0	101.2
Outbound velocity	21.3	−23.5	7.2	32.5
Lander coordinate system	v_x	v_y	v_z	*Amplitude*
Inbound velocity	0	0	−101.2	101.2
Outbound velocity	24.5	21.3	2.0	32.5

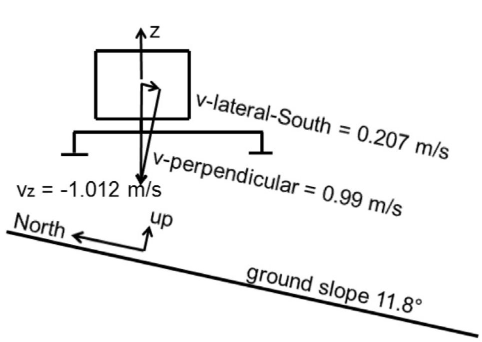

Fig. 1. Incoming velocity vector and its components in perpendicular and lateral direction in East view. The outgoing velocity is in South-East direction (more details Fig. 3).

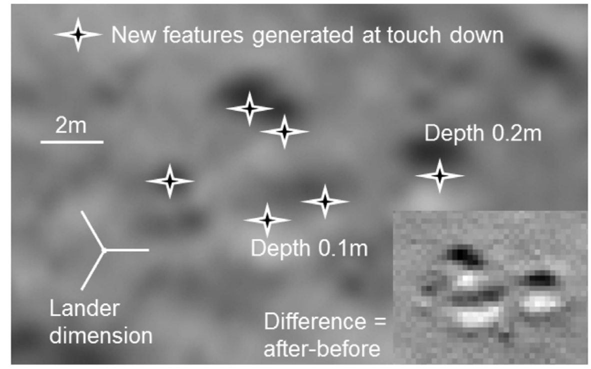

Fig. 2. OSIRIS (Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA) difference image of the touch-down area – exposure after minus exposure before touch-down. New features for the lander ground contact spread over about 10 m, while the lander footprint area has 3 m diameter only. The lander legs dimension is sketched for comparison. The pattern at the surface shows that just a reflection on the surface cannot explain these features.

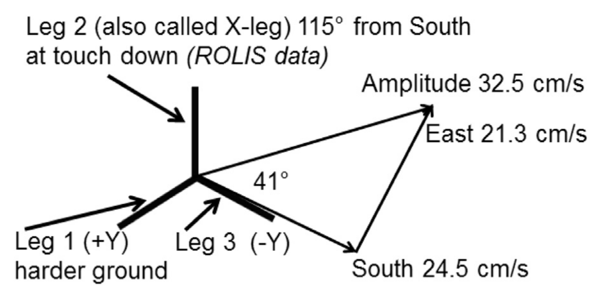

Fig. 3. Lander velocity vectors, sketched in the lander reference system. The inbound velocity is perpendicular to the plane of the drawing. The outbound velocity in the lander coordinate system is almost in the paper plane (like indicated), since the v_z velocity is only 2 cm/s. The direction of the velocity vector was changed by almost 90° at touch-down. East and South are slightly tilted to the paper plain.

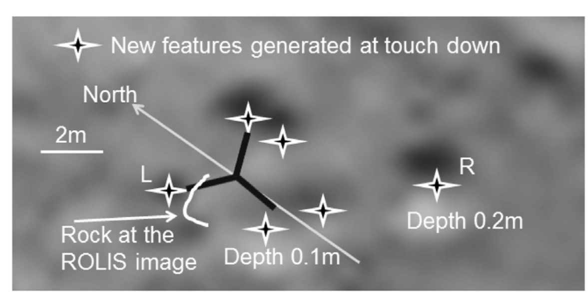

Fig. 4. Superposition of the ROLIS "rock" and the OSIRIS (Credit: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA) image. New features produced by the lander touch-down at the Agilkia site are marked by star symbols. Note: The alignment accuracy between ROLIS and OSIRIS images is about 0.4 m. The new feature most left is marked L, the most right one R.