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PHILAE LANDING TEST AT THE LANDING AND MOBILITY TEST FACILITY (LAMA)

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Abstract

In the recent decades the number of spacecraft visiting asteroids and comets has risen. But only a few of them entered into an orbit of these small bodies and even only two had physical contact to the surface. The ESA mission Rosetta is on the way to meet the comet 67P/Churyumov-Gerasimenko in May 2014. Once in orbit the spacecraft will release the small lander Philae which is supposed to land softly on the cometary surface, anchor itself to the ground with harpoons and perform its scientific observations.

This will be the first time in history a lander will touch down on a comet nucleus. The greatest challenges of the landing manoeuver are the unknown surface properties and the fact that the original target, comet 46P/Wirtanen, had to be re-designated into a much larger target with higher mass. Especially the second fact is a critical point, because the higher mass of the comet leads to a higher landing velocity and therefore a higher kinetic energy which has to be absorbed. This effect could not be compensated by a design change, because it was too late to change the design significantly, since the lander was ready at launch site at that time. For this reason a new test campaign in 2012/2013, led by a consortium of DLR Institutes and the Max-Planck-Institute of Solar System Research, has been set up at DLR's Landing & Mobility Test Facility (LAMA) where further touchdown conditions could be tested which have been out of capability of the pendulum test facility used for the original qualification of Philae.

This paper gives an overview of the performed work and introduces the test facility concepts with its operation modes. The paper also presents and discusses the preliminary results from this recent campaign and gives an outlook to its further use in the upcoming landing preparations.

I. MISSION & SPACECRAFT DESCRIPTION

Rosetta is a 3000 kg space probe with dimensions of about 2.8 x 2.1 x 2.0 meters and additional two 14-meter solar panels. Philae is attached at one side to Rosetta. This three legged lander is a partial hexagonal cylinder, approximately 1 meter across and 80 cm high, with an open "balcony" on one side. It is supported on a long squat tripod and consists of a baseplate, experiment platform and hood.

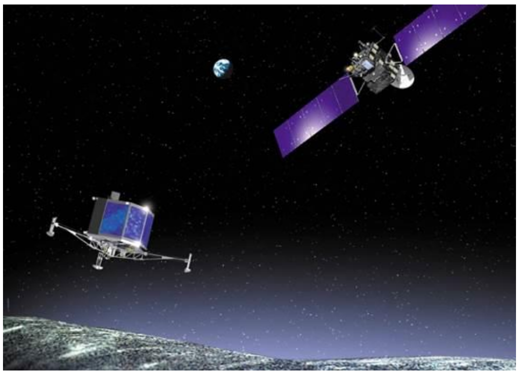

Fig. 1: Rosetta Mission with Philae Lander [1]

From launch in 2004 till 2009 Rosetta travelled through the inner solar system and performed a series of swing-by maneuvers at Earth and Mars to gather enough speed to rendezvous the comet Churyumov-Gerasimenko in 2014. After an observation campaign the lander will be released from the spacecraft at an altitude of approx. 1 km and will fall down freely to the surface only stabilized by a flywheel. Directly after touchdown two harpoons will fire up and anchor Philae to the ground. Additionally, a cold gas engine will fire and press the lander to the ground. The landing strategy and involved mechanisms are described in further detail by Ulamec and Biele [2]. All Rosetta instruments, including the 10 PI instruments aboard Philae are described in detail in [3].

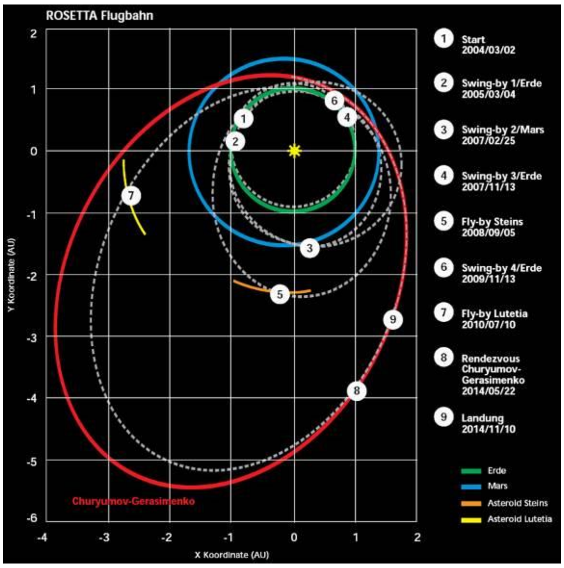

Fig. 2: Rosetta flight path [4]

I.I The Landing Gear Subsystem

Philae's operation is supported by a Landing Gear (LG), which provides the mechanical interface between the comet and the main body. It consists of a foldable tripod with legs and feet and a central structure hosting several mechanisms to execute the various LG functions [5]. The main task of the Landing Gear is absorbing the kinetic energy at touch-down during the landing on the comet. In addition the LG provides a mechanical interface for the anchors harpoons, which are attached to the LG's central structure, and the Sesame CASSE and PP sensors, which are located in the feet. So called "ice screws" in the feet provide additional anchoring to the surface and hinder gliding. An electronics system provides commanding and telemetry of the LG functions.

II. OBJECTIVES

The development of the Philae Lander started in the 90's. The design and qualification tests of the Philae lander were done in the 1996 to 2002 timeframe. These primary tests made use of a pendulum facility, allowing the test object to swing against a vertical wall to separate the Earth gravity from the forces of inertia. However, a limitation of this concept is a severely constrained motion of the test object and the inability to touch down on loose granular material. These disadvantages have been overcome by using an active weight-offloading device which is provided for the recent new tests at DLR's Landing & Mobility Test Facility (LAMA). (see section IV).

Since Rosetta is en route and Philae will land soon, the new tests can only serve to optimize the landing strategy (optimal ranges of velocities and angles at touchdown) and determine the landing gear performance envelope more precisely.

Primary objectives for the new tests are:

- Especially touchdown configurations constricted by the limited capabilities of the pendulum test facility are of particular interest and are reflected in the test objectives. This refers primarily to asymmetric load cases which become testable with DLR's LAMA facility (operational since 2010).
- To broaden the test data base on the influence of the landing gears tilt limiter.
- To broaden the data base on the contact phenomenon on soft soil as (i) later missions (such as Deep Impact [6]) contributed to the comet surface property knowledge with relevance for Philae and (ii) touchdown test in granular media become possible with the LAMA facility as compared to the pendulum facility.

III. TEST MODES

The test matrix build-up reflects these objectives and groups the test cases into four basic (Base tests) and three special load case groups (Spec tests). Table 1 shows these load cases and the associated touchdown conditions.

Base 1: The Base 1 tests, thus, shall ensure the consistency and seamless connectedness between the test data generated on the pendulum facility and the LAMA facility. This group falls in line with similar touchdown tests executed during the development and qualification phase of the landing gear. A side-effect is a quantification of the strength and weaknesses of both touchdown test facility concepts for small body landings. The Base 1 tests act as further reference for the subsequent Base and Spec tests.

Base 2: the test cases in this group vary in comparison to the Base 1 group the lander pitch (around the body y-axis), the surface friction and the flywheel status. This group particularly addresses tilt limiter and flywheel effects on the touchdown dynamics.

Base 3: this group is similar to the Base 1 group, however with the difference that the touchdown occurs on a granular, soft surface. The objective is the quantification of soft soil contact mechanics and the ice screw operation.

Base 4: these tests add lateral velocity and vary the terrain slope to excite destabilizing momentums. The objective is to gather data to verify the numerical simulations for the toppling stability boundary determination.

The special load cases are used to address additional questions which are not directly related to the touchdown system performance, in particular:

Spec 1: this test case is used to gather data on the lander precession motion induced by the flywheel and applied external torques during the descend phase.

Spec 2: addresses further stability load cases and complements the Base 4 group.

Spec 3: this group is basically a repetition of the Base 3 group, however with partly different touchdown velocities. During these tests the footpads were equipped with the scientific instrument CASSE [7], integrated into the foot soles. The focus of this test group is to assess whether this instrument is also able to utilize the touchdown loads to acquire scientifically meaningful data on the comets soil mechanical properties.

Identifier	Objective	Vvertical [m/s]	Vhorizontal [m/s]	Pitch /Yaw [°]	Fly Wheel Status	Surface Cond.
Base_1a	Damping / Stiffness Characterization	0.2	0.0	0.0 / 0.0	off	wood
Base_1b		0.5	0.0	0.0 / 0.0	off	wood
Base_1c		0.8	0.0	0.0 / 0.0	off	wood
Base_1d		1.1	0.0	0.0 / 0.0	off	wood
Base_2a	Fly Wheel / Tilt Limiter Effects Characterization	1.1	0.0	17.0 / 0.0	off	wood
Base_2b		1.1	0.0	17.0 / 0.0	on (slow)	wood
Base_2c		1.1	0.0	17.0 / 0.0	on (fast)	wood
Base_2d		n/a	n/a	n/a	n/a	n/a
Base_2e		0.5	0.0	17.0 / 0.0	off	steel / oil
Base_2f		0.8	0.0	17.0 / 0.0	off	steel / oil
Base_3a	Soft Soil Effects Charact. (Energy Absorption Contrib.)	0.5	0.0	0.0 / 0.0	off	soft soil (Wf34)
Base_3b		1.1	0.0	0.0 / 0.0	off	soft soil (Wf34)
Base_3c		0.5	0.0	0.0 / 0.0	off	soft soil (MSS-D)
Base_3d		0.8	0.0	0.0 / 0.0	off	soft soil (MSS-D)
Base_3e		0.8	0.0	0.0 / 0.0	off	soft soil (Wf34)
Base_4a	Landing Stability Characterization	0.5	0.13	17.0 / 0.0	off	wood
Base_4b		0.8	0.21	17.0 / 0.0	off	wood
Base_4c		0.8	0.0	0.0 / 0.0	off	Slope / mixed surf.
Base_4d		1.1	0.0	0.0 / 0.0	off	Slope / mixed surf.
Spec_1a	Fly Wheel Effects	n/a	n/a	n/a	on (fast)	n/a
Spec_1b		n/a	n/a	n/a	on (fast)	n/a
Spec_2a	Advanced Landing Stability	0.8	0.21	17.0 / 90.0	off	wood
Spec_2b		0.8	0.21	17.0 / 0.0	off	wood + blocked leg1
Spec_3a	CASSE	0.1	0.0	0.0 / 0.0	off	concrete
Spec_3b		0.1 - 1.1	0.0	0.0 / 0.0	off	soft soil (MSS-D)
Spec_3c		0.1 - 1.1	0.0	0.0 / 0.0	off	soft soil (Wf34)

Table 1: Test plan

IV. TEST FACILITY & SETUP

Generally several methods are known to test planetary landing systems under an apparently gravity environment. Relevant methods are hereby model scaling, the pendulum concept and weight off-loading.

Model scaling [8]: Scaled model tests are quite elegant in that way that full 6-DOF testing is possible without any interference with suspension and support devices. However this principle comes to a practical end if applied to small spacecraft and/or to low gravity environment as it leads to unacceptable miniaturization of the model.

Pendulum / Tilted Plane: In this test configuration a test object is suspended by cables like a pendulum and lands/moves against a tilted plane. Due to the vectorial decomposition a large reduction in apparent gravity is possible. In the lunar case, the plane is tilted 9.5° degree out of the vertical plane. In the small body case the wall is vertical. This principle has been used successfully during Philae's development and qualification program (Fig. 3). However, the slope of the plane does not allow tests on granular media. This test object motion is severely constrained by the pendulum set-up.

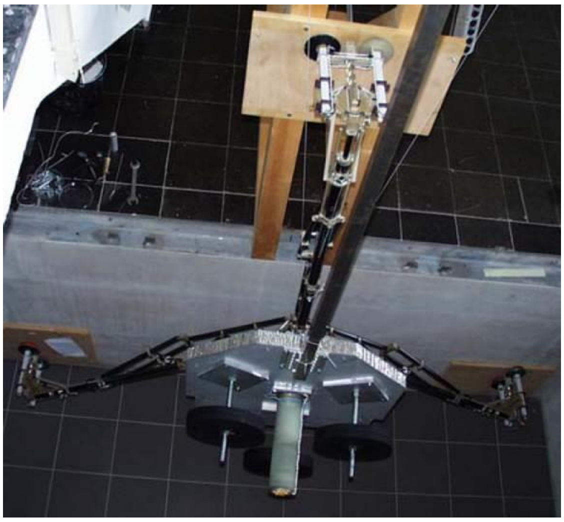

Fig. 3: Pendulum test with Philae LG [9]

Weight off-loading: Test object is suspended in its center of gravity. Parts of its (Earth-) weight are offloaded by a suitable device. Three dimensional testing and tests on soft soil are possible. However interferences with the offloading device remain.

These weight off-loading tests have now been performed at the Landing & Mobility Test Facility (LAMA) at the DLR-Institute of Space Systems in Bremen, Germany. The LAMA facility consists of five major elements, which are a standard type 6-axis industrial robot system (KR500) plus a rail track used typically for factory automation purpose, a suspension device to mount rover or lander, a controller to set up, control and maintain the experiment conditions, a soil bin containing the planetary soil simulant and a test cell which integrates all elements and provides the necessary infrastructure.

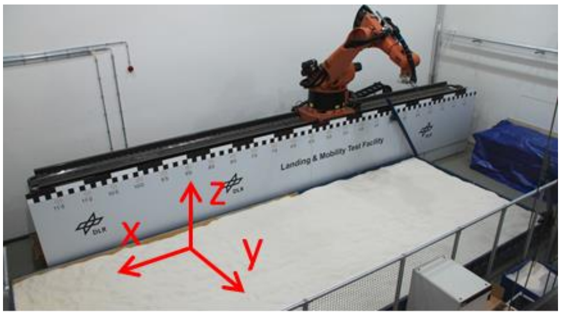

Fig. 4: LAMA test cell and Philae coordinate system

The original purpose of this facility is the provision of a test bed to study vehicle-soil-interactions (i.e. tip-over stability of landing vehicles or terrain accommodation for rovers) in a reduced gravity environment by weight offloading of the robot system.

IV.I Robot system

The key element of LAMA facility is the heavy-duty class robot KR500 [10]. The main reason for using an industrial robot is to provide a fully active, self-supporting and in the use cases highly flexible device for setup and maintaining load scenarios and test object handling. The nominal static load bearing capacity of this robot is 500 kg. The KR500 sits atop a rail track system provided by a KUKA KL1500-2 linear axis, allowing a lateral travel distance of 12 m (see Fig. 4).

IV.II Weight Off-Loading Suspension

The test object suspension has to fulfill three functions:
(i) transmit a (quasi-)static reduction or weight offloading force, (ii) provide sufficient degree of freedom to the test object and (iii) dynamically decouple the dynamics of the robot and the test object from each other.

The build-up consists of the major elements as shown in Fig. 5: the upper flange plate (1) connecting the suspension to the force-torque sensor in the robot hand, linear guide pillars (2) limiting the degree of freedom to the vertical or “gravity axis”, a set of tension springs (3) whose stiffness has to be selected dependent to the test object mass, the movable lower attachment plate (4), slide bearings (5) and a piezoelectric brake (not shown) and (6) a carbon fibre beam attached to the lower attachment plate. The beam is characterized by a high load bearing capacity in its longitudinal direction, but a low bending stiffness in its lateral direction, which supports degrees of freedom of the mounted test object. The beams stiffness has to be selected in an analogous way as the tension springs stiffness, which depends to the test objects mass.

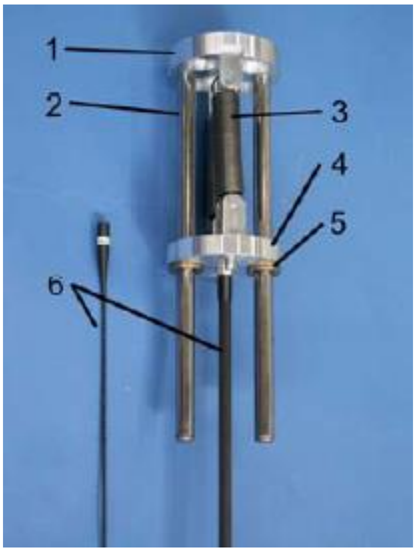

Fig. 5: Weight offloading device (upper part)

The lower end of the carbon fiber beam is connected to a cardanic joint which is adjusted by mass trimming in a way that the test objects center of gravity coincides with the center of the cardanic axes. This leads to a rotational degree of freedom around the x- and y-axis (coordinate system in Fig. 4) of around 30°, however due to equipment constructions inside the hood the rotation around the y-axis is blocked to around 17°.

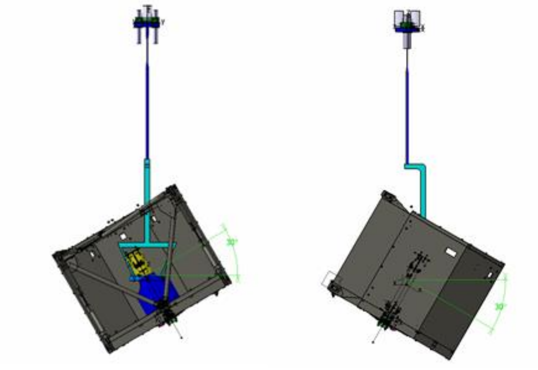

Fig. 6: Cardanic Joint and test object suspension (lower part)

IV.III Robot Control

Two loops exist for control and data acquisition tasks. The first one is an inner loop for the robotic realtime control (e.g. the force-torque transducer mounted on the robot hand), with integrated sensors for direct manipulation, such as path planning and correction. The second, outer loop is dedicated primarily for data acquisition and tasks which are not critical in time. The robot controller coordinates the axis in a way that a user-defined tool center point (TCP) follows a trajectory in a user-defined Cartesian coordinate system. This trajectory can be either a predefined path of waypoints, a purely sensor driven motion or a combination of both, where a sensor determined correction is superimposed to a predetermined path. The LAMA facility uses all control modes, depending on the test mode.

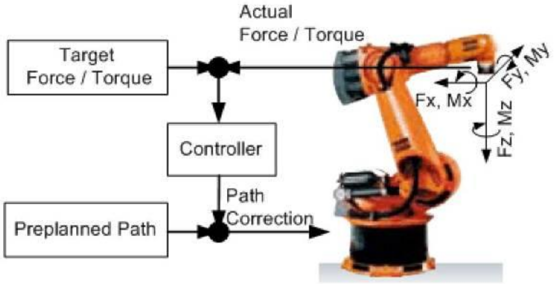

Fig. 7: Control scheme for sensor-driven modes [10]

The robot guides the test object on a pre-selected path to initial setup the required position and velocity state. A release command is triggered in the drop test mode, whereas in the sensor-driven mode the objective is to maintain a constant weight load in the vertical direction and zero lateral forces in the robot hand.

IV.III Surface Conditions

For the investigation of a soft underground two different types of soils (WF34 a fine-grained quartz sand and MSSD a very fine-grained olivine-quartz mixture) have been prepared and as a reference for the hard contacts wooden plates have been used.

VI.III. Data acquisition concept

A central DAQ unit has been used to synchronize data from three main areas during test operations. This was first of all the test object itself where test mode specific analog sensors such as potentiometer, IMU and tri-axial accelerometer are mounted on predefined positions. Second, external video cameras have been used for test documentation (frame rates up to 600 fps) and subsequent motion analysis. And third, the robot controller itself delivered data about its hand position and orientation as well as forces and torques in the hand root.

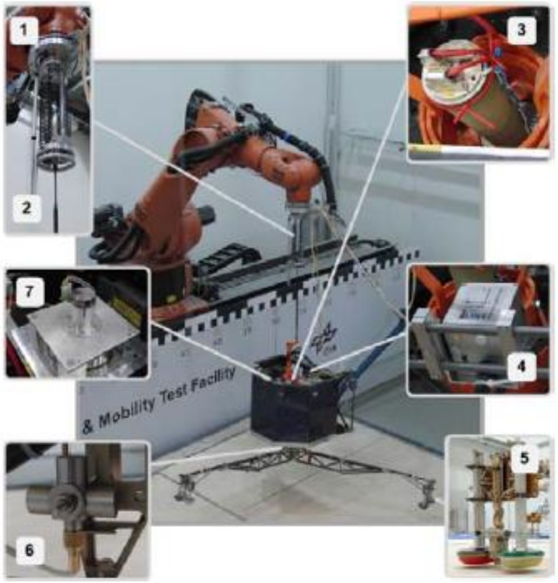

Fig. 8: Sensor and actuator equipment of the Philae test specimen

(1) The robot hand flange has an integrated 3-axis force-torque transducer (ATI Automation Theta series). The force-torque data as well has position and velocity information of the robot arm is acquired from the robot control data bus at a clock interval of 12ms.

(2) The test objects suspension’s stroke is measured by a potentiometric linear transducer (type Megatron RC20 series) at a sampling rate of 1kHz.

(3) Signal pick-ups and sensors are integrated in Philae’s landing gear bubble as part of its housekeeping data architecture. Signals include the landing gear stroke, the tilt angle between gear and body as well breaking currents and touchdown signals. This data read out during the tests and sampled at 1kHz.

(4) An inertial reference unit (IMU, type iMAR iVRU-BB-M, sampling rate 100Hz) measures the body acceleration in its three axes as well as angular rates and the body attitude.

(5) During Spec_3 tests the footpads carried a triaxial accelerometer (type Bruel&Kjaer DeltaTron 4506) which is part of Philae’s scientific instrument CASSE (Comet Acoustic Sounding Experiment).

(6) A three-component accelerometer (type Kistler 8792A25, 1kHz sampling rate) measures the shocks and vibrations of the landing gear close to its center underneath the interface to the central damper.

(7) A flywheel generates the angular momentum as Philae’s flight qualified flywheel will do to stabilize Philae’s descend phase.

Ballast and trim masses are installed at determinate points to match Philae’s flight model mass, center of mass and moments of inertia.

V. TEST RESULTS

This newly initiated test campaign revealed many effects which now have to be analyzed and evaluated. In this this section only extractions of the test analysis are presented. Other test observation with focus on e.g. damping characteristics and asymmetrical load cases are reported in Witte et.al [11].

V.I Touchdown Signal Activation

The determination of the Touchdown (TD) is a critical moment in the landing phase because it marks the point when the harpoons have to be activated and anchor Philae to the ground. For that reason a TD signal in the LG’s damper unit gives out a current threshold signal (TDI). Fig. 9 shows the set-up of a standard landing with no horizontal velocity.

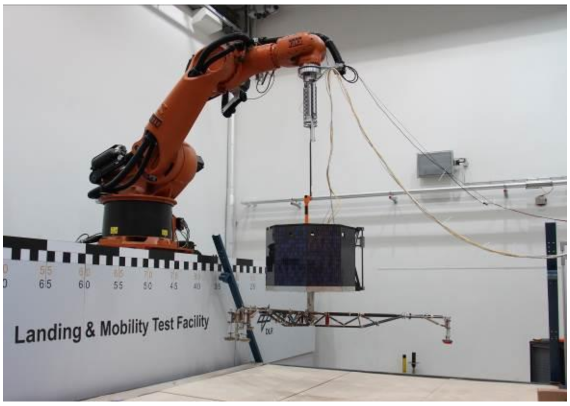

Fig. 9: Configuration of Base_1 test

Fig. 10 shows two test runs on hard ground, the second one in an inclined pitch angle of ca. 17°. Presented are the first milliseconds of the touchdown, where t = 0 is the point of first contact of any foot.

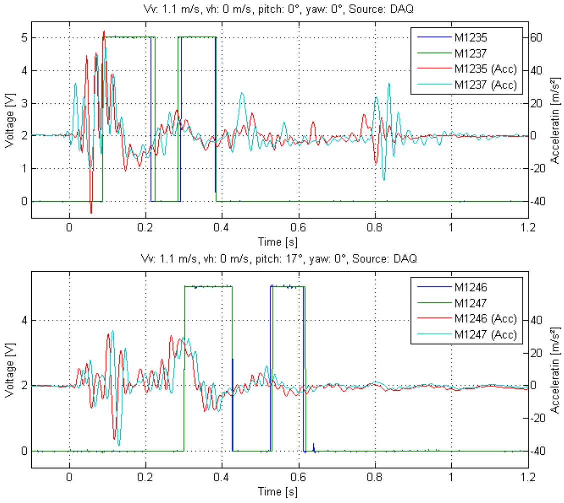

Fig. 10: TDI signal comparison of Base_1d and Base_2a

It can be seen that the TD is detected 87 ms after contact. In the asymmetric landing case the signal needs considerably longer especially when it takes into account that the time period from the first foot contact to the point where all feet have touched the ground, is 83 ms (video data). The overall time of first foot contact to signal activation is 301 ms.

This difference can be explained with the later starting of the damping process since the sensor measures the current induced by the damper stroke.

The acceleration data in these graphs are synchronized with the TDI signal and shows the moment of first TD.

The gap in the signal comes from the landing gear (LG) shock strut compression and the induced oscillation of it so that in a short moment the LG is moving synchronal to the damping stroke direction and no voltage is induced.

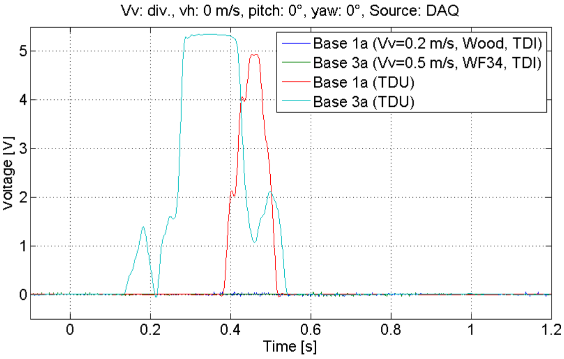

Fig. 11: TDI and TDU signals with low velocity

At small velocities (Vv < 0.2 m/s on hard terrain, Vv < 0.5 m/s on soft terrain) the TDI signal is missing although the TDU gives out a clear voltage signal. This is not a problem for Anchor, since the harpoons are not required in this case. The same applies for the Active Descent System (ADS) hold-down thrust. But the Descent Imaging System (DIS) activation of Rolis needs to be stopped and the Central Data Management System (CDMS) needs to be informed about landing. Therefore an alternative method has been implemented.

This signal will be calculated by CDMS from the readings of the potentiometer, which is measuring the LG bubble movements during landing. The result is forwarded to the Lander units, where Rolis will use this indication as alternative to stop their descent imaging. [12] Thresholds for this calculation can be set by parameters.

V.II Tilt Limiter characterization

After the change of the Rosetta mission to a new destination the Philae lander had to be adapted for the bigger comet with its higher gravity. Since only slight changes in the hardware could be implemented, a so-called tilt limiter, which is a metal ring around the Hooke Joint of the hood, has been installed to reduce the tilt angle of the hood to ±3°. The Base_2 tests now have characterized this construction.

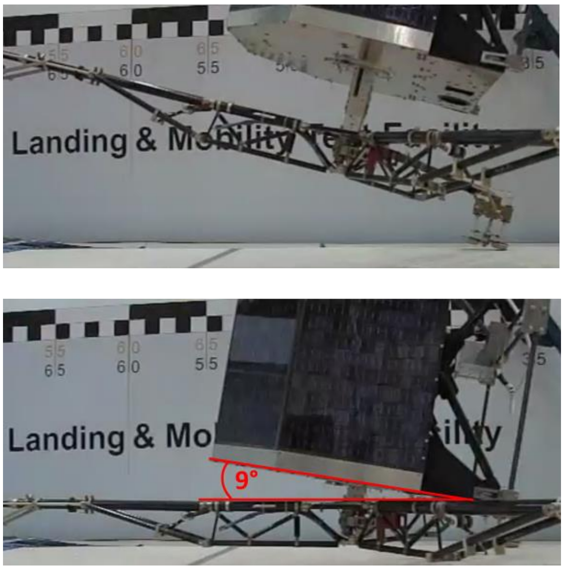

Fig. 12: Attitude of Philae Lander (top: t = 0 s, bottom: t= 1.6 s)

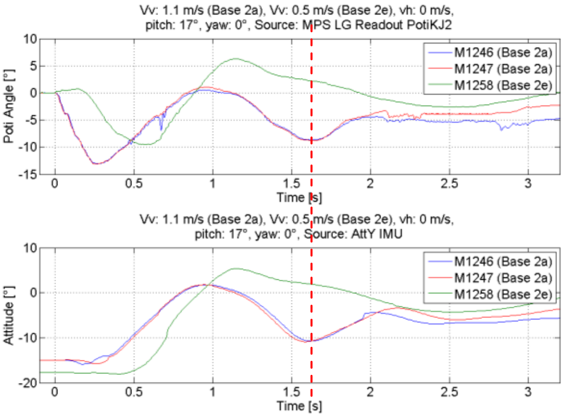

Fig. 13: Potentiometer Angle and Attitude of the hood for Base 2a and 2e test run

The graph shows the attitude of the hood and the angle of the damper against the landing leg. As seen the initial inclination of the lander body is in the range of 15° to 18°. As described in chap. V.I all feet have touched the ground at t= 0.083 s. From this point the curves of IMU and KJ2 show the same trend, but different amplitudes, since the feet are aligned parallel to the ground. What also strikes out is that the maximal inclination is bigger than the ±3° as adjusted by the tilt limiter. Also the video data proofs that the angle is at least 9°, regardless of the landing velocity as the Base_2e test proves this. Explanations for that could be the elastic deformation of the tilt limiter powered by the rotational energy during the TD phase, but also a shifted zero-point coming from the calibration (error in the range of ±1°).

Nevertheless it can be stated, that the tilting angle of the hood is much higher than adjusted by the tilt limiter. This has to be taken into account for the landing stability simulation.

V.III Soil effects

A major objective of the newly initiated test campaign was the possibility to test on granular media. Some results are presented in this section.

Whilst it is acknowledged that surface soil conditions on the comet cannot be reproduced in this type of test facility the results shall provide a cue on the principal behavior of a surface with a plastic deformation behavior. A simple but physics based model of the touchdown forces on granular material as described e.g. in [13] shall be verified and prepared for use in the numerical touchdown analysis. Fig. 14 shows the lander model in its “landed” condition with the feet resting on top of the soil filled tub.

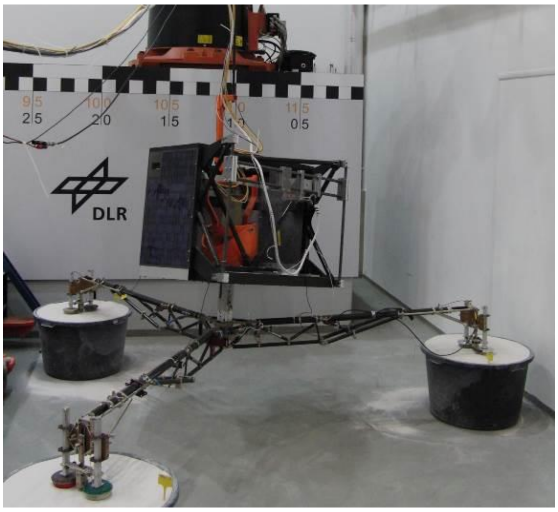

Fig. 14: Set-up for granular soil test

In Fig. 15 the acceleration of a TD on wood, MSSD and WF34 are displayed, where the curves of MSSD and WF34 have been endued with a time off-set for a better illustration.

Note: the high negative peak of test run M1234 comes from a hard contact of the sliding part of the weight-offloading suspension to its end block. This is an interference with the effective landing acceleration and has to be separated in the calculation for following numerical simulations.

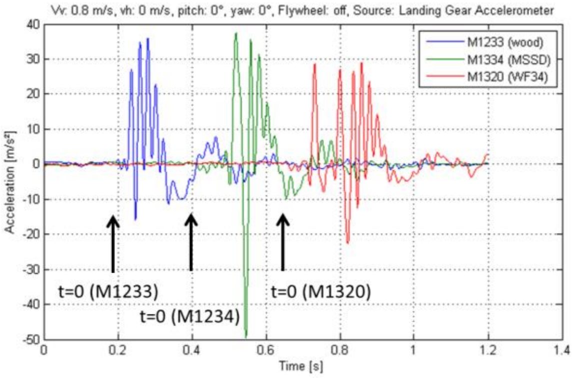

Fig. 15: Comparison of LG acceleration for different underground conditions

Overall the amplitudes of the accelerations are in the same order of magnitude although the values of WF34 are lower, which means the landing is softer and the soil is damping more. The very fine grained MSSD acts more like the hard underground. This could also be seen in the video and photo documentation (Fig. 16).

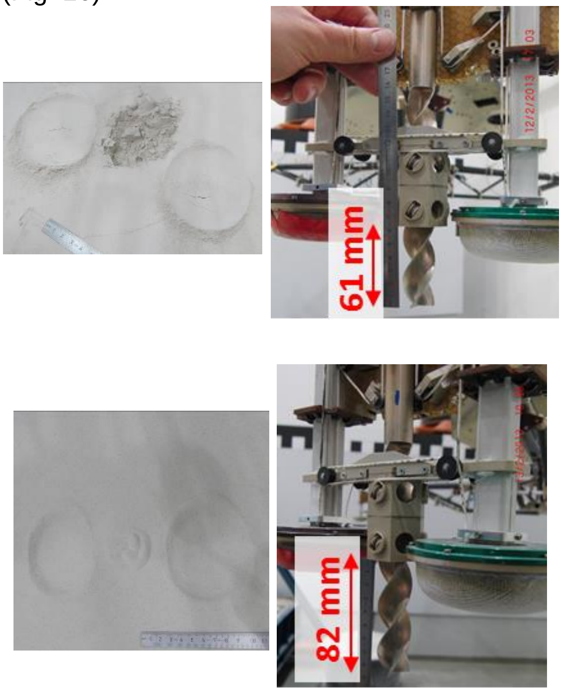

Fig. 16: Post touchdown foot imprint and ice screw position

Landing on MSSD leads to a smaller sinking of the ice screws. This is compliant with former drop test campaigns made on the same soil conditions. On the other hand the retraction of the ice screws out of the soil bin is much harder with this kind of soil.

VI. CONCLUSIONS & OUTLOOK

Test data has been acquired from dedicated tests addressing test objectives with a focus on the upcoming landing preparation. A brief summary of the test results is given in this section.

1. The tests have confirmed the detection boundaries of the TDI signal from former test campaigns, but also added new data for landing on soft ground where the detection boundary is higher (0.5 m/s compared to 0.2 m/s on hard ground) This new fact has to be taken into account during the Separation-Descent-Landing (SDL) phase.
2. The tests revealed a larger deflection of the hood than originally planned. Instead of a rotational degree of freedom of ±3° the tilt angle is at least ±9° even for low velocity landings.
3. Touchdown data on a stiff (hard) surface as well as different granular media (soft) allow understanding soil mechanical effects. An improved understanding is of relevance for both the landing dynamics and reference data for the interpretation of scientific instrument data on the comets geotechnical properties.

VII. REFERENCES

[1] www.esa.int/our_activities/Space_Science/Rosetta

[2] Ulamec, S. and Biele J., Surface elements and landing strategies for small bodies missions – Philae and beyond, Advances in Space Research, Vol. 44, pp.847-858, 2009

[3] Schulz, R., Alexander, C., Böhnhardt, H. and Glaßmeier, K.-H. (Eds.), Rosetta-ESA's Mission to the Origin of the Solar System, Springer, 2009.

[4] DLR Institute of Planetary Research, Mission Rosetta, Berlin, January 2010

[5] Landing Gear User Manual RO-LAN-UM-3100-LG Issue 1 Revision 1, 2012 (unpublished)

[6] Biele, J. et.al, The putative mechanical strength of comet surface material applied to landing on a comet, Acta Astronautica 65 (2009) 1168-1178, 2009

[7] Knapmeyer, M. et.al, Recording the PHILAE Touchdown using CASSE: Laboratory Experiments, EPSC, 2013

[8] Blanchard, U., Evaluation of a Full-Scale Lunar Gravity Simulator by Comparison of Landing-Impact Tests of Full-Scale and a 1/6-Scale Model, NASA TN D-4474, 1968

[9] Richards, M.L. and Jung, H.J., Landing Gear Landing Velocity Test Procedure & Report, DLR, 2003

[10] Technical Data, KR500-2 MT and KL1500-2, KUKA Roboter GmbH, 2008

[11] Witte, L. et.al, Philae-Lander Touchdown Dynamics Revisited – Tests for the Upcoming Landing Preparations, IPPW, 2013

[12] Maibaum, M., Philae Separation-Descent-Landing (SDL) and Lander Delivery Preparation (LDP), Technical Note, 2013

[13] Biele, J. et.al, The putative mechanical strength of comet surface material applied to landing on a comet, Acta Astronautica 65 (2009) 1168-1178, 2009