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TECHNICAL NOTE

PHILAE: DESCRIPTION OF DATA DELIVERED TO PSA & PDS

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INDEX SHEET

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TITLE :

TECHNICAL NOTE

PHILAE: DESCRIPTION OF DATA DELIVERED TO PSA & PDS

AUTHOR(S) :

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SUMMARY : This technical note present the data delivered to the PDS/PSA. It contains a short description of the landing and rebound trajectory and attitude, the estimated final landing site and attitude

RELATED DOCUMENTS : Stand alone document.	LOCALIZATION :

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1. OVERVIEW

1.1. REFERENCE DOCUMENTS

[RD1] “The landing(s) of Philae and inferences about comet surface mechanical properties”, Biele J. et al, Science 31 July 2015, VOL 349 ISSUE 6247: aaa9816

[RD2] “Philae Landing on Comet Churyumov-Gerasimenko: Understanding of Its Descent Trajectory, Attitude, Rebound and Final Landing Site”, R. Garmier et al., proceeding for ISSFD 2015, Munich

[RD3] “Attitude reconstruction of ROSETTA's lander PHILAE using two-point magnetic field observations by ROMAP and RPC-MAG”, P. Heinisch, et al., submitted to Acta Astronautica, sept. 2015

[RD4] “Philae localization from CONSERT/ROSETTA measurement”, A. Herique et al., Planetary and Space Science (sept. 2015, in press).

[RD5] “Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar” Kofman W. et al., Science 31 July 2015, VOL 349 ISSUE 6247: aab0639

[RD6] “Identification and Characterization of the landing site of Philae from OSIRIS-NAC Images”, P. Lamy et al., Proceeding, EPSC Abstracts,Vol. 10, EPSC2015-783, 2015

[RD7] « Philae Localization and Science Support by Robotic Vision Techniques», E. Remetean et al. submitted to Acta Astronautica

[RD8] “The gravitational potential of a homogeneous polyhedron or don't cut corners”, Werner R.A., Celestial Mechanics and Dynamical Astronomy, Volume 59, Issue 3, pp 253-278 , July 1994

1.2. APPLICABLE DOCUMENTS

1.3. SCOPE OF THE DOCUMENT

This document presents the data delivered to Planetary Science Archive (PSA) and Planetary Data System (PDS). The data were generated by CNES/SONC-FD team.

The document and delivered data concern 3 different phases of the Philae mission:

1) SDL (Separation Descent Landing): The descent ranging from the release of Philae to the first touchdown (section 3)
2) RBD (Rebound): The rebound ranging from first touchdown to final landing (section 4)

3) FSS (First Science Sequence): The rest on the final landing site (section 5)

Section **Erreur ! Source du renvoi introuvable.** introduces describe the format of the delivered data while the next 3 sections present the delivered data.

Remark: Philae ended its First Science Sequence and fall into hibernation. It seems it wake-up the 26th April 2015. First communication with Rosetta occurred the 13th of June 2015 and the last one the 9th of July. At the date of writing this document, no scientific measurement was collected after the end of FSS. In consequence, delivered data concerning the position of final landing site does not exceed the 14th of November 2014.

Mission Phase	Event	Time (UTC)	Time (TDB)
SDL	Release of Philae	2014/11/12 - 08:35:00	2014/11/12 - 08:36:07
SDL	Unfolding of the landing gear	2014/11/12 – 09:05:00	2014/11/12 – 09:06:07
SDL/RBD	First Touchdown (TD1)	2014/11/12 - 15:34:03	2014/11/12 - 15:35:10
RBD	Second Touchdown (TD2)	2014/11/12 - 16:20:00	2014/11/12 - 16:21:07
RBD	Third Touchdown (TD3)	2014/11/12 - 17:25:26	2014/11/12 - 17:26:33
RBD/FSS	Final landing (FL)	2014/11/12 - 17:31:17	2014/11/12 - 17:32:23
FSS	Start of First Science sequence	2014/11/12 - 17:31:17	2014/11/12 - 17:32:23
FSS	End of First Science sequence	2014/11/14 22:18:01	2014/11/14 22:19:08

Table 1: timetable of the main events occurring during the Philae mission

2. DESCRIPTION OF THE DELIVERED DATA

2.1. OVERVIEW OF DELIVERED DATA

The delivery is composed of four kinds of data:

- Trajectory
- Attitude
- Position
- Sun directions

All files are ascii files.

2.2. SHORT DESCRIPTION OF FRAME AND TIMESCALE

The deliveries used three kinds of frame:

- EME2000 frame: its an intertial frame centered on the comet (cf. 2.2.2),
- CFF is a Comet Fixed Frame with the same center than EME2000 but rotating with the comet (cf. 2.2.3),
- LDR is a Philae frame rotated with Philae (cf. 2.2.4).

Table 2 summarize the reference frame used for the various delivered data.

Phase	Reference Frame used for the Trajectory	Reference Frame used for the attitude	Reference frame used for the sun direction
Descent	EME2000, CFF	EME2000 to LDR, CFF to LDR	EME2000, CFF
rebound	EME2000, CFF	EME2000 to LDR, CFF to LDR	EME2000, CFF
Final position	CFF	CFF to LDR	EME2000, CFF

Table 2: frame used for the various delivered data.

2.2.1. Time scale

All delivered data are using Board Time (TBD).

2.2.2. Earth Mean Equator and Equinox of J2000 (EME2000) centred on the comet

This Reference frame is also known as Mean Equator and Equinox. It is a standard inertial but instead of being centred on Earth centred, equatorial mean of epoch reference system, it is centred on the comet nucleus. It is an inertial Reference frame defined as follows:

- The Reference epoch is January 1st, 2000 at 12h00 (TDB time scale, Julian date 2451545.0)
- The origin 0 is the centre of comet
- $\mathbf{Z_{2000}}$ points along the mean Earth rotational axis at the reference epoch oriented towards the North pole
- $\mathbf{X_{2000}}$ axis points toward the mean vernal equinox of the reference epoch.
- $\mathbf{Y_{2000}}$ axis completes the right handed coordinate system.
- ($\mathbf{X_{2000}}$, $\mathbf{Y_{2000}}$) lies in the mean equatorial plane of the reference epoch

2.2.3. Comet Fixed Frame

The Comet Fixed Frame is a non-inertial frame rotating along with the comet. The comet nucleus shape model determines this reference frame.

The Comet Fixed Frame is defined as follows:

- Centred on the centre of masses of the comet.
- Z axis along the rotational axis of the comet and in the direction of the positive pole
- X axis: intersection between the equator of the comet and the prime meridian (established in the shape model)
- Y axis: completes the right hand system

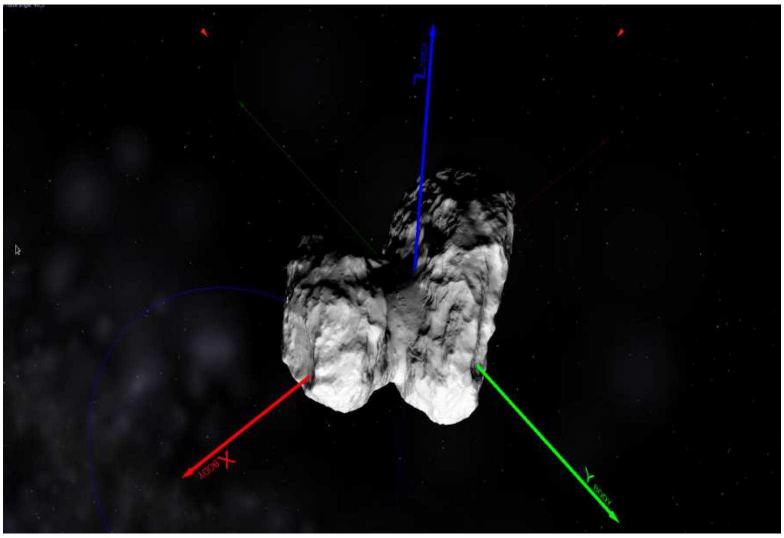

Figure 1: Comet Fixed Frame

2.2.4. Philae Lander Reference Frame - R_{LDR}

This is the main frame of the Philae Lander. Lander equipment's and instruments (cameras) positions are defined in this frame.

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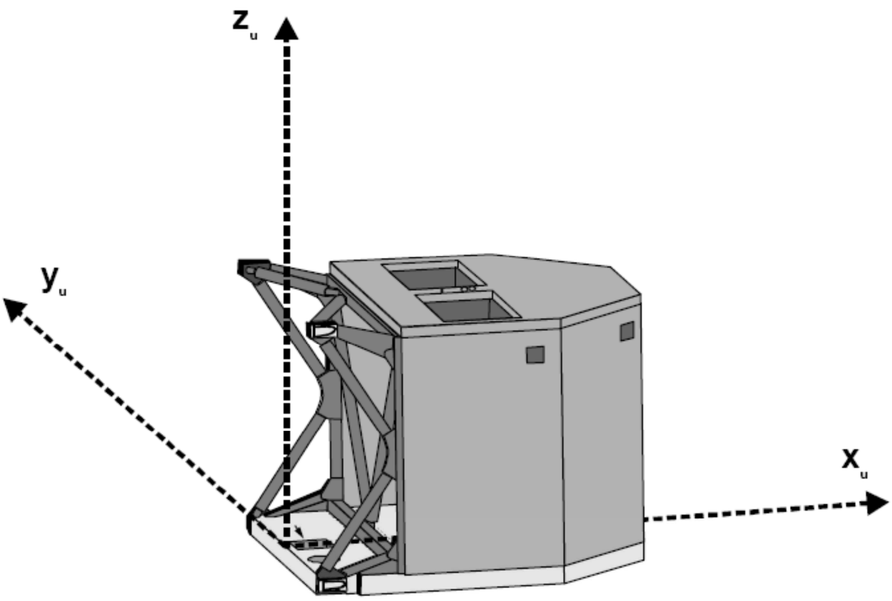

Figure 2 Philae Lander Reference frame (URF).

The Philae Lander Reference Frame is defined as follows (see Figure 2):

- Origin: On the upper surface of the balcony plate, in the middle of the free edge.
- X_{LDR} is pointing at the middle of the wall opposite to the balcony (direction of the Lander separation).

- Z_{LDR} is pointing from the baseplate to the solar hood lid.
- Y_{LDR} axis completes the right handed coordinate system

2.3. TRAJECTORY FILE (LORB)

Delivered files are composed of one or several trajectory blocks. Each trajectory bloc is starting by a header (cf. Table 3) and it is then followed by a data block (cf. Table 4). The data block is composed of M lines and 7 columns for LORB_EME2000_XXX files and M lines and 8 columns for LORB_CFF_XXX files.

Header line	comments
ESOC_TOS_GFI_ORBIT_FILE_VERSION = 1.0	
META_START	
OBJECT_NAME = PHILAE	SONC FD only delivered data for Philae. So OBJECT_NAME is always Philae.
OBJECT_ID = PHILAE	
CENTER_NAME = CHURYUMOV-GERASIMENKO	Central body, origin of REF_FRAME
REF_FRAME = EME2000	REF_FRAME is either EME2000 (inertial frame) or CFF (Comet fixed Frame).
TIME_SYSTEM = TDB	Timescale used for the dating within the file
START_TIME = 2015-05 31T21:25:20.185	Starting date for the trajectory block
#STOP_TIME = 2015-10- 21T01:41:08.182	last date for the trajectory block
#CREATION_DATE = 2015-09- 16T09:21:20.000	Creation date of the file
#FILE_TYPE = ORBIT FILE	Type of file
#VARIABLES_NUMBER = 6	• If REF_FRAME=EME2000 => VARIABLES_NUMBER = 6 (3 position + 3 velocity component) • If REF_FRAME=CFF => VARIABLES_NUMBER = 7 (3 position + 3 velocity components + 1 altitude)
#DERIVATIVES_FLAG = 0	Always 0. No derivatives are provided.
#META_STOP	
	Blank line

Table 3: description of the header for LORB files.

Column number	comments

1	Calendar date (year-month-dayT:hour:minute:second) in TDB
2	Cartesian coordinate X (unit km) for the position expressed in the reference frame indicated in the header.
3	Cartesian coordinate Y (unit km) for the position expressed in the reference frame indicated in the header
4	Cartesian coordinate Z (unit km) for the position expressed in the reference frame indicated in the header
5	Cartesian coordinate VX (unit km/s) for the velocity expressed in the reference frame indicated in the header
6	Cartesian coordinate VY (unit km/s) for the velocity expressed in the reference frame indicated in the header
7	Cartesian coordinate VZ (unit km/s) for the velocity expressed in the reference frame indicated in the header
8	Only present if the REF_FRAME=CFF Distance spacecraft/surface (unit km). the surface point is at the intersection between the line origin of CFF / spacecraft position and shape model surface.

Table 4: trajectory data block for LORB files.

2.4. ATTITUDE FILE (LATT)

Delivered files are composed of one or several attitude blocks. Each attitude block is starting by a header (cf. Table 5) and it is then followed by a data block (cf. Table 6). The data bloc is composed of M lines and 5 columns for LATT_EME2000_XXX as well as LATT_CFF_XXX files.

Header line	comments
ESOC_TOS_GFI_ATTITUDE_FILE_VERSION = 1.0	
META_START	
OBJECT_NAME= PHILAE	SONC FD only delivered data for Philae. So OBJECT_NAME is always Philae.
OBJECT_ID= PHILAE	
REF_FRAME = EME2000	REF_FRAME is either EME2000 (inertial frame) or CFF (Comet fixed Frame). The file contain the rotation quaternion between REF_FRAME to Philae LDR frame.
TIME_SYSTEM = TDB	Timescale used for the dating within the

	file
START_TIME = 2015-06-14T21:15:20.18456706	Starting date for the trajectory block
STOP_TIME = 2015-09-15T23:26:08.18243834	last date for the trajectory block
CREATION_DATE = 2015-09-16T09:24:21	Creation date of the file
FILE_TYPE = ATTITUDE FILE	Type of file
VARIABLES_NUMBER = 4	Quaternion (always 4 components).
DERIVATIVES_FLAG = 0	Always 0. No derivatives are provided.
META_STOP	

Table 5: description of the header for LATT files

Column number	comments
1	Calendar date (year-month-dayT:hour:minute:second) in TDB
2	Q1, Imaginary part of the quaternion
3	Q2, Imaginary part of the quaternion
4	Q3, Imaginary part of the quaternion
5	Q0, real part of the quaternion

Table 6: description of a data line of an attitude file

Test case with quaternion:

To avoid any confusion with quaternion, we provided a test case.

Let's suppose that the following line is extracted from an attitude file with REF_FRAME=EME2000:

```
2015-06-14T21:15:20.18456706    -6.693315908e-01 8.34716602e-02 -4.17880845e-02 7.37076291e-010.0802549613
```

Then the quaternion of rotation between EME2000 to LDR frame is:

(q1, q2 q3, q0) = (-6.693315908e-01 8.34716602e-02 -4.17880845e-02 7.37076291e-01)

If X = [0 0 1] expressed in the LDR frame then by applying the quaternion (q1, q2 q3, q0), we obtain :

X = [0.1789901 0.9797207 0.0900554] expressed in the inertial frame EME2000.

2.5. POSITION FILES (PHILAE_POS)

Position files contain one or several Philae positions expressed in CFF frame.

The file is composed of a header (cf. Table 7) and data block (cf. Table 8). Each position is given by a line of the data block.

Header line	comments
META_START	
ORIGINE = CNES/SONC-FD	SONC FD computations
TIME_SYSTEM = TDB	Timescale used for the dating within the file
CREATION_DATE = 2015-10-05T09:24:33.000	Date of creation of the file
COL1 = SITE NAME	Name of the landing site (ascii)
COL2 = POSITION X CFF (km)	X component in CFF Frame (unit km)
COL3 = POSITION Y CFF (km)	Y component in CFF Frame (unit km)
COL4 = POSITION Z CFF (km)	Z component in CFF Frame (unit km)
META_STOP	

Table 7: description of the header of PHILAE_POS file

Column number	comments
1	Site name (ASCII)
2	Cartesian Component X of the position expressed in CFF Frame (unit km)
3	Cartesian Component Y of the position expressed in CFF Frame (unit km)
4	Cartesian Component Z of the position expressed in CFF Frame (unit km)

Table 8: description of the data block for the PHILAE_POS file

2.6. SUN DIRECTION FILES (SUN_POS)

A Sun direction files contains:

- A date
- The sun direction (Right ascension, Declination) expressed in CFF frame
- The sun direction (Right ascension, Declination) expressed in EME2000 frame
- The distance comet Churyumov-Gerasimenko to Sun

- The distance comet Churyumov-Gerasimenko to Earth

The file is composed of a header (cf. Table 9) and data block (cf. Table 10). The data block is composed on M lines and 7 colonnes. Each line corresponds to the sun direction for a specific date.

Header line	comments
META_START	
ORIGINE = CNES/SONC-FD	SONC FD computations
TIME_SYSTEM = TDB	Timescale used for the dating within the file
START_TIME =	Starting date for the sun direction block
STOP_TIME =	Ending date for the sun direction block
CREATION_DATE =	Date of creation of the file
COL1 = EPOCH (TDB))	Content of the first column of the data block
COL2 = SUN RIGTH ASCENSION, CFF FRAME (DEGREE)	Content of the 2th column of the data block
COL3 = SUN DECLINATION, CFF FRAME (DEGREE)	Content of the 3th column of the data block
COL4 = SUN RIGTH ASCENSION, EME2000 FRAME (DEGREE)	Content of the 4th column of the data block
COL5 = SUN DECLINATION, EME2000 FRAME (DEGREE)	Content of the 5th column of the data block
COL6 = DISTANCE COMET SUN (AU)	Content of the 6th column of the data block
COL7 = DISTANCE COMET EARTH (AU)	Content of the last column of the data block
META_STOP	

Table 9: description of the header of SUN_POS file

Column number	comments
1	Date (TDB timescale)
2	Sun Right Ascension, CFF frame (unit=degree)

3	Sun declination, CFF frame (unit=degree)
4	Sun Right Ascension, EME2000 frame (unit=degree)
5	Sun declination, EME2000 frame (unit=degree)
6	Distance comet to Sun (unit=AU)
7	Distance comet to Earth (unit=AU)

Table 10: description of the data block for the SUN_POS file

2.7. ADDITIONAL DATA

2.7.1. Gravity field model

We join to the delivery a model of gravity field. This file contains the gravitational acceleration for various point of space (cube). The point and the gravitational acceleration is expressed in the CFF frame.

It contain a header presenting containing the GM, the lower left and up right coordinates of the cube as well as its dimension and resolution.

The data block contains M lines by 6 columns. The three first columns contains the position [X, Y, Z] and the last three column the gravitational acceleration created by the comet nucleus at point [X, Y, Z].

3. THE DESCENT

3.1. INTRODUCTION

The descent is defined as the landing trajectory that starts at lander release and that finished when the lander touches the ground for the first time.

3.2. TRAJECTORY

3.2.1. Method

The descent trajectory is computed by propagating an initial state vector (epoch, position and velocity) corresponding to the release point up to the surface of the comet [RD2].

Both outgassing and solar radiation pressure were considered as negligible for the descent duration.

The gravity field is derived from a constant density shape model with the help of methods described in RD8. The shape model is a high resolution polyhedron wit triangular faces. The density is chosen in order to have a GM = 667 m/s3 (value obtained by RMOC)

RMOC delivered a Spherical Harmonic Expansion (SHE) derived from the navigation data of Rosetta. We did not use it for two reasons:

- Spherical harmonics expansion may diverge inside the smallest sphere enclosing the whole body (so called Brillouin sphere). Then the computing of the landing trajectory may be numerically wrong. The divergence rate is increasing with the degree and order of the expansion
- Due to Rosetta altitude, outgassing of the comet, RMOC was only able to derive a degree and order 3 gravity fields. As the nucleus is very far from a sphere, much higher degree and order would be necessary to properly model the gravity field.

The inaccuracy of the polyhedron method has two origins:

- Density is not constant through the body
- The shape model is an approximation of the real shape.

CFF frame origin is located the centre of gravity (COG) of the comet. We derived the centre of mass of the polyhedron assuming a constant density. This point, called the Center Of Figure (COF), appears to be less than 10 m from the real centre of mass (cf. table 11).

Unfortunately RMOC does not provide the accuracy of its gravity field so it is not possible to say if the offset COF/COG is coherent with the accuracy.

Nevertheless the offset was consider as small enough and validate the approximation of constant density.

Remark: the resolution of the shape model is between 5m and 6 m.

Center of mass of the constant density polyehdron	Distance (m)
X component of the center of mass (CFF, unit=m)	19.5
Y component of the center of mass (CFF, unit=m)	-33.3
Z component of the center of mass (CFF, unit=m)	14.1
Distance between the center of mass polyhedron and origin of CFF (m)	41

Table 11: position of the center of mass of the polyhedron shape model with respect to the CFF frame.

3.2.2. Input data

Table 12 present the list of models used to propagate the trajectories.

Comet models	Reference of the model	comment
Shape models	cg-spc-shap5-v1.0-cheops	Provided by OSIRIS team
Comet ephemerides	CORB_DV_106_01_______00173.ROS	Provided by RMOC team
Comet rotation	CATT_DV_106_01_______00173.ROS	Provided by RMOC team
Gravity model	GRA_GRGS_OSIRIS_V5_CU_grav.ROS	The gravity is derived from the shape model considering that nucleus has a constant density. GM =
Release bulletin	LORB_DV_106_01_______00173.ROS	Extracted from RMOC

Table 12: comet models used to realize the propagation of the trajectory during the descent and the rebound

3.2.3. Output data and quality estimation.

Two different files were delivered. The first one is expressed in EME2000 and the second one in CFF. They represent exactly the same trajectory.

File name	Frame	comments
LORB_EME2000_SDL_V1.0.ROS	EME2000	
LORB_CFF_SDL_V1.0.ROS	CFF	

Table 13: trajectory files delivered for the descent

The touchdown point was estimated by CNES [RD1, RD7] using CSHP_DV_085_01_______00145.ROS.

Table 14 provides the Cartesian coordinates of the two different estimations of the touchdown 1. They are determined by using the shape model of Table 12.

	X CFF (m)	Y CFF (m)	Z (CFF)
Estimated landing position [RD7] of touchdown 1	2123.5	-959.3	497.0
Position of touchdown 1 obtained by propagation	2116.6	-962.0	497.0

Table 14: comparison of touchdown position estimated from ROLIS images [RD7] and position obtained after propagation the trajectory [RD3]

The landing point obtained by propagation is 11 m away from the estimated touchdown site and occurred 5.1s after the observed date. The accuracy of the landing trajectory is considered as good.

The error on the propagated trajectory mainly comes from:

- The estimation of the release point of Philae (the accuracy is around 10 m)
- The gravity model and shape model

Remark: RD7 provided the touchdown coordinates for another DTM than the one used for the propagation. We used this position to characterize the accuracy of the propagated trajectory. Theoretically this work should be done with geographical data expressed in the same DTM. The coordinate determination of touchdown was a heavy process and CNES team did not have time to realize it again for a new DTM. Nevertheless the difference should be minor. As a consequence the 11 m should be considered as an order of magnitude rather than an absolute value.

3.3. ATTITUDE

3.3.1. Method

Rosetta is equipped with a scientific magnetometer named RPC_MAG. Philae is also equipped with a scientific magnetometer named ROMAP.

During some part of the descent ROMAP team use its magnetometer of a compass (with respect to RPC mag measurement) to determine the Philae attitude.

The details of the method is described in RD3.

To derive its attitude, ROMAP method requires assuming a constant period of rotation and Z lander direction for a 20 minutes time span.

3.3.2. Input data

The attitude is provided by ROMAP to SONC-FD for validation. Attitude at release date is the targeted attitude (attitude of Philae used at release). Last attitude was determine by CNES team before the touchdonw1. In between latitude were provided by ROMAP.

3.3.3. Output data and quality estimation.

File name	Frame	comments
LATT_EME2LDR_SDL_V1.0.ROS	EME2000 to LDR	NA

Table 15: attitude file delivered for the descent

The quality estimation of attitude data is tricky. We nevertheless have some idea of the attitude of Philae at release and at landing:

- The release attitude was commended to ensure that the Z lander frame is collinear with the normal to the targeted landing site.
- The landing attitude was derived by CNES using ROLIS images [RD7].

Unfortunately ROMAP was not deployed at release and the attitude was not estimated.

The HK data containing the current produces by the Philae solar arrays may help to validate the attitude proposed by ROMAP. Unfortunately as each current output is recorded each 4 minutes and as the rotation period is 9 minutes, the validation may only be very approximate.

The ROMAP attitude is used to determine which solar arrays are illuminated during the descent. The forecast are compared to the HK data. Results are rather coherent. ROMAP predict constant illumination of the lid. This is confirmed with HK data. The predicted illumination of the lateral walls is more or less coherent with HK. Nevertheless there is some discrepancy. Sometime ROMAP, especially at the end of the trajectory, ROMAP is predicted illumination 2 minutes later than what is observed.

As ROMAP has a rotation period around 9 minutes, it means 2 minutes delay is 80° on the X LDR direction…

Z LDR axis seems to be better determined and the error is probably around 10/20°.

3.4. THE SUN DIRECTION

3.4.1. Method

The sun direction in CFF and EME2000 is computed for various times by using the comet ephemeris and rotation.

3.4.2. Input data

We used the comet ephemeris and rotation provided in Table 12

3.4.3. Output data and quality estimation

The output data is referenced in Table 16. The sun direction is considered as very accurate.

File name	Frame	comments
SUN_POS_SDL_V1.0.ROS	FSS and EME2000	NA

Table 16: attitude file delivered for the descent

4. REBOUND

4.1. INTRODUCTION

The rebound starts after touchdown 1 (TD1) and finishes when Philae lies on its final landing site (FL).

There were 2 intermediate touchdowns. Dates are provided in Table 1 and may be found in RD1.

4.2. TRAJECTORY

4.2.1. Method

The available data to rebuild the rebound trajectories are:

- The touchdowns and final landing dates
- An estimation of the position of the first touchdown and final landing position
- An estimations of Philae position during the fly between touchdown 1 and 2 derived from an OSIRIS camera took pictures

The construction of a rebound trajectory was realized by optimizing a trajectory taken into account the available data. The optimization was based on the classical Nelder-Mead algorithm.

The parameters of the optimization are for each considered rebound (cf. Figure 3):

- The norm of the rebound velocity
- The direction of the rebound velocity (two angles).

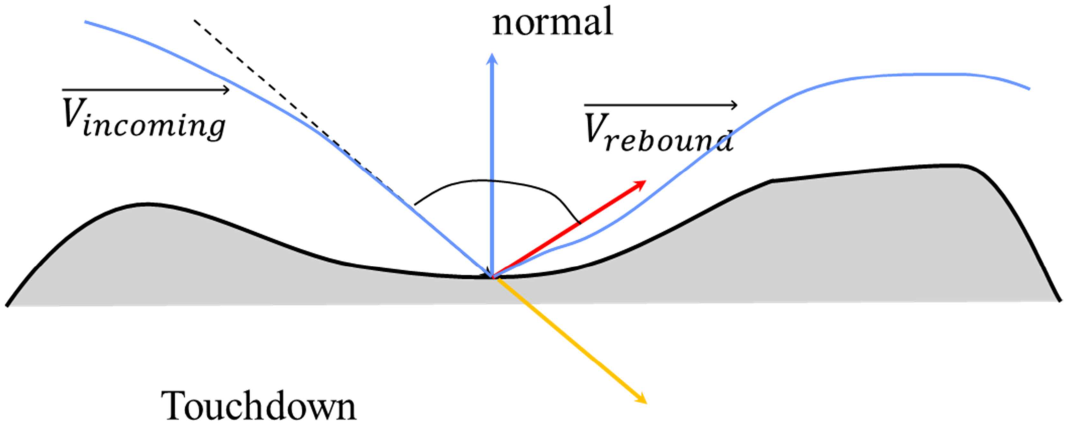

Figure 3: geometry of a rebound

The physics of the rebound is not modelled: the incoming velocity at a touchdown point is not related to the rebound velocity after the touchdown. We only impose that the norm of the rebound velocity is lower than the norm of the incoming velocity.

The trajectory is optimized according to the following constraints:

- The flight duration of each rebound (plus or minus one minutes)
- At the date where the second OSIRIS picture was realized, the lander should be at 75 m from the position determined by the CNES team
- The final landing site should be at less than 20 m from the determined ones.

We decided to not model the last rebound as it flying time was less than 6 minutes. In other word, we consider that the touchdown 3 is close enough to the real final landing site.

Between two rebounds, the trajectory is obtained through a classical propagation.

Remark: as there is some degree of freedom for the constraints, the optimizer found several acceptable trajectories.

4.2.2. Input data

The data and models used to rebuild the rebound trajectories are:

- The touchdowns and final landing dates (cf. Table 1, RD1),
- An estimation of the position of the first touchdown and final landing position (cf. Table 17, RD1, RD7),
- An estimation of Philae position during the fly between touchdown 1 and 2 derived from an OSIRIS camera took pictures [RD7]
- The comet models described in Table 12.

	X CFF (km)	Y CFF (km)	Z CFF(km)
Touchdown 1	2.114	-0.503	0.961
Point observed during Philae flight	2.268	-0.883	0.355
Final landing site	2.449	-0.070	-0.355

Table 17: coordinates of the TD1, point observed during the flight and final landing site used to determine the rebound trajectories. (expressed on DTM of Table 12)

4.2.3. Output data and quality estimation.

We computed 6 trajectories all possible according to the optimization problem. Each trajectory is expressed in EME 2000 frame and CFF frame (i.e. two files delivered per trajectory).

All these trajectories are rather different (cf **Figure 4**) but it is not possible to say which one is the closest to the real trajectory. There are not obtained with measured data and should be considered as hypothetical trajectories.

File name	Frame	comments
LORB_EME2000_RBD_048_V1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_048_V1.0.ROS	CFF	This is possible trajectory
LORB_EME2000_RBD_050_1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_050_1.0.ROS	CFF	This is possible trajectory
LORB_EME2000_RBD_052_1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_052_1.0.ROS	CFF	This is possible trajectory
LORB_EME2000_RBD_055_1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_055_1.0.ROS	CFF	This is possible trajectory
LORB_EME2000_RBD_056_1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_056_1.0.ROS	CFF	This is possible trajectory
LORB_EME2000_RBD_058_1.0.ROS	EME2000	This is possible trajectory
LORB_CFF_RBD_058_1.0.ROS	CFF	This is possible trajectory

Table 18: attitude file delivered for the descent

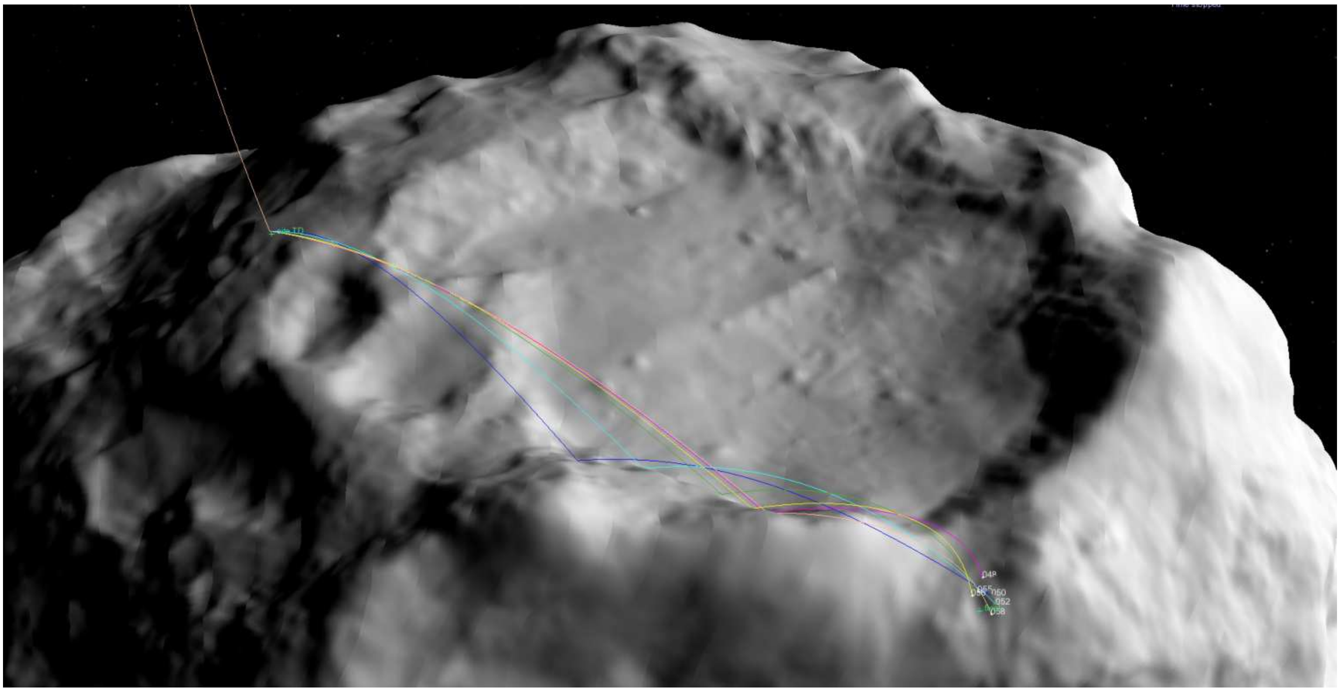

Figure 4: 6 rebound trajectories obtained through optimization.

4.3. ATTITUDE

For the moment, no attitude during the rebound is available.

4.3.1. Method

NA

4.3.2. Input data

NA

4.3.3. Output data and quality estimation.

NA

4.4. THE SUN DIRECTION

4.4.1. Method

The sun direction in CFF and EME2000 is computed for various times by using the comet ephemeris and rotation.

4.4.2. Input data

We used the comet ephemeris and rotation provided in Table 12

4.4.3. Output data and quality estimation

The output data is referenced in Table 16. The sun direction is considered as very accurate.

File name	Frame	comments
SUN_POS_RBD_V1.0.ROS	CFF and EME2000	NA

Table 19: attitude file delivered for the descent

5. FINAL LANDING SITE

5.1. INTRODUCTION

The final landing site is the point where Philae came at rest on the comet.

5.2. POSITION

5.2.1. Method

By using its ranging measurement, CONSERT team was able to derive [RD4, RD5] two areas:

- A possible area: this area is 22.5m x 106.5 m. Philae may be possibly located here. This area is obtained independently from a DTM.
- A most probable are: this area is 22.6 m x 41.5 m. it is the south part of the possible area. This area is obtained by taking into account a DTM.

SONC-FD analysed CONSERT area. The idea was to produce exclusion zones. It is obviously hard to know where is Philae but it is quiet easy to map places where it cannot be.

The realization of such map is possible thanks to:

- The illumination period of the lander. The HK voltages and currents indicate when Philae's solar arrays are illuminated.
- The communication windows period between Rosetta/Philae.

The process is the following:

1. We extract an area to analyze from a Digital Terrain Model (DTM). The DTM consists of polyhedron with triangular faces (typical ridge is 5 m long). We extract triangles located in a 200 m radius circle around the candidate site from the DTM.
2. For each center of triangle, we determine if the triangle is illumined during the daytime observed during FSS. If not, the candidate landing site may not be located on the triangle. This triangle is excluded as the landing site may not be located here.
3. For the remaining triangles, considering Philae's attitude proposed by ROMAP, we check whether any of the individual solar arrays is illuminated as observed during FSS. If not, the triangle is excluded.
4. For the remaining triangles, we compute if the communication between Philae and Rosetta are possible during the real communication period of FSS.

This process is very easy to implement and has a lot of advantages. At each level of the process, one produces an exclusion map based on a given data.

Map of step 2 are considered very reliable and the largest error sources are the Digital Terrain Models. Maps of step 3, 4 required to trust the Philae attitude provided by ROMAP. Nevertheless, they are rather close to the map of step 2, so results are convergent.

Based on CONSERT area and its own analysis, SONC-FD proposed a possible landing site. It is located in the north of the possible zone, slightly outside.

OSIRIS analysed pictures of the comet performed on board of Rosetta. The process was to compare pictures of the same area taken before and after the landing, if possible with equivalent illumination conditions. Most of the pictures used for the comparison were taken at 40 km altitude. As the lander has a metric size, it should be only a few pixels on these images. It discovered a possible landing site.

SONC-FD and OSIRIS site are very close, less than 10 m.

5.2.2. Output data and quality estimation.

It is hard to quantify exactly the accuracy of the landing site. OSIRIS landing site is located around 50m from the most probable CONSERT area (center of zone).

We decided to deliver three possible landing site:

- The OSIRIS landing site [RD6] based on image analysis. This landing site is consider as the best candidates.
- The SONC FD landing site [RD2]. It is a few tens meter away from OSIRIS landing site but slightly outside the CONSERT possible area.
- The CONSERT landing site. It is located at the center of the CONSERT most probable zone. It is more south than the two previous landing site.

All site coordinates of Table 20 are expressed on DTM presented in Table 12.

	X CFF (km)	Y CFF (km)	Z CFF(km)	Longitude (°)	Latitude (°)	Radius (km)
OSIRIS landing site	2.4440	-0.7010	-0.3546	358.35	-8.25	2.4706
SONC-FD landing site	2.4443	-0.0853	-0.3524	358.2	-8.1	2.4711
CONSERT landing site	2.4164	-0.1012	-0.3938	357.6	-9.25	2.4503

Table 20: comparison between the various proposed landing site.

5.3. ATTITUDE

5.3.1. Method

The attitude was derived by ROMAP magnetometer [RD3] and later it was evaluated by SONC-FD by using the current output produced by the Philae solar arrays [RD2]. ROMAP attitude is supposed to present a better accuracy than SONC-FD attitude. SONC attitude was used only to cross check ROMAP attitude. We did not deliver this attitude to PSA/PDS.

Both methods do not require knowing the Philae position to determine the attitude of Philae. It means that this work may be realized independently from the search of the landing site.

These methods provide the orientation of the lander frame with respect to the Comet Fixed Frame.

5.3.2. Input data

ROMAP is using its measurement.

SONC FD is using HK currents of the 13th of June 2015 and comet position and attitude described in Table 12.

5.3.3. Output data and quality estimation.

At the end of the First Science Sequence (FSS) the head of Philae was rotated to improve the solar illumination of Wall 1. It means that the LDR framed was rotated as it attached to the head. As a consequence, we deliver an attitude file containing attitude before and after rotation of the head. The description of the rotation may be found in RD7.

File name	Frame	comments
LATT_CFF2LDR_FSS_V1.0.ROS	EME2000 to LDR	Corresponding to the FSS

Table 21: delivered attitude file.

The accuracy of ROMAP attitude was derived by performing a comparison with the SONC-FD attitude. ROMAP and SONC-FD attitude are rather close: The angle between the two Z LDR axes is 5.5°. The Euler angle (X, Y, Z) between ROMAP attitude and SONC-FD attitude are [1.9° 2.6° -14.2°].

5.4. THE SUN DIRECTION

5.4.1. Method

The sun direction in CFF and EME2000 is computed for various times by using the comet ephemeris and rotation.

5.4.2. Input data

We used the comet ephemeris and rotation provided in Table 12

5.4.3. Output data and quality estimation

The output data is referenced in the following table. The sun direction is considered as very accurate.

File name	Frame	comments
SUN_POS_FSS_V1.0.ROS	CFF and EME2000	NA

Table 22: attitude file delivered for the descent

6. SUMMARY OF THE DELIVERY

The following table summarize the whole files delivered for each phase of Philae missions.

Mission Phase	File name	Content
SDL	LORB_EME2000_SDL_V1.0.ROS	Trajectory in EME2000
	LORB_CFF_SDL_V1.0.ROS	Trajectory in CFF
	LATT_EME2LDR_SDL_V1.0.ROS	Attitude EME2000 to LDR
	SUN_POS_SDL_V1.0.ROS	Sun direction
RDB	LORB_EME2000_RBD_048_V1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_048_V1.0.ROS	Trajectory in CFF
	LORB_EME2000_RBD_050_1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_050_1.0.ROS	Trajectory in CFF
	LORB_EME2000_RBD_052_1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_052_1.0.ROS	Trajectory in CFF
	LORB_EME2000_RBD_055_1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_055_1.0.ROS	Trajectory in CFF
	LORB_EME2000_RBD_056_1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_056_1.0.ROS	Trajectory in CFF
	LORB_EME2000_RBD_058_1.0.ROS	Trajectory in EME2000
	LORB_CFF_RBD_058_1.0.ROS	Trajectory in CFF
	SUN_POS_RBD_V1.0.ROS	Sun direction
FSS	PHILAE_POS_CFF_V1.0.ROS	Philae position in CFF
	LATT_CFF2LDR_FSS_V1.0.ROS	Philae latitude CFF to LDR
	SUN_POS_FSS_V1.0.ROS	Sun direction

Additional data	GRA_GRGS_OSIRIS_V5_CU_grav.ROS	Gravity field of Comet Churyumov-Gerasimenko

Table 23: summary of the all the delivered files.