PHILAE localization from CONSERT / ROSETTA measurement

Alain Herique(1), Yves Rogez(1), Pierre Pasquero(1), Sonia Zine(1), Pascal Puget(1), Wlodek Kofman(1)

(1) Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France
CNRS, IPAG, F-38000 Grenoble, France

Corresponding author:
alain.herique@obs.ujf-grenoble.fr
tel +33 476 51 41 73 / fax +33 476 51 41 46

ABSTRACT

On 12 November 2014 at 15:34 UTC, after a 7-hour descent, the Philae lander made contact with the surface of the comet Churyumov-Gerasimenko (67P/CG) in the centre of the intended landing zone. Following the failure of its anchoring systems, it bounced and continued to fly ballistically. A couple of hours later, telemetry transmitted to Rosetta showed that Philae was stabilized on the surface and working properly although its precise and final location was and still is not known. (Biele et al, 2015).

From the morning of 13 November 2014, CONSERT data enabled an initial estimate to be made of Philae's location based on signals propagated through the 67P/CG nucleus. This rough location was then refined through three sets of measurements carried out during periods of direct visibility between Rosetta and Philae during the Philae's First Science Sequence (FSS) on 13 and 14 November. This paper presents these measurements and the estimate of the final position of Philae in November 2014.

1. CONSERT

The Comet Nucleus Sounding Experiment by Radio wave Transmission (CONSERT) instrument is a radar designed to study the internal structure of the nucleus of the comet Churyumov-Gerasimenko (67P/CG). It uses measurements of electromagnetic wave propagation between the Philae lander, resting on the comet's surface, and the Rosetta orbiter (Kofman et al, 1998). Measurements provide the propagation delay and the signal amplitude for each trajectory.

During data acquisition, the propagation delay and geometry are used to calculate the additional delay caused by propagation through the nucleus. This additional delay is directly related to the dielectric permittivity of the medium that is traversed and can be used to identify the electrical properties of the material found in the comet nucleus. At the same time, absorption can be derived from the radiowave path loss as the signal propagates through the nucleus; this makes it possible to identify the class of refractory materials found in the nucleus. The CONSERT experiment was programmed to begin during the first 67P/CG revolution immediately following Philae's planned landing (12 November 18:56 to 13 November 04:06 UTC). The experiment started on time and made initial measurements of the internal structure of the nucleus. However, the question of the final landing site complicates the interpretation of measurements, as it introduces new uncertainties and the need to estimate jointly the permittivity of the nucleus and the lander's final position (Kofman et al., 2015).

In direct visibility, the permittivity of the medium – very low density coma with low levels of ionisation – is practically equal to 1. The propagation delay is therefore a direct measure of the distance between the Rosetta orbiter and the Philae lander. Repeated distance measurements, taken at different Rosetta positions, made it possible to deduce Philae’s position from Rosetta’s position. This localization technique is the basic principle for all radio triangulation systems, such as GPS.

The design of the CONSERT instrument has been described in many papers (e.g. Kofman et al., 1998; Kofman et al., 2004; Kofman et al., 2007; Kofman et al., 2009) and its principal parameters are summarised in Table 1. The accuracy requirement on the propagation delay measurement determines the clock stability specification (OCXO) of both the CONSERT orbiter (OCN) and the CONSERT lander (LCN) electronic devices and the instrument had to be designed around this requirement. The final transponder structure made it possible to relax this demanding clock stability requirement: an initial wave propagation from the OCN to the LCN is used to synchronize the two devices, while the propagation of a second wave from the LCN to the OCN is the actual science measurement (Fig. 1). The cycle begins with a tuning phase, where the two devices are synchronized by adjusting the frequency ($\Delta f / f < 10^{-7}$) and the time ($\Delta t < \text{a few ms}$) of the two clocks. The two devices then work autonomously throughout the measurement sequence that can last up to more than thirty hours:

- when the orbiter transmits, the lander listens;
- then when the lander transmits, the orbiter listens;
- this ‘ping-pong’ cycle is repeated usually every 2.5 seconds.

Tuning requires that there is direct visibility between the OCN and the LCN, and a sufficiently strong signal between the two antennas (less than 105 dB loss, including polarization mismatch). In practice, it was not possible to either guarantee, or even respect, this constraint during the First Science Sequence (FSS) as the orbiter-lander distance could exceed the specified 30 km. Furthermore, Philae’s final position limited antenna gain, and lack of knowledge of its immediate environment made it impossible to correctly estimate a link budget or to coordinate in advance the operational sequences between the OCN and the LCN. This operational difficulty was resolved by the implementation of a stroboscopic mode that did not require a tuning phase. OCXO monitoring during the cruise phase showed that the frequency tuning was almost constant and it could be replaced by a command sent from the ground. It then remained to temporally synchronize the two devices so that one listened while the other transmitted. This was achieved using a stroboscopic method: an OCN cycle takes 2.448 seconds, while that of the LCN is exactly 2.5 seconds. Thus, the timing of the orbiter slowly drifts (in 52 ms increments) from that of the lander. From time to time the two instruments come into phase: there are 4 correct measurements every 2 minutes, while the remaining 96% of measurements are desynchronised. Three sequences of distance measurements were collected. These consist of respectively 3, 12 and 3 sets, each of 4 to 5 measurements; this data was analysed and is summarized in Table 4.

2. TRIANGULATION

Triangulation is based on CONSERT’s measurement of the distance and Rosetta’s position. For each measurement, we analysed the various error terms in order to estimate the accuracy of Philae’s final location (Table 4).

2.1 Orbitography and Dating

For triangulation, Rosetta’s position in the Comet Fixed Frame (CFF) was calculated using SPICE (Kernels DV_098_01_____00163 RORB/RATT of 13/04/2015). To calculate Rosetta’s trajectories in the CFF repository, we also used kernels RMOC DV_098_01_____00163

(CORB/CATT). The selected points on the trajectory were calculated from CONSERT measurement dates (Kernel ROS_141113_STEP.TSC for SPICE epoch to UTC time conversions).

Orbit restitution is accurate to about a dozen meters (1 sigma) in three directions: along track, cross track and radial (private communication Pablo Munoz/ESOC). We found a systematic orbital positioning error in the same measurement sequence. As satellite operations (change of trajectory or wheel offload) were ongoing between measurement sequences, we considered the error to be decorrelated from one sequence to another one. In order to take the spacecraft position error directly into account in the triangulation, we expressed it as a distance error: the drift of Rosetta in a given direction causes a change in the orbiter/lander distance equal to the projection of the drift on the target orbiter/lander line. Therefore, for each position error, we calculated the equivalent distance error: the radial error is the main contributor to the distance error. This resulted in a standard deviation ranging from 11 to 16 metres (1 sigma).

The calculation of Rosetta's position on its orbit requires each CONSERT measurement to be dated. The orbiter dates every measurement in 'CONSERT time' (relative to the end of the tuning phase) and in Spacecraft Event Time (SCET). The date is converted to universal time (UTC) as follows:

- SCET is used to date the telemetry. It corresponds to the date of the reporting carried out after each measurement. It is therefore necessary to correct SCET for the delay between the middle of the CONSERT measurement and the end of the reporting phase. This bias (-250ms) is constant for all measurements.
- Decimal part of the SCET is rounded to 4 digits in the telemetry. This rounding is corrected on ground using CONSERT time which has an accuracy of the order of one millisecond. This correction is equivalent to a 20 ms bias and results in a random error of up to 32 ms.
- SCET is calculated from the time the acquisition sequence of the CONSERT experiment began. The decimal part of the hour (seconds), is measured in 8 bits. The error due to quantization at 8 bits is negligible.
- Finally, SCET is corrected by the time correlation aboard Rosetta to obtain the UTC ($UTC - SCET = 71.2$ seconds typically on 14 November at 10:20 from DDS APID 1966).

Following the correction and bias compensation of SCET, the accuracy of UTC dating is estimated to be better than 50 ms. This can be expressed as an along track position error (<50 cm), which reduces to a distance error between the orbiter/lander of less than a few centimetres. This error term is therefore negligible.

2.2 CONSERT Distance Measurements

Triangulation is based on measuring the distance between the lander and the orbiter. The calibration of this measurement and the estimate of the associated error is twofold: one concerns signal processing linked to the detection of signal arrival time and correction of the transponder; the second concerns the calibration of electronic devices.

The CONSERT signal processing chain consists of several steps that make it possible to correct for the transponder (Kofman et al., 2007) and improve the accuracy of the measurement:

- CONSERT measures the radio signal propagated between the lander and the orbiter as a function of time. When there is direct visibility, the signal mainly comprises the trajectory between the lander and the orbiter. The signal shown in Fig. 2 shows that secondary trajectories are ten times less powerful than the principal trajectory and may correspond to reflections (at the Hathemit depression rim for example). The main echo is clearly identifiable

and is not affected by scattering. This signal is not subject to pollution from other instruments and we did not need to remove any spectral line.

- The design of the transponder introduced an additional delay, equal to the propagation delay of the principal trajectory (Kofman et al., 2007). The real delay was calculated by measuring the propagation delay of the main peak and dividing it by two (Fig. 1).
- The CONCERT signal was sampled at 10 MHz for both the OCN and the LCN. The accuracy of the resynchronization is therefore around ± 100 ns (30 m in free space). In order to improve this accuracy, we interpolated OCN and LCN signals using a signal model (the method will be the subject of a future publication, Fig. 2 red curve). The interpolation was tested on ground calibration data, resulting in a final accuracy of ± 5 ns (1.5 m).
- Finally, CONCERT time measurements were done modulo 25.5 μ s (i.e. 7.6 km in free space) due to the periodic transmission of the signals. This modulo is corrected based on *a priori* knowledge of the orbitography.

The processing provided a propagation delay measurement with a relative accuracy of ± 5 ns (i.e. ± 1.5 m) over the final distance measurement for Signal to Noise Ratio larger than 20 dB. This error is decorrelated from one measurement to another one. Assuming it has a uniform distribution; it corresponds to an error of 0.8 m RMS (root mean square).

This measurement requires the absolute calibration of electronic devices. Therefore, any additional delay introduced by the device and on-board processing must be compensated for. Initially we anticipated that the direct visibility measurement would be used to calibrate absolute system delay, based on the position of the lander and the lander/orbiter distance. However, as Philae's exact position was unknown, it proved impossible to take this measurement, and instead we estimated the delay based on ground calibrations, cruise checkouts and descent acquisition (SDL). Multiple measurements of the system delay were made during the orbiter's cruise phase. However, as Philae's antenna was attached to the side opposite to the orbiter, propagation modelling was not straightforward and our measurements contained an error of the order of a few tens of nanoseconds. We believe that the most reliable measurement is the one recorded just after Philae separated from the orbiter. This time is 580 ns. After correction for the propagation between the orbiter and lander antennas (3.8 m) we obtain a system delay of 555 ns. This time is known to vary as a function of temperature: ground calibration showed that it increases by 82 ns when the temperature varies from -30° C to $+57^{\circ}$ C (the internal temperature of the LCN) i.e. almost one nanosecond per degree. As the separation temperature was $+9^{\circ}$ C, the system delay is estimated to be 549 ns ($+3^{\circ}$ C), 541 ns (-5° C) and 535 ns (-11° C) for the three measurement sequences. The system delay includes all transponder and processing delays and (when divided by two) contributes to the final measurement distance. The accuracy of the system delay calibration is limited, and we estimate it to be ± 20 ns, i.e. ± 6 m over the final distance measurement. This error is highly correlated between sequences and corresponds to 3.4 m RMS assuming a uniform distribution.

3. LOCATION OF THE LANDER

3.1 Error Analysis

The previous section shows that the CONCERT distance measurement has two main sources of error:

- Errors related to the restitution of Rosetta's orbit. This is a Gaussian distribution with a standard deviation ranging from 11–16 m RMS and we assume errors decorrelated between different measurement sequences. Dating errors are assumed to be negligible.
- Errors related to the estimation of the propagation delay, both in terms of signal processing (± 1.5 m) and instrument calibration (± 6 m) corresponding to an RMS error of 0.8 m and 3.4 m respectively.

The accuracy of the triangulation is also highly dependent on geometry, therefore Rosetta's position during the three measurement sequences. Fig. 3 shows the limits of the potential zones for each of the three sets of measurements (green, blue and yellow bands indicate the boundaries limited by a min/max distance of 1 sigma). The limits of each band correspond to the intersection with a sphere of radius equal to the distance between the orbiter and the surface. These bands are very close to each other and almost parallel, which results into an unfavourable triangulation configuration. The three sequences were acquired in close proximity to each other because the lander and the orbiter were only able to communicate for a short period during the FSS (minimal longitude window) and Rosetta's slow motion in the 26-hour period during which the set of measurements were taken (little variation in latitude). To improve the triangulation geometry we included data acquired during transmission through the comet (Kofman et al., 2015). These data provide different geometries, but have a larger error coming from the additional delay generated by the propagation through a material medium with uncertainties on dielectric permittivity and propagation length. We assumed a permittivity of between 1 and 1.5 for propagation through the comet at depths of between 350 and 1000 m (Fig. 3, grey bands and Table 4). For these measurements, the orbit restitution error is much lower: of the order of 5 metres (private communication Pablo Munoz/ESOC).

Finally, the 67P shape model can also introduce errors: the lander is located at the edge of the zone that had been imaged by Rosetta's NAVCAM and the OSIRIS camera, which may introduce a large-scale bias. In order to address these potential errors, we prepared an initial 3D localization without the 67P shape model.

3.2 Min/max 3D localisation

Fig. 4 shows the volume bounded by the measured min/max distances plus ± 1 sigma. A transparent shape model was added. The volume is therefore defined as 30 m x 390 m on the surface, and a 340 m perpendicular to the surface. As this volume is oriented almost perpendicular to the surface, large-scale errors in the shape model should not result in a drastic change in the location that is obtained (coordinates of the volume are given Table 2). This figure also shows that the potential volume zone at 1 sigma is at least 35m from the rim of the crater.

Fig. 5 shows the projection of the zone on the surface taking into account the orbitography error at 1 and 3 sigma (light and dark green limits respectively). The same figure shows the limits based on propagation through 67P using the sequence of 13 November at 04:00 UTC, and a maximum propagation depth through the comet of between 325 m and 1000 m (light and dark blue limits respectively). For this sequence, the 350m estimate is directly related to the shape model and propagation, while 1000 m is a maximum value.

3.3 RMS localisation

Next, we adopted a statistical approach and calculated for each point in space, the RMS error with respect to the measured distance. As the overriding error (both for orbitography and system delay) is constant within each sequence of measurements, we only really have 3 independent estimates. Average RMS error was calculated for each sequence, followed by the average RMS of the 3 sequences weighted by their variance. The normalised RMS errors calculated in the 3D zone ranged from 0.25 to 1.17. With only 3 independent measurements, this was not a reliable estimator of standard deviation and the values obtained were much less than 1 over a wide area. We therefore have to take into account a larger zone where RMS error was low: we decided to use 1.0 as limit (Fig. 5, red ellipse).

3.4 CONSERT tomography

This statistical calculation did not take into account propagation measurements through the comet. This was because the associated error depends heavily on the shape model, permittivity assumptions, and the propagation model. In practice, it is the analysis that is carried out for the inversion of tomographic data, and the joint estimate of the average permittivity and the position of the lander (Kofman et al., 2015). This inversion relies on the assumption that permittivity is comparable in the probed zone to the east and to the west of the lander. The resulting zone is about (34*21m) 50m in diameter (Fig. 5, purple circle).

4. CONCLUSION

This extended analysis describes the full set of CONSERT measurements that attempted to determine Philae's location. It takes into account differences in temperature for measurements taken in stroboscopic mode, which explains the slight shift of the detected zone compared to previous estimates. The orbitography error (the main source of inaccuracy in line-of-sight measurements) was also taken into account, which explains why the detected zone was widened.

- The estimate of Philae's position is based on all of these analyses. The data indicate with high probability that the lander is in the Yellow zone, consistent with direct measurements and the end of the science sequence in transmission through the comet. The calculation is mainly based on the 3D analysis and only the eastern boundary takes account of the general 67P/CG shape model (low resolution). This wide zone (22.5 x 106.5 m) is insensitive to errors in the shape model and can be refined and limited to its western part (the Orange zone - 22.6 x 41.5 m). It is therefore based on the inversion of CONSERT signals, which are much more sensitive to errors in the shape model. Coordinates of the yellow and orange areas are summarized Table 3.

Additional measurements are anticipated for when the lander wakes up: it will be essential to choose favourable geometries to optimize triangulation, and to combine these measurements with an orbit determination to reduce the uncertainty of each measurement.

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REFERENCES

- Biele, J. et al., 2015, The landing(s) of Philae and Inferences on Comet Surface Mechanical, Science, in press
- Herique, A. et al., 2012, Rosetta rendezvous and CONSERT operations in 2014: A chimeric surface model of 67P/Churyumov Gerasimenko , PSS, DOI: 10.1016/j.pss.2012.03.003
- Kofman, W., et al., 1998. Comet nucleus sounding experiment by radiowave transmission. *Advances in Space Research* 21, 1589–1598.
- Kofman, W., et al., 2004. Consert experiment: description and performances in view of the new target. In: Colangeli, et al. (Eds.), *New Rosetta Targets: Observations, Simulations And Instrument Performances*, 311. *Astrophysics and Space Science Library*, pp.237–256. BookSeries.
- Kofman, W., et al., 2007. The Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT). A short description of the instrument and of the commissioning stages. *Space Science Review* 128, 413–432.
- Kofman, W., et al., 2009. The comet nucleus sounding experiment by radio-wave transmission (CONSERT). A short description of the instrument and commissioning stages. In: Shultz, Rita (Ed.), *Rosetta*.
- Kofman, W., et al., 2015, Internal properties of the nucleus of Comet 67P/ Churyumov- Gerasimenko as measured by the CONSERT instrument. *Science*, in press

Table 1: Main parameters of the Philae Lander and Orbiter instruments (from Herique et al., 2012)

Mass	3 kg on Orbiter, 2.3 kg on Philae
Average power	3 W on Orbiter and on Philae
Clocks	10 MHz Sorep micro-OCXO (Oven Controlled Crystal Oscillator)
Nominal operation	$\Delta f/f < 2 \cdot 10^{-7}$
Degraded mode if offset	$2 \cdot 10^{-7} < \Delta f/f < 4 \cdot 10^{-7}$
Transmission	90 MHz carrier, BPSK modulation
Pseudo noise code	$255 \times 100 \text{ ns} = 25.5 \mu\text{s}$
Code repetition	Up to 200 ms
RF power	2 W/Orbiter, 0.2 W/Lander
Receiver	Band 86–94 MHz (–3 dB), linear phase
Gain range	30–90 dB with AGC
Demodulation	I and Q “synchronous” detection
ADC	8 bits 10 MHz ADC on each channel
Processing	
Real time coherent integrations	1,024 code periods (26 ms, +30 dB on SNR) 256 periods (+24 dB on SNR), in degraded mode.
On-board the Lander	Code compression (+24 dB on SNR) and peak detection
Telemetry (data rate)	Orbiter: 8 kbits/measurement point ~ 65 Mbits/Orbit Lander: ~20 Mbits/Orbit (depending on how often the complete set of data will be transmitted)

Table 2: Coordinates of the localization volume given by direct measurements in CFF cartesian coordinates (m)

		x	y	z	semi-axis
center		2459	-39	-322	
Main axis	Top point	2496	95	-117	248
(~ radial)	Bottom point	2423	-174	-527	248
second axis	SW point	2381	-94	-273	108
(SW / NE)	NE Point	2538	15	-371	108
Third axis	NW point	2471	-22	-316	17
(NW-SE)	SE point	2448	-57	-328	17

Table 3: Localization zones on OSIRIS shape model in CFF cartesian coordinates (m)

	x	y	z	Latitude (°)	Longitude (°)
Yellow zone					
1	2423	-118	-390	-9.3	357.2
2	2408	-106	-402	-9.6	357.5
3	2461	-28	-351	-8.2	359.3
4	2474	-46	-330	-7.7	358.9
Orange zone					
3'	2429	-76	-383	-9.1	358.2
4'	2433	-106	-380	-9.0	357.5

Table 4: Consort Measurement

Sounding Reference			orbito							Propagation delay							Ranging						
ID	sounding number		UTC time (s)	position			position error rms			ranging error (m)	Peak position (code step)			Modulo code	system delay (ns)	Equivalent distances (1)			Min / Max ± 1 sigma (2)		Min / Max ± 3 sigma (2)		total sigma (3) (m)
	OCN	LCN		x (m)	y (m)	z (m)	Rad. (m)	long (m)	Cros (m)		OCN (step)	LCN (step)	Final (step)			Ranging (m)	min (m)	max (m)	min (m)	max (m)	min (m)	max (m)	
1.01	520	36	13 Nov 22:04:26.79	26664	-25873	9697	11	10	7	11	165.70	0.15	165.55	9	555	36800	36792	36807	36781	36818	36759	36840	11.56
1.01	521	37	13 Nov 22:04:29.24	26656	-25883	9697	11	10	7	11	165.90	0.35	165.55	9	555	36800	36792	36807	36781	36818	36759	36840	11.56
1.01	522	38	13 Nov 22:04:31.69	26648	-25892	9697	11	10	7	11	165.05	-0.30	165.35	9	555	36797	36789	36804	36778	36815	36756	36837	11.56
1.01	523	39	13 Nov 22:04:34.14	26640	-25902	9697	11	10	7	11	165.70	0.05	165.65	9	555	36801	36794	36809	36783	36820	36761	36842	11.56
1.02	568	83	13 Nov 22:06:24.29	26284	-26328	9699	11	10	7	11	170.60	0.15	170.45	9	555	36873	36865	36880	36854	36891	36832	36913	11.56
1.02	569	84	13 Nov 22:06:26.73	26276	-26338	9699	11	10	7	11	171.90	1.40	170.50	9	555	36874	36866	36881	36855	36892	36833	36914	11.56
1.02	570	85	13 Nov 22:06:29.18	26268	-26347	9699	11	10	7	11	170.60	0.05	170.55	9	555	36874	36867	36882	36856	36893	36834	36915	11.56
1.02	571	86	13 Nov 22:06:31.63	26260	-26357	9699	11	10	7	11	170.90	0.25	170.65	9	555	36876	36868	36883	36857	36894	36835	36916	11.56
1.03	616	130	13 Nov 22:08:21.78	25896	-26778	9702	11	10	7	11	175.90	0.40	175.50	9	555	36949	36941	36956	36930	36967	36908	36989	11.56
1.03	617	131	13 Nov 22:08:24.23	25888	-26788	9702	11	10	7	11	175.50	0.05	175.45	9	555	36948	36940	36955	36929	36966	36907	36988	11.56
1.03	618	132	13 Nov 22:08:26.67	25880	-26797	9702	11	10	7	11	175.90	0.25	175.65	9	555	36951	36943	36958	36932	36969	36910	36991	11.56
1.03	619	133	13 Nov 22:08:29.12	25871	-26806	9702	11	10	7	11	175.50	0.00	175.50	9	555	36949	36941	36956	36930	36967	36908	36989	11.56
2.01	3264	1	14 Nov 10:20:50.49	40633	-24487	12784	15	7	15	15	93.35	-0.50	93.85	12	547	47193	47186	47201	47171	47216	47141	47246	15.42
2.01	3265	2	14 Nov 10:20:52.94	40625	-24501	12784	15	7	15	15	94.15	0.30	93.85	12	547	47193	47186	47201	47171	47216	47141	47246	15.42
2.01	3266	3	14 Nov 10:20:55.39	40616	-24514	12784	15	7	15	15	93.90	0.10	93.80	12	547	47192	47185	47200	47170	47215	47140	47245	15.41
2.01	3267	4	14 Nov 10:20:57.84	40608	-24528	12785	15	7	15	15	93.70	-0.10	93.80	12	547	47192	47185	47200	47170	47215	47140	47245	15.42
2.02	3312	48	14 Nov 10:22:47.99	40220	-25134	12803	15	7	15	15	94.80	0.20	94.60	12	547	47204	47197	47212	47182	47227	47152	47257	15.41
2.02	3313	49	14 Nov 10:22:50.44	40211	-25147	12803	15	7	15	15	94.60	0.05	94.55	12	547	47204	47196	47211	47181	47226	47151	47256	15.41
2.02	3314	50	14 Nov 10:22:52.88	40202	-25160	12803	15	7	15	15	94.45	-0.10	94.55	12	547	47204	47196	47211	47181	47226	47151	47256	15.42
2.02	3315	51	14 Nov 10:22:55.33	40194	-25174	12804	15	7	15	15	94.25	-0.35	94.60	12	547	47204	47197	47212	47182	47227	47152	47257	15.42
2.03	3359	94	14 Nov 10:24:43.03	39805	-25760	12821	15	7	15	15	95.15	-0.25	95.40	12	547	47216	47209	47224	47194	47239	47164	47269	15.41
2.03	3360	95	14 Nov 10:24:45.48	39796	-25773	12822	15	7	15	15	94.95	-0.40	95.35	12	547	47216	47208	47223	47193	47238	47163	47268	15.41
2.03	3361	96	14 Nov 10:24:47.93	39787	-25786	12822	15	7	15	15	94.85	-0.55	95.40	12	547	47216	47209	47224	47194	47239	47164	47269	15.42
2.03	3362	97	14 Nov 10:24:50.38	39778	-25800	12823	15	7	15	15	95.70	0.35	95.35	12	547	47216	47208	47223	47193	47238	47163	47268	15.41
2.03	3363	98	14 Nov 10:24:52.82	39769	-25813	12823	15	7	15	15	95.60	0.20	95.40	12	547	47216	47209	47224	47194	47239	47164	47269	15.41
2.04	3407	141	14 Nov 10:26:40.53	39371	-26393	12840	15	7	15	15	96.40	0.20	96.20	12	547	47228	47221	47236	47206	47251	47176	47281	15.41
2.04	3408	142	14 Nov 10:26:42.97	39362	-26406	12841	15	7	15	15	96.25	0.05	96.20	12	547	47228	47221	47236	47206	47251	47176	47281	15.41
2.04	3409	143	14 Nov 10:26:45.42	39353	-26419	12841	15	7	15	15	96.10	-0.05	96.15	12	547	47228	47220	47235	47205	47250	47175	47280	15.41
2.04	3410	144	14 Nov 10:26:47.87	39344	-26432	12842	15	7	15	15	96.00	-0.15	96.15	12	547	47228	47220	47235	47205	47250	47175	47280	15.42
2.05	3455	188	14 Nov 10:28:38.02	38928	-27018	12859	15	7	15	15	97.15	0.10	97.05	12	547	47241	47234	47248	47219	47263	47189	47293	15.42
2.05	3456	189	14 Nov 10:28:40.47	38918	-27031	12860	15	7	15	15	97.05	0.05	97.00	12	547	47240	47233	47248	47218	47263	47188	47293	15.41
2.05	3457	190	14 Nov 10:28:42.91	38909	-27044	12860	15	7	15	15	96.95	-0.05	97.00	12	547	47240	47233	47248	47218	47263	47188	47293	15.41
2.05	3458	191	14 Nov 10:28:45.36	38900	-27057	12861	15	7	15	15	96.85	-0.15	97.00	12	547	47240	47233	47248	47218	47263	47188	47293	15.41
2.06	3502	234	14 Nov 10:30:33.06	38484	-27623	12878	15	7	15	15	98.45	0.45	98.00	12	547	47255	47248	47263	47233	47278	47203	47308	15.41
2.06	3503	235	14 Nov 10:30:35.51	38474	-27636	12879	15	7	15	15	98.35	0.35	98.00	12	547	47255	47248	47263	47233	47278	47203	47308	15.42
2.06	3504	236	14 Nov 10:30:37.96	38465	-27649	12879	15	7	15	15	98.20	0.25	97.95	12	547	47254	47247	47262	47232	47277	47202	47307	15.41
2.06	3505	237	14 Nov 10:30:40.41	38455	-27662	12879	15	7	15	15	98.05	0.15	97.90	12	547	47254	47246	47261	47231	47276	47201	47306	15.41
2.06	3506	238	14 Nov 10:30:42.86	38446	-27674	12880	15	7	15	15	98.00	0.10	97.90	12	547	47254	47246	47261	47231	47276	47201	47306	15.41
2.07	3550	281	14 Nov 10:32:30.56	38021	-28234	12897	15	7	15	15	99.15	0.25	98.90	12	547	47269	47261	47276	47246	47291	47216	47321	15.42

2.07	3551	282	14 Nov 10:32:33.00	38011	-28246	12898	15	7	15	15	99.00	0.20	98.80	12	547	47267	47260	47275	47245	47290	47215	47320	15.41
2.07	3552	283	14 Nov 10:32:35.45	38001	-28259	12898	15	7	15	15	98.95	0.15	98.80	12	547	47267	47260	47275	47245	47290	47215	47320	15.41
2.07	3553	284	14 Nov 10:32:37.90	37991	-28272	12898	15	7	15	15	98.90	0.10	98.80	12	547	47267	47260	47275	47245	47290	47215	47320	15.41
2.08	3598	328	14 Nov 10:34:28.05	37548	-28836	12916	15	7	15	15	99.95	0.15	99.80	12	547	47282	47275	47290	47260	47305	47230	47335	15.41
2.08	3599	329	14 Nov 10:34:30.50	37538	-28849	12917	15	7	15	15	99.90	0.10	99.80	12	547	47282	47275	47290	47260	47305	47230	47335	15.41
2.08	3600	330	14 Nov 10:34:32.94	37528	-28861	12917	15	7	15	15	99.90	0.10	99.80	12	547	47282	47275	47290	47260	47305	47230	47335	15.41
2.08	3601	331	14 Nov 10:34:35.39	37518	-28874	12917	15	7	15	15	99.85	0.05	99.80	12	547	47282	47275	47290	47260	47305	47230	47335	15.41
2.09	3645	374	14 Nov 10:36:23.09	37076	-29419	12935	15	7	15	15	101.00	0.25	100.75	12	547	47296	47289	47304	47274	47319	47244	47349	15.41
2.09	3646	375	14 Nov 10:36:25.54	37065	-29431	12935	15	7	15	15	101.20	0.30	100.90	12	547	47299	47291	47306	47276	47321	47246	47351	15.41
2.09	3647	376	14 Nov 10:36:27.99	37055	-29443	12936	15	7	15	15	101.40	0.40	101.00	12	547	47300	47293	47308	47278	47323	47248	47353	15.41
2.09	3648	377	14 Nov 10:36:30.44	37045	-29456	12936	15	7	15	15	100.50	-0.45	100.95	12	547	47299	47292	47307	47277	47322	47247	47352	15.41
2.09	3649	378	14 Nov 10:36:32.89	37035	-29468	12936	15	7	15	15	100.60	-0.35	100.95	12	547	47299	47292	47307	47277	47322	47247	47352	15.41
2.10	3693	421	14 Nov 10:38:20.59	36584	-30006	12954	15	7	15	15	102.25	0.35	101.90	12	547	47314	47306	47321	47291	47336	47261	47366	15.41
2.10	3694	422	14 Nov 10:38:23.03	36574	-30018	12954	15	7	15	15	102.40	0.45	101.95	12	547	47314	47307	47322	47292	47337	47262	47367	15.41
2.10	3695	423	14 Nov 10:38:25.48	36563	-30030	12955	15	7	15	15	101.55	-0.40	101.95	12	547	47314	47307	47322	47292	47337	47262	47367	15.41
2.10	3696	424	14 Nov 10:38:27.93	36553	-30042	12955	15	7	15	15	101.70	-0.20	101.90	12	547	47314	47306	47321	47291	47336	47261	47366	15.41
2.11	3741	468	14 Nov 10:40:18.08	36083	-30585	12973	15	7	15	15	102.90	0.10	102.80	12	547	47327	47320	47335	47305	47350	47275	47380	15.41
2.11	3742	469	14 Nov 10:40:20.53	36073	-30596	12973	15	7	15	15	102.95	0.10	102.85	12	547	47328	47320	47335	47305	47350	47275	47380	15.41
2.11	3743	470	14 Nov 10:40:22.98	36062	-30608	12974	15	7	15	15	103.05	0.20	102.85	12	547	47328	47320	47335	47305	47350	47275	47380	15.41
2.11	3744	471	14 Nov 10:40:25.42	36052	-30620	12974	15	7	15	15	103.25	0.30	102.95	12	547	47329	47322	47337	47307	47352	47277	47382	15.41
2.12	3789	515	14 Nov 10:42:15.58	35573	-31155	12992	15	7	15	15	104.00	0.15	103.85	12	547	47343	47335	47350	47320	47365	47290	47395	15.41
2.12	3790	516	14 Nov 10:42:18.02	35563	-31167	12992	15	7	15	15	104.20	0.20	104.00	12	547	47345	47338	47353	47323	47368	47293	47398	15.41
2.12	3791	517	14 Nov 10:42:20.47	35552	-31178	12993	15	7	15	15	104.45	0.35	104.10	12	547	47347	47339	47354	47324	47369	47294	47399	15.41
2.12	3792	518	14 Nov 10:42:22.92	35541	-31190	12993	15	7	15	15	103.65	-0.50	104.15	12	547	47347	47340	47355	47325	47370	47295	47400	15.41
3.01	2312	1	14 Nov 23:42:00.24	27436	-31726	20443	16	12	20	16	227.95	0.15	227.80	11	541	45379	45372	45387	45356	45403	45324	45435	16.39
3.01	2313	2	14 Nov 23:42:02.68	27426	-31735	20443	16	12	20	16	227.65	-0.35	228.00	11	541	45382	45375	45390	45359	45406	45327	45438	16.39
3.01	2314	3	14 Nov 23:42:05.13	27415	-31744	20443	16	12	20	16	227.95	0.15	227.80	11	541	45379	45372	45387	45356	45403	45324	45435	16.39
3.02	2359	47	14 Nov 23:43:55.28	26926	-32145	20461	16	12	20	16	229.85	0.20	229.65	11	541	45407	45400	45415	45384	45431	45352	45463	16.39
3.02	2360	48	14 Nov 23:43:57.73	26915	-32153	20461	16	12	20	16	229.40	0.00	229.40	11	541	45403	45396	45411	45380	45427	45348	45459	16.39
3.02	2361	49	14 Nov 23:44:00.17	26904	-32162	20461	16	12	20	16	229.90	0.30	229.60	11	541	45406	45399	45414	45383	45430	45351	45462	16.39
3.02	2362	50	14 Nov 23:44:02.62	26893	-32171	20462	16	12	20	16	229.55	0.00	229.55	11	541	45406	45398	45413	45382	45429	45350	45461	16.39
3.03	2407	94	14 Nov 23:45:52.77	26398	-32563	20479	16	12	20	16	230.90	-0.35	231.25	11	541	45431	45424	45439	45408	45455	45376	45487	16.39
3.03	2408	95	14 Nov 23:45:55.22	26387	-32572	20479	16	12	20	16	231.55	0.20	231.35	11	541	45433	45425	45440	45409	45456	45377	45488	16.39
3.03	2409	96	14 Nov 23:45:57.67	26375	-32581	20480	16	12	20	16	230.95	-0.05	231.00	11	541	45427	45420	45435	45404	45451	45372	45483	16.39
3.03	2410	97	14 Nov 23:46:00.12	26364	-32589	20480	16	12	20	16	231.80	0.30	231.50	11	541	45435	45427	45442	45411	45458	45379	45490	16.39

Sounding Reference				orbito							Propagation delay										Ranging			
ID	sounding number		UTC time	position			position error rms			rangin g error	Peak position (code step)			Modulo	system delai	in-comet propagation dela y		Equivalent distances (1)			Min / Max ± 1 sigma (2)		Min / Max ± 3 sigma (2)	
	OCN	LCN		x (m)	y (m)	z (m)	Rad. (m)	long (m)	Cros (m)		rms (m)	OCN (step)	LCN (step)			Final (step)	dist. (m)	y (ns)	Rangin g (m)	min (m)	max (m)	min (m)	max (m)	min (m)
measurement throughout the nucleus																								
4.01	9158	9161	12 Nov 18:56:40.26	0	-17	6	6	4	4	6	229.10	0.40	229.50	4	569	793	594	18644	18459	18652	18453	18658	18441	18670
4.01	9159	9162	12 Nov 18:56:42.76	0	-17	6	6	4	4	6	229.00	0.35	229.35	4	569	793	594	18642	18456	18649	18450	18655	18438	18667
4.01	9160	9163	12 Nov 18:56:45.26	0	-17	6	6	4	4	6	229.20	0.45	229.65	4	569	794	595	18646	18461	18654	18455	18660	18443	18672
4.01	9161	9164	12 Nov 18:56:47.76	0	-17	6	6	4	4	6	230.05	-0.45	229.60	4	569	794	595	18646	18460	18653	18454	18659	18442	18671
4.02	9570	9573	12 Nov 19:13:50.35	-2	-17	6	6	4	4	6	4.50	-0.45	4.05	5	570	994	745	19087	18856	19095	18850	19101	18838	19112
4.02	9571	9574	12 Nov 19:13:52.85	-2	-17	6	6	4	4	6	4.50	-0.40	4.10	5	570	994	745	19088	18857	19095	18851	19101	18839	19113
4.02	9572	9575	12 Nov 19:13:55.35	-2	-17	6	6	4	4	6	4.50	-0.40	4.10	5	570	994	745	19088	18857	19095	18851	19101	18839	19113
4.02	9573	9576	12 Nov 19:13:57.85	-2	-17	6	6	4	4	6	4.50	-0.45	4.05	5	570	994	745	19087	18856	19095	18850	19101	18838	19112
5.01	20855	20858	13 Nov 03:04:05.10	1	15	8	5	3	4	5	111.70	-0.25	111.45	4	581	792	594	16873	16687	16880	16682	16885	16673	16895
5.01	20856	20859	13 Nov 03:04:07.59	1	15	8	5	3	4	5	111.70	-0.30	111.40	4	581	792	594	16872	16687	16880	16682	16885	16672	16895
5.01	20857	20860	13 Nov 03:04:10.10	1	15	8	5	3	4	5	111.70	-0.25	111.45	4	581	791	593	16873	16688	16880	16683	16885	16673	16895
5.01	20858	20861	13 Nov 03:04:12.60	1	15	8	5	3	4	5	111.70	-0.35	111.35	4	581	790	592	16871	16686	16879	16681	16884	16671	16894
5.02	22315	22318	13 Nov 04:04:55.39	7	13	8	5	3	4	5	82.65	0.45	83.10	4	580	327	245	16448	16367	16456	16362	16461	16352	16471
5.02	22316	22319	13 Nov 04:04:57.89	7	13	8	5	3	4	5	82.60	0.50	83.10	4	580	327	245	16448	16367	16456	16362	16461	16352	16471
5.02	22317	22320	13 Nov 04:05:00.39	7	13	8	5	3	4	5	82.55	0.50	83.05	4	580	327	245	16447	16366	16455	16361	16460	16351	16470
5.02	22318	22321	13 Nov 04:05:02.89	7	13	8	5	3	4	5	82.55	-0.45	82.10	4	580	326	244	16433	16352	16441	16347	16446	16337	16456

(1) Distance calculated from the propagation delay. Min and Max distances take into account the error in the delay measurement and the additional delay due to the propagation throughout the nucleus (if needed). Not taken into account orbitography errors.

(2) Min and max values as done from previous colon (1) and the the orbitography RMS error.

(3) total RMS error taking into account the orbitography errors and the delay estimation error. Not relevant for signals propagated throughout the nucleus

Fig. 1: Lander synchronization principle (from Kofman et al., 2007)

Fig. 2: Examples of measured and interpolated signals

Fig. 3: In color, constraint introduced by each of the measurement sequences, taking into account the measurement and orbitography error at 1 sigma (green: sequence 1; yellow: sequence 2; blue: sequence 3) . In grey constraint introduced by the measurement in transmission through the comet

Fig. 4: 3D location of Philae: the volume is bounded by min/max plus ± 1 sigma (orbitography), and includes measurements through 67P (coordinates given Table 2)

Fig. 5: Projected location of Philae on the surface of 67P

- Green polygon: boundaries of zone based on line of sight measurements min/max ± 1 sigma. In dark green: min/max distance ± 3 sigma.
- Blue polygon: boundaries of zone based on propagation through the comet measurements. Light blue: at a maximum of 325 m and ± 3 sigma. Dark blue: at a maximum of 1000 m and ± 3 sigma.
- Red ellipse: zone with RMS error below 1.0.
- Purple circle: estimated zone based on the inversion of permittivity and position (Kofman et al., 2015).
- Yellow zone: possible position of the lander taking into account all measurements (Dimensions are 22.5 x 106.5 m)
- Orange zone: the most likely estimate (Dimensions are 22.6 x 41.5 m)