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Invited Paper

Attitude reconstruction of ROSETTA's Lander PHILAE using two-point magnetic field observations by ROMAP and RPC-MAG

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A B S T R A C T

As part of the European Space Agency's ROSETTA Mission the Lander PHILAE touched down on comet 67P/Churyumov–Gerasimenko on November 12, 2014. The magnetic field has been measured onboard the orbiter and the lander. The orbiter's tri-axial fluxgate magnetometer RPC-MAG is one of five sensors of the ROSETTA Plasma Consortium. The lander is also equipped with a tri-axial fluxgate magnetometer as part of the ROSETTA Lander Magnetometer and Plasma-Monitor package (ROMAP). This unique setup makes a two point measurement between the two spacecrafts in a relatively small distance of less than 50 km possible. Both magnetometers were switched on during the entire descent, the initial touchdown, the bouncing between the touchdowns and after the final touch-down. We describe a method for attitude determination by correlating magnetic low-frequency waves, which was tested under different conditions and finally used to reconstruct PHILAE's attitude during descent and after landing. In these cases the attitude could be determined with an accuracy of better than $\pm 5^{\circ}$. These results were essential not only for PHILAE operations planning but also for the analysis of the obtained scientific data, because nominal sources for this information, like solar panel currents and camera pictures could not provide sufficient information due to the unexpected landing position.

1. Introduction

The release of the Lander PHILAE [1] to the cometary surface was one of the major scientific and technical achievements of the ROSETTA Mission [2]. Onboard of both, orbiter [3] and lander [4], fluxgate magnetometers measured the ambient magnetic field for investigating the plasma environment and magnetization of comet 67P/Churyumov–Gerasimenko (67P). Because PHILAE is not equipped with dedicated navigation instruments, its position and attitude during the Descent and Landing Phase (SDL) and First Science Sequence (FSS) must be reconstructed using results from the scientific instruments. Nominally this should have been done using CIVA [5] panoramic images and an analysis of the

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different solar panel currents [6] together with CONSERT [7] ranging results. Unfortunately, the conditions for attitude determination during both, SDL and FSS were more complex than anticipated. Due to a malfunction of its harpoons, PHILAE bounced three times after the first touchdown before coming to a final rest [8,9]. At the final landing site, illumination conditions were worse than expected for the nominal landing site, as only for about two hours of day light per cometary day three out of six solar panels were illuminated and generated power [10]. Hence insufficient information for attitude reconstruction, based solely on solar panel currents, was available [6]. As CIVA images [9] clearly indicate, PHILAE was tilted towards the comet surface after the final touchdown and some of the cameras were pointing away from the comet. It was therefore not possible to identify landmarks on any of the CIVA images, that could reliably be used for attitude reconstruction. Based on PHILAE's self shadow it was only possible to estimate the solar position above the comet for the specific time the images were taken, which was not sufficient for complete attitude determination. [6] The tri-axial fluxgate magnetometer of the ROSETTA Lander Magnetometer and Plasma Monitor package (ROMAP) [4] as well as the two tri-axial fluxgate magnetometers from the ROSETTA Plasma Consortium (RPC-MAG) [2] were switched on during SDL and the first part of the FSS, which gave the unique opportunity to use the combined results from both experiments to reconstruct the attitude by magnetic field measurements. This method was initially only intended as a possible backup approach to the above-mentioned options. Actually, the presence of band-limited low-frequency magnetic field oscillations [11] strongly enhanced the possibility to use combined measurements to determine PHILAE's attitude successfully. In contrast to the unfavorable conditions for the two primary methods, conditions for attitude determination by magnetic field comparison were thus much better than anticipated. Therefore, the former backup option, using the comparison of magnetic field variations onboard the orbiter and lander became the primary method for attitude determination. The details of this method and its results are described below.

2. Attitude reconstruction: the method

Attitude reconstruction as presented here is based on correlating magnetic field vector measurements made at the same time at two different points in space, assuming the magnetic field conditions are nearly identical at both locations. If the attitude of the magnetic field sensor at point P is known, but unknown at position Q, then the unknown attitude at point Q can be determined by rotating the sensor coordinate system at Q in such a way that the correlation coefficient between time series of the magnetic field components at Q maximizes with that one at P. Let $\underline{B}_P$ and $\underline{B}'_Q$ be the measured vectors at P and Q respectively and $\underline{B}_Q$ the field vector at location Q after rotation, that is

$$\underline{B}_Q = \underline{\underline{M}} \cdot \underline{B}'_Q \tag{1}$$

with the matrix

$$\underline{\underline{M}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & -\sin(\alpha) \\ 0 & \sin(\alpha) & \cos(\alpha) \end{pmatrix} \begin{pmatrix} \cos(\beta) & 0 & \sin(\beta) \\ 0 & 1 & 0 \\ -\sin(\beta) & 0 & \cos(\beta) \end{pmatrix} \begin{pmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

denoting the rotation matrix constructed from the Euler angles α, β, and γ. To reconstruct the attitude of the magnetometer at Q relative to the attitude of the reference magnetometer at P, $\underline{\underline{M}}$ has to be determined in such a way that the correlation coefficient between all components, defined as

$$\bar{\rho} = \frac{1}{3}\left(\frac{\mathrm{Cov}(\underline{B}_{X,Q}, \underline{B}_{X,P})}{\sigma(\underline{B}_{X,Q})\sigma(\underline{B}_{X,P})} + \frac{\mathrm{Cov}(\underline{B}_{Y,Q}, \underline{B}_{Y,P})}{\sigma(\underline{B}_{Y,Q})\sigma(\underline{B}_{Y,P})} + \frac{\mathrm{Cov}(\underline{B}_{Z,Q}, \underline{B}_{Z,P})}{\sigma(\underline{B}_{Z,Q})\sigma(\underline{B}_{Z,P})}\right) \tag{3}$$

where $\mathrm{Cov}(X)$ denotes the covariance of X and $\sigma(X)$ the standard deviation of X, is maximized. This can either be done by solving the extremum problem analytically or by discretizing the angles and for instance using an exhaustive brute force approach to find the angles corresponding to the maximum correlation. Among the two methods described above, the latter was chosen, as it gives the correlation coefficient for each individual angle and allows a detailed analysis of the sensitivity of the tool relative to changes in the individual Euler angles.

As this approach is based on correlating variations in the magnetic field, a prerequisite for this method is a sufficient signal to noise ratio, so that field fluctuations can clearly be separated from the background field and any external interference for example caused by spacecraft (s/c) operations and the noise floor of the instruments which is typically around $10\ \mathrm{pT}/\sqrt{\mathrm{Hz}}$. In addition the field variations have to be clearly detectable at both locations simultaneously. Thus our method is only applicable if a clear fluctuating signal is present. This implies either a sufficiently strong background magnetic field such as a planetary magnetic field or predominating magnetic field fluctuations. When this method is applied to observations in the interplanetary medium, the interplanetary background magnetic field, close to 67P at 3 AU is not sufficiently strong [12] to apply the suggested attitude reconstruction tool, as solar wind fluctuations are smaller than approximately 2 nT [11]. Fortunately upon arrival of the ROSETTA spacecraft in August 2014 at 67P, low frequency waves in the range of 30–50 mHz with amplitudes of ~ 5 nT caused by the solar wind – comet interaction dominated the magnetic-field measurements of the RPC-MAG [11] and ROMAP instruments. An example of these oscillations observed on October 17, 2014 is presented in Fig. 1. This clear signal provides for a most suitable situation to apply our method to RPC-MAG and ROMAP data.

As the set of available observations was much larger than initially anticipated and necessary for attitude reconstruction, it was only possible to select the most suitable intervals. This was done based on whether the fluctuations described above were clearly detectable in the individual intervals. To accomplish this, the magnitude