Determination of Variometer Alignment by using Variation Comparison with DI3-Flux

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ABSTRACT

By comparing magnetic field variations measured by two separate magnetometers the alignment of the individual axis of one of these magnetometers can be determined relative to the other one. The motivation for this analysis was to determine the attitude of the magnetometer equipped lander "PHILAE" on the surface of Comet 67P/Churyumov-Gerasimenko with respect to the mother spacecraft, the ESA satellite ROSETTA. The algorithm has been tested in the geomagnetic observatory at Niemegk. The DI3-Flux method for absolute measurement was used in this case, to predetermine the orientation of a three component reference magnetometer within the geographic reference system with an accuracy much better than 1 arcmin. After performing the absolute measurement the three component reference fluxgate magnetometer (s). A correlation analysis then allows the determination of all six angles of misalignment (non-orthogonality and orientation) of the observatory variometer with respect to the DI3 system by comparing both measurements. We discuss the algorithm and limitation of this method. We show that all variometer alignment errors can be determined with an accuracy of better than 0.1°.

Keywords: Variometer, Magnetometer, Alignment, Variation, Comparison.

INTRODUCTION

The initial motivation for the development of a method to determine the orientation of a three axis magnetometer relative to a reference magnetometer came from the ESA ROSETTA mission (*Glassmeier et al., 2007a*). As part of this mission the lander PHILAE was released to comet 67P/Churyumov-Gerasimenko. This lander as well as the orbiter is equipped with fluxgate magnetometers to measure the ambient magnetic field and for investigating the plasma environment and magnetization of the comet and its tail.

Because PHILAE is not equipped with dedicated navigation instruments, the position and attitude during the Descent and Landing Phase (SDL) and after touchdown must be reconstructed using results from scientific instruments. The tri-axial fluxgate magnetometer of the Rosetta Lander Magnetometer and Plasma Monitor package (ROMAP) (*Auster et al., 2007*) as well as the two tri-axial fluxgate magnetometers from the Rosetta Plasma Consortium (RPC-MAG) (*Glassmeier et al., 2007b*), were all switched on during these phases, which gave the unique ability to use the combined results from both experiments to reconstruct the attitude by magnetic field measurements.

Therefore an algorithm for determining these mission critical parameters from the magnetic field measurements was to be developed and initial ground tests should provide the necessary expertise for applying a similar method under the harsh conditions of the ROSETTA mission. Additionally the determination of observatory variometer alignment errors, even if not specified explicitly in the observatory standards (*Jankowski and Sucksdorff, 1996*), might be of interest, especially for instruments, which cannot be recalibrated in external calibration facilities, because they are impossible to replace once installed, without interrupting the observatory baseline.

ALIGNMENT DETERMINATION PROCESS

The alignment of the variometer axis is determined by comparing the three dimensional spatial orientation of low frequency variations in the earth's magnetic field with observations of a reference variometer with known axis alignment. Using low frequency variations instead of a DC signal has the advantage that measurement errors caused by offsets can be neglected. Scale factor and non-orthogonality errors are below 10^{-4} and therefore considerably lower than the ratio between signal (about 10 nT) and resolution (10 pT).

To ensure the process is not influenced by sensor temperature dependence or sensor noise, very low frequencies in the range of the daily magnetic field changes had to be excluded. Higher frequencies were also not usable, because the signal periods are too short and therefore, depending on the sampling rate, not enough data points are available for accurate comparison.

The alignment reconstruction process for the variometer x-axis is illustrated as an example in Figure



Figure 1. Illustration of the alignment reconstruction process exemplarily shown for the x-axis.

1. To determine the axis alignment the signal from each component is numerically rotated around the two other perpendicular components. Afterwards the signal from the axis that is used as reference is subtracted from the unknown axis' signal. The correlation coefficients between this difference signal and the remaining two perpendicular reference components are then minimized by continuously rotating to reconstruct the alignment. This way all six angles describing the orientation and orthogonality error of the unknown variometer can be determined.

Depending on the magnetic background conditions and the field activity, the length of the input signal necessary for this method, ranges from about 30 minutes to 14 hours. Using even longer intervals has no further advantages, as temperature effects limit the accuracy and the additional data leads to no significant increase in statistical significance.

As the algorithm depends on comparing low frequency variations, the accuracy of the results depend mostly on the level of variance in the magnetic field, which can be quantified by the standard deviation of the signal. Since signal variance alone is not a sufficient criterion for accurate alignment reconstruction, because the fluctuations could be caused by local interference, the correlation coefficients between the absolute values of both input signals were considered, too. To get a quality parameter, the mean standard deviations for the components are weighted with the correlation coefficient between the absolute values.

To further check the results, the alignment results can be used to rotate the data from the variometer with unknown alignment into the coordinate system of the reference variometer. The correlation coefficients between the individual components before and after rotation can then be compared to get an estimate of the quality of the results.

MEASUREMENTS PERFORMED AT NIEMEGK OBSERVATORY

The process described above was applied to the two Niemegk observatory variometers "Ng0" and "Ms0" relative to a reference variometer using the DI3-Flux setup [Hemshorn et al., 2009]. As only the main observatory variometer Ng0 is in a climate controlled environment, the Ms0 and reference variometer are subject to daily temperature variations which had to be taken into account by filtering ultra-low frequency variations from the signals, as discussed above.

In total 10 days of data observed from 23.01.2014 until



Figure 2. 10-day raw input dataset for the two Niemegk variometers "Ms0" and "Ng0" and the reference variometer "Ref". Ms0 and Ng0 were shifted by 6nT and 4nT respectively for better visibility.



Figure 3. Dynamic coherence spectra between the reference variometer and Ng0 signal. Each interval has a length of 14h with an overlap of 7h.

01.02.2014 were used, as shown in Figure 2, even though much less would have been sufficient. This way it was possible to separate the entire dataset into smaller intervals of about 14h, which were then individually processed. This way it was possible to exclude intervals with strong external interference and use a statistical approach for error determination.

In the next step, a band-pass filter was used to remove frequency components not suitable for alignment reconstruction, as described above.

The dynamic coherence spectra for the three components of the Ng0 and reference variometer shown in Figure 3



Figure 4. Mean correlation coefficient between the Ng0 *z*-axis differences and the x- and y-components depending on the corresponding rotation angles. The alignment result is given by the minimum in the middle.



Figure 5. X-Axis alignment results for the NgO variometer, the blue lines denotes the y-axis rotation and black the z-axis rotation. The corresponding mean values are indicated by the two lines. The color coded background illustrates the data quality.

shows clear differences in the presentations of coherent wave activity. Especially around the 24th and the 28th of January strong coherent waves with a maximum frequency of 0.06Hz were detected, which is in the range of Pc3 and Pc4 pulsations. To reduce the impact of local interferences and noise, frequencies above this threshold were removed by filtering the signals. Because coherent structures in the z-component are as expected not as frequent as in the other two components, the error of this method for the z-axis alignment is bigger than for the x- and y-components.

The intermediate results are shown for one of the intervals of the Ng0 *z*-axis in Figure 4. As shown in Figure 1 the algorithm determines the minimum of the mean correlation coefficient between, in this case the Ng0 *z*-axis differences and the reference variometer x- and y-components, depending on the corresponding rotation angles to reconstruct the alignment. This sharp minimum is clearly visible in Figure 3 as the mean correlation

	Ng0	Ms0
Ortogonality X/Y	0.00°	0.00°
Ortogonality X/Z	0.02°	0.00°
Ortogonality Y/Z	0.03°	0.02°
Orientation X vs. vertical axis	0.02°	-0.06°
Orientation Y vs. vertical axis	0.01°	0.04°
Orientation Z vs. geogr. north	-0,18° (w)	2,72° (e)

Table 1: Mean alignment results for Ng0 and Ms0 using individual 14h intervals.

decreases to zero in the middle of the figure. The process is done for all three axes to determine all six alignment angles and then repeated for all of the individual intervals.

The final Ng0 alignment results for the individual intervals are shown for the x-axis as an example in Figure 5. The color coded background indicates the data quality, as discussed above.

The mean alignment results for all intervals and both variometers are shown in table 1. Orthogonality errors of the observatory variometers as well as errors in the alignment versus horizontal plane are very small. The orientation within the horizontal plane depends on the time of variometer installation. Thus the results are in the expected range and validate that the proposed method is applicable for the determination of the axis orientation.

CONCLUSION

Using the presented method, it was possible to verify variometer orientation with accuracies better than 0.1° using the DI3-Flux setup. Applied to both Niemegk observatory variometers the orthogonality and vertical alignment errors were determined to be below 0.1°. The alignment in the horizontal plane is 0.18° (w) for NG0 and 2.72 (e) for MS0. Thus by using the DI3-flux absolute measurement this method can be offered for orientation verification for observatory variometers without interrupting the continuous data acquisition process.

As intended, an algorithm derived from this method was used very successfully to reconstruct the attitude of the ROSETTA PHILAE lander on the surface of comet 67P/ Churyumov-Gerasimenko, using concurrent magnetic field observations by the orbiter magnetometer RPC-MAG and the lander magnetometer ROMAP with an accuracy better than 15° (*Heinisch et al., 2015*). The results were not only used for scientific analyses (*Auster et al., 2015*), but also to narrow down the possible landing sites and as input for the prediction of the possible communication slots, which were used to reestablish contact with PHILAE in June 2015.

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