Spin axis offset calibration on THEMIS using mirror modes

Dennis Frühauff1, Ferdinand Plaschke2, and Karl-Heinz Glassmeier1
1Institut für Geophysik und extraterrestrische Physik, Braunschweig, Germany
2Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Correspondence to: Dennis Frühauff (d.fruehauff@tu-bs.de)

Received: 28 November 2016 – Revised: 6 January 2017 – Accepted: 6 January 2017 – Published: 19 January 2017

Abstract. A newly developed method for determining spin axis offsets of magnetic field instruments on spacecraft is applied to THEMIS. The formerly used determination method, relying on solar wind Alfvénic fluctuations, was rarely applicable due to the orbital restrictions of the mission. With the new procedure, based on magnetic field observation of mirror modes in the magnetosheath, updated spin axis offsets can be estimated approximately once per year. Retrospective calibration of all THEMIS magnetic field measurements is thereby made possible. Since, up to this point, spin axis offsets could hardly ever be calculated due to the mission’s orbits, this update represents a substantial improvement to the data. The approximate offset stability is estimated to be \(< 0.75 \text{nT year}^{-1}\) for the complete course of the mission.

Keywords. Magnetospheric physics (magnetosheath; MHD waves and instabilities; planetary magnetospheres)

1 Introduction

Accurate in-flight calibration of magnetic field instruments has always been an important prerequisite in space physics. On ground, proper calibration can be easily realized using defined reference setups. In space, reference fields are rarely available and additional disturbances and non-stationary magnetic field profiles make calibration difficult. In case of a spinning spacecraft, such as CLUSTER (Balogh et al., 1997), THEMIS (Auster et al., 2008), and MMS (Russell et al., 2016), the calibration of components perpendicular to the spin axis can be performed to a very high degree of accuracy. The determination of the spin axis component’s offset, though, suffers from the aforementioned difficulties. Obviously, the situation is the same for three-axis-stabilized spacecraft, such as Rosetta (Glassmeier et al., 2007) and, prospectively, BepiColombo’s Mercury Planetary Orbiter (MPO) (Glassmeier et al., 2010). So far, only few methods have been developed to determine fixed-axis component offsets. Among these are the Hedgecock method (i.e., calibration using Alfvénic fluctuations in the solar wind; see Hedgecock, 1975, and Leinweber et al., 2008) and the electron drift method (Plaschke et al., 2014; Nakamura et al., 2014). The first method requires the presence of solar wind measurements, while the latter needs an electron drift instrument aboard the probe.

The THEMIS (Time History of Events and Macroscale Interactions During Substorms) (Angelopoulos, 2008) and ARTEMIS (Acceleration, Reconnection, Turbulence, and Electrodynamics of the Moon’s Interaction with the Sun) (Angelopoulos, 2011) missions consist of a total of five identical spinning spacecraft, of which none features electron drift instruments. Therefore, calibration of the spin axis components has been consistently possible only for the two probes orbiting the Moon (spacecraft THB and THC), since the solar wind is seen very frequently and calibration through the detection of Alfvénic waves is possible. Figure 1 shows the behavior the spin axis offset since the beginning of the scientific mission in 2008. The ARTEMIS probes (lower panel) were monthly calibrated using solar wind data. The Earth-orbiting satellites (probes THA, THD, and THE) were only calibrated occasionally, with only one calibration instance during the last 5 years of the mission. While probes THB and THC show an offset stability of around 0.1 nT year\(^{-1}\), it is likely that the other probes face larger offset drifts. Due to their orbits, the spacecraft are exposed to stronger temperature changes and enhanced radiation in the Van Allen belts, advancing the sensors’ and electronics’ aging processes (THA, THD, THE). These effects are currently not incorporated in the routine instrument calibration procedures. The reason for the nonavailability of solar wind
encounters can be attributed to the probes’ orbits. Figure 2 illustrates the range of maximum X distance of the probes on the Earth–Sun line (i.e., in geocentric solar ecliptic coordinates, GSE). Using a simple model for magnetopause and bow shock position on the Earth–Sun line (Nabert et al., 2013), and smoothed solar wind data from OMNI database the magnetospheric coverage upstream Earth can be visualized. On average, the three THEMIS probes have never seen solar wind data. Of course, variations on shorter timescales might have occasionally pushed the magnetospheric boundaries inwards, thereby making a few short calibration intervals possible. In total, though, offset determination using solar wind methods is not an adequate method for probes orbiting only inside the magnetosphere.

Recently, Plaschke and Narita (2016) have presented a method using mirror mode observations during magnetosheath passages. Figure 2 also indicates that sheath encounters are much more likely than solar wind observations. Therefore, the mirror mode method appears to be a good candidate to catch up on spin axis offset calibrations for THEMIS.

2 Brief summary of the mirror mode method

The mirror mode method is based on the assumption that mirror modes are highly compressible fluctuations (Price et al., 1986; Tsurutani et al., 2011). Consequently, the direction of maximum variance (Sonnerup and Scheible, 1998) is expected to be parallel to the mean magnetic field direction. If analyzed in a non-rotating, spin-axis-oriented coordinate system, this assumption leads to an equation containing the remaining spin axis offset. The method is outlined in detail in Plaschke and Narita (2016). It consists of four basic steps:

1. Identify magnetosheath passages using THEMIS data from the electrostatic analyzer (ESA) at ≈ 3 s resolution (McFadden et al., 2008) and OMNI solar wind density data (Plaschke et al., 2013).

2. For each subinterval, calculate an estimate for the spin axis offset, \( O_x \), and its uncertainty, \( \Delta O_x \), using maximum variance analysis and the equations presented in Plaschke and Narita (2016).

3. Since not all of the subintervals represent mirror mode structures, select those fulfilling the criteria and thresholds in Price et al. (1986), Plaschke et al. (2014), and Schmid et al. (2014).

4. For all remaining offset estimates within a certain interval (e.g., a month, a science phase), calculate an estimate for the final spin axis offset, \( O_x \), using a kernel density estimator (KDE) with a Gaussian kernel (Parzen, 1962; Botev et al., 2010). This final offset will be the value for which the probability density function maximizes. Since the selection of data points is influenced by the magnetic field measurements, and, hence, their offset value, an iterative repetition of these steps is necessary until the method converges to a final estimate.

To enhance the accuracy of the KDE method, we have incorporated weights, \( w_i \), for each measurement computed from their uncertainties, \( \Delta O_x \):

\[
w_i = \exp\left(\frac{-(\Delta O_x)^2}{2\sigma^2}\right),
\]

where the width of the error distribution function, \( \sigma \), is determined by the maximum of the probability density distribution of all \( \Delta O_x \). The probability density distribution for...
the offsets, $O_{zi}$, is then computed as

$$P(\bar{O}_z) = \frac{1}{\sqrt{2\pi Nh}} \sum_{i=1}^{N} w_i \exp\left(-\frac{(\bar{O}_z - O_{zi})^2}{2h^2}\right),$$

with the number of observations, $N$, and the bandwidth, $h$, which is determined adaptively by the procedure (see, e.g., Botev et al., 2010). An example distribution is shown in Fig. 3. Plaschke and Narita (2016) used uniform weights and a fixed bandwidth of $h = 1$ nT. For comparison, the resulting density functions for both the unweighted and weighted calculations are shown. While the differences in the maximum position are generally small, the THEMIS data have shown that the use of individual weights and an auto-determined bandwidth can severely influence the offset calculations:

1. The weight distribution prevents the algorithm from repetitively micro-adjusting the result to nonphysically large values.
2. Through the adaptive bandwidth the overall shape of the distribution is improved, thereby especially pronouncing the maximum, making the position estimate more accurate.

3 Results and discussion

The identification of magnetosheath encounters results in a database visualized in Fig. 4. For the three THEMIS probes it can be seen that the major part of the observations will be made when the spacecraft are in their dayside conjunction (Angelopoulos, 2008). As a comparison, the number of possible observations for the two ARTEMIS probes is shown in the lower panel. Obviously, in the first 2 years of the mission, when the spacecraft were still in orbit around Earth, a fair amount of data is available (yet, THB and THC did also see solar wind due to their greater apogee distance). Then, when lifted into orbit around the Moon, the probes only rarely encountered mirror modes in the Earth’s magnetosheath.

As a first criterion intervals are selected when the probes’ apogee projection onto the $X$–$Y$ plane (in GSE coordinates) is not more than 30° away from the Earth–Sun line: the spacecraft are in a subsolar region where mirror mode observations are expected to be observed frequently (Price et al., 1986). These intervals are depicted by the black lines in Fig. 4.

From Fig. 4 the following strategy for implementing new spin axis offsets can be deduced:

- For probes THA, THD, and THE a new $O_{zf}$ will be estimated for all data during each of the aforementioned intervals. This will lead to a single updated spin axis offset value approximately once per year. The determined value will be kept constant until a new estimate is available.
- Spacecraft THB and THC did and still do see solar wind frequently. To prevent any discontinuity in the determination method, these two probes will continue to be calibrated using solar wind data (Leinweber et al., 2008).

The complete set of results is displayed in Fig. 5. For spacecraft THA, THD, and THE the new spin axis offsets are shown together with the past results from spurious solar wind calibrations. As suspected earlier, the total offset drift of the three Earth-orbiting probes is stronger than the offset drift of THB and THC. The overall drift is in the range of 0.5–0.75 nT year$^{-1}$ while each of the probes show a similar trend.
Acknowledgement. We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission – specifically, C. W. Carlson and J. P. McFadden for use of ESA data. This project is financially supported by the German Ministerium für Wirtschaft und Energie and the Deutsches Zentrum für Luft- und Raumfahrt under contract 50 OC 1403.

The topical editor, Y. Miyoshi, thanks A. Matsuoka and C. Nakamura, R., Plaschke, F., Teubenbacher, R., Giner, L., Baumjohann, W., Magnes, W., Aydogar, O., Baumjohann, W., Constantinescu, D., Fischer, D., Fornaon, K. H., Georgescu, E., Harvey, P., Hillenmaier, O., Kroth, R., Ludlam, M., Narita, Y., Nakamura, R., Okrafka, K., Plaschke, F., Richter, I., Schwarzl, H., Stoll, B., Valavanoglou, A., and Wiedemann, M.: The THEMIS Fluxgate Magnetometer, Space Sci. Rev., 141, 235–264, doi:10.1007/s11214-008-9365-9, 2008.

Balogh, A., Dunlop, M. W., Cowley, S. W. H., Southwood, D. J., Thomlinson, J. G., Glassmeier, K. H., Musmann, G., Lühr, H., Buchert, S., Acuna, M. H., Fairfield, D. H., Slavin, J. A., Riedler, W., Schwingenschuh, K., and Kivelson, M. G.: The Cluster Magnetic Field Investigation, Space Sci. Rev., 79, 65–91, doi:10.1023/A:1004970907748, 1997.

Botev, Z. I., Grotowski, J. F., and Kroese, D. P.: Kernel density estimation via diffusion, ArXiv e-prints, doi:10.1214/10-AOS799, 2010.

Glassmeier, K.-H., Boehnhardt, H., Koschny, D., Küht, E., and Richter, I.: The Rosetta Mission: Flying Towards the Origin of the Solar System, Space Sci. Rev., 128, 1–21, doi:10.1007/s11214-006-9140-8, 2007.

Glassmeier, K.-H., Auster, H.-U., Heyner, D., Okrafka, K., Carr, C., Berghofer, G., Anderson, B. J., Balogh, A., Baumjohann, W., Cargill, P., Christensen, U., Delva, M., Dougherty, M., Fornaon, K.-H., Horbury, T. S., Lucek, E. A., Magnes, W., Mandea, M., Matsuoka, A., Matsushima, M., Motsschmann, U., Nakamura, R., Narita, Y., O’Brien, H., Richter, I., Schwingenschuh, K., Shibuya, H., Slavin, J. A., Sotin, C., Stoll, B., Tsunakawa, H., Vennerstrom, S., Vogt, J., and Zhang, T.: The fluxgate magnetometer of the BepiColombo Mercury Planetary Orbiter, Planet. Space Sci., 58, 287–299, doi:10.1016/j.pss.2008.06.018, 2010.

Hedgcock, P. C.: A correlation technique for magnetometer zero level determination, Space Science Instrumentation, 1, 83–90, 1975.

Leinweber, H. K., Russell, C. T., Torkar, K., Zhang, T. L., and Angelopoulos, V.: An advanced approach to finding magnetometer zero levels in the interplanetary magnetic field, Measurement Science and Technology, 19, 055104, doi:10.1088/0957-0233/19/5/055104, 2008.

McFadden, J. P., Carlson, C. W., Larson, D., Ludlam, M., Abiad, R., Elliott, B., Turin, P., Marckwordt, M., and Angelopoulos, V.: The THEMIS ESA Plasma Instrument and In-flight Calibration, Space Sci. Rev., 141, 277–302, doi:10.1007/s11214-008-9440-2, 2008.

Nabert, C., Glassmeier, K.-H., and Plaschke, F.: A new method for solving the MHD equations in the magnetosheath, Ann. Geophys., 31, 419–437, doi:10.5194/angeo-31-419-2013, 2013.

Nakamura, R., Plaschke, F., Teubenbacher, R., Giner, L., Baumjoann, W., Magnes, W., Steller, M., Torbert, R. B., Vaith, H., Chutter, M., Fornaon, K.-H., Glassmeier, K.-H., and Carr, C.: Interinstrument calibration using magnetic field data from the fluxgate magnetometer (FGM) and electron drift instrument (EDI) onboard Cluster, Geosci. Instrum. Method. Data Syst., 3, 1–11, doi:10.5194/gi-3-1-2014, 2014.

Ann. Geophys., 35, 117–121, 2017

We acknowledge NASA contract NAS5-02099 and V. Angelopoulos for use of data from the THEMIS Mission – specifically, C. W. Carlson and J. P. McFadden for use of ESA data. This project is financially supported by the German Ministerium für Wirtschaft und Energie and the Deutsches Zentrum für Luft- und Raumfahrt under contract 50 OC 1403.

The topical editor, Y. Miyoshi, thanks A. Matsuoka and C. Smith for help in evaluating this paper.
Parzen, E.: On Estimation of a Probability Density Function and Mode, Ann. Math. Stat., 33, 1065–1076, doi:10.1214/aoms/1177704472, 1962.

Plaschke, F., and Narita, Y.: On determining fluxgate magnetometer spin axis offsets from mirror mode observations, Ann. Geophys., 34, 759–766, doi:10.5194/angeo-34-759-2016, 2016.

Plaschke, F., Hietala, H., and Angelopoulos, V.: Anti-sunward high-speed jets in the subsolar magnetosheath, Ann. Geophys., 31, 1877–1889, doi:10.5194/angeo-31-1877-2013, 2013.

Plaschke, F., Nakamura, R., Leinweber, H. K., Chutter, M., Vaith, H., Baumjohann, W., Steller, M., and Magnes, W.: Flux-gate magnetometer spin axis offset calibration using the electron drift instrument, Measurement Science and Technology, 25, 105008, doi:10.1088/0957-0233/25/10/105008, 2014.

Price, C. P., Swift, D. W., and Lee, L.-C.: Numerical simulation of nonoscillatory mirror waves at the earth’s magnetosheath, J. Geophys. Res.-Space, 91, 101–112, doi:10.1029/JA091iA01p00101, 1986.

Russell, C. T., Anderson, B. J., Baumjohann, W., Bromund, K. R., Dearborn, D., Fischer, D., Le, G., Leinweber, H. K., Leneman, D., Magnes, W., Means, J. D., Moldwin, M. B., Nakamura, R., Pierce, D., Plaschke, F., Rowe, K. M., Slavin, J. A., Strange-way, R. J., Torbert, R., Hagen, C., Jernej, I., Valavanoglou, A., and Richter, I.: The Magnetospheric Multiscale Magnetometers, Space Sci. Rev., 199, 189–256, doi:10.1007/s11214-014-0057-3, 2016.

Schmid, D., Volwerk, M., Plaschke, F., Vörös, Z., Zhang, T. L., Baumjohann, W., and Narita, Y.: Mirror mode structures near Venus and Comet P/Halley, Ann. Geophys., 32, 651–657, doi:10.5194/angeo-32-651-2014, 2014.

Sonnerup, B. U. Ö. and Scheible, M.: Minimum and Maximum Variance Analysis, ISSI Scientific Reports Series, 1, 185–220, 1998.

Tsurutani, B. T., Lakhina, G. S., Verkhoglyadova, O. P., Echer, E., Guarnieri, F. L., Narita, Y., and Constantinescu, D. O.: Magnetosheath and heliosheath mirror mode structures, interplanetary magnetic decreases, and linear magnetic decreases: Differences and distinguishing features, J. Geophys. Res.-Space, 116, A02103, doi:10.1029/2010JA015913, 2011.