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Spin axis offset calibration on THEMIS using mirror modes

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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 $< 0.75\,\mathrm{nT\,year^{-1}}$ 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 $0.1\,\mathrm{nT\,year^{-1}}$, 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

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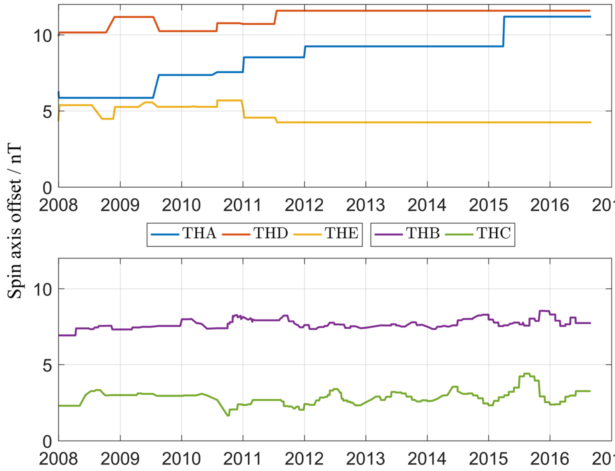

Figure 1. Offset stability of THEMIS (upper panel) and ARTEMIS (lower panel) for the complete mission. After 2012 no updates on the spin axis offsets were calculated but for a single occasion on THA in 2015.

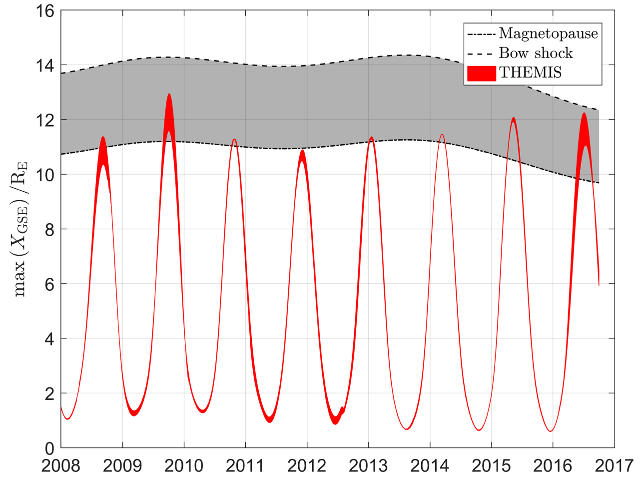

Figure 2. THEMIS (THA, THD, THE) GSE-X distance upstream Earth and magnetopause and bow shock models. The magnetosheath is shaded gray.

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_{zi}, and its uncertainty, ΔO_{zi}, 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_{zf}, 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, ΔO_{zi}:

$$w_i = \exp\left(\frac{-(\Delta O_{zi})^2}{2\sigma^2}\right), \tag{1}$$

where the width of the error distribution function, σ, is determined by the maximum of the probability density distribution of all ΔO_{zi}. The probability density distribution for

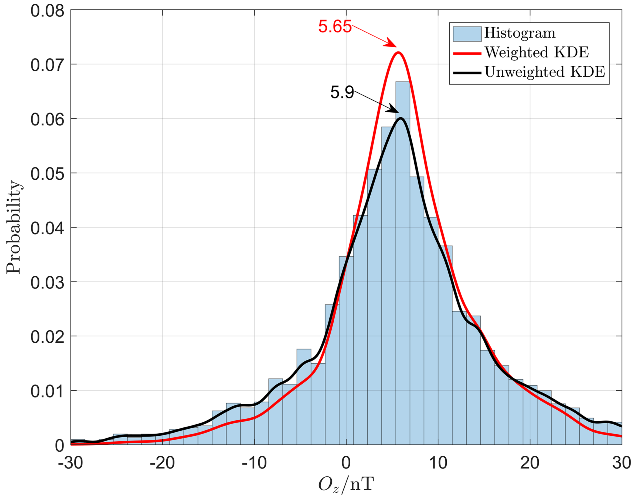

Figure 3. Histogram of mirror mode offset estimates for THE in the sixth sheath interval and KDE probability distribution functions (first iteration).

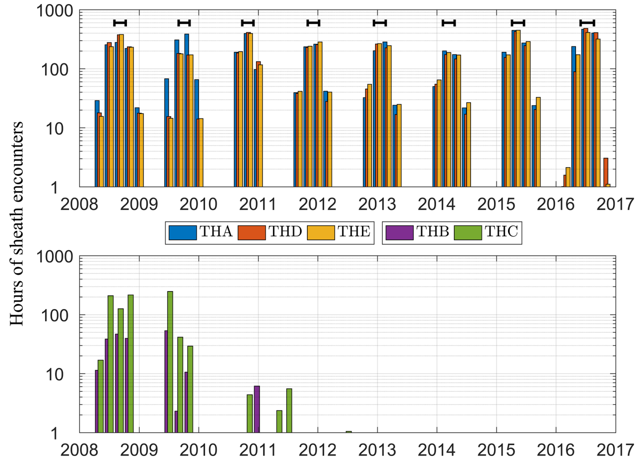

Figure 4. Sheath encounters of THEMIS (upper panel) and ARTEMIS (lower panel) probes. The designated offset determination intervals are marked by black lines. The histogram bin size is 2 months.

the offsets, $O_{z\mathrm{i}}$, is then computed as

$$P(\widetilde{O}_z) = \frac{1}{\sqrt{2\pi}Nh}\sum_i^N \frac{1}{w_\mathrm{i}} \exp\left(-\frac{(\widetilde{O}_z - O_{z\mathrm{i}})^2}{2h^2}\right), \tag{2}$$

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 $O_{z\mathrm{f}}$ 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

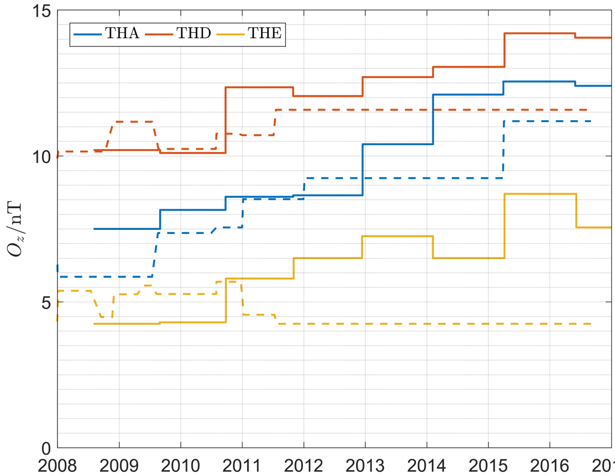

Figure 5. Full spin axis offsets of the three THEMIS spacecraft as recalculated by the mirror mode method. Dashed lines indicate the past results. With the beginning of each sheath interval, a new value becomes effective.

in the offset data. As indicated by the dashed lines, which display the past calibration values, the updated data compare within < 2 nT to the previous parameters (during the time when past updates were actually calculated, i.e., until 2012).

The possibility to update spin axis offsets on the THEMIS probes constitutes a major improvement to the previous approach. While relative changes of a few nanoteslas do not make a big difference in the high field regions of the magnetosphere, they will certainly have an influence on scientific studies in high-beta regions, such as the plasma sheet in the near-Earth magnetotail. With the publication of this work, the new offsets will be incorporated into the THEMIS database.

4 Data availability

THEMIS data and the latest calibration files are publicly available at http://themis.ssl.berkeley.edu/ or via the SPEDAS software. Solar wind data are available at https://omniweb.gsfc.nasa.gov/, and auroral electrojet data can be found at http://wdc.kugi.kyoto-u.ac.jp/.

Competing interests. The authors declare that they have no conflict of interest.

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