

First we would like to thank the referee for taking the time to evaluate the manuscript and for the constructive comments which helped to identify potential misunderstandings in the paper.

Anonymous Referee #1

The submitted manuscript presents an approach to calibrating offsets on the magnetometers onboard BepiColombo's Mercury Planetary Orbiter and Mercury Magnetospheric Orbiter spacecraft. This calibration analysis includes the use of mirror mode wave observations as a method to determine the spin-axis offset. Mio would be able to utilize this approach as a complementary method to an analysis of Alfvénic fluctuations in the pristine solar wind. MPO, on the other hand, will not measure the solar wind and therefore, observations within Mercury's magnetosphere must be used to calibrate measurements. The manuscript presents an analysis of the compressional fluctuations in Mercury's space environment by analyzing four years of MESSENGER magnetometer data. While the analysis presented here is sound and nicely justified, the paper did not convincingly demonstrate that this calibration technique would be sufficient to perform scientific investigations with the MPO magnetic field observations.

We will lower our claims that the method developed and presented in the manuscript is stand-by for immediate applications to the MPO magnetic field data. However, as mentioned in the paper, the method is immediately applicable to the Mio magnetometer because of the need of a single-axis offset determination.

The conclusion describes that 780 hours of observations within the magnetosphere are needed to achieve an accuracy better than 1.0 nT; however, many MESSENGER publications including magnetic field data report on signatures that require measurements within this level of uncertainty.

The magnetic field data, even though not reaching a 1-nT accuracy in the measurements, can certainly be used to a number of publications, but there is no guarantee about the uncertainty or accuracy in the data and care needs to be taken. In particular, if one is interested in finding a magnetic-null (reconnection diffusion region) or low-field phenomena (small-amplitude waves, for example), our method will be of great importance to guarantee how high or low the errors in the data are.

Additionally, the manuscript did not describe whether it is expected that MPO will be able to collect compressible fluctuations for 780 hours or more during the mission lifetime.

Well, a value of 780 hours is a conclusion given by the study; if it is really fulfilled by MPO, we need further studies (MESSENGER data or numerical simulations) and the application of 3D mirror mode method, which is beyond the scope of this paper.

Finally, the major conclusion for application to MPO is that "the 3D mirror mode method developed by (Plaschke et al., 2017) should be applicable to MPO . . ." but the paper does not describe this method or how it differs from the analysis presented here.

The paper primarily focus whether the mirror mode method can be applied in the hermean space environment at all. Indeed the result show that the method can be

directly applied onto Mio. However, the application of the 3-D mirror mode method onto MPO is beyond the scope of the manuscript and is planned to be addressed in a further work. Yet, we will add a paragraph and explain the concept of the 3-D mirror mode method in view of MPO spacecraft.

The analysis in this paper only provides a single-axis offset– how does this methodology provide vector calibration?.

We focus on applications to single-axis offset in the manuscript. Generalization to 3-D offset components is a related yet different issue. We will discuss a paragraph and discuss how to generalize the method to 3 components.

Prior to publication, these issues need to be addressed regarding a demonstration of the 3D mirror mode and the ability to use MPO calibrated data with an accuracy of ~1.0 nT for mission science.

There might be a misunderstanding. The manuscript focuses on the calibration method to single-axis offset and discuss the applicability and limits with respect to Mio and MPO magnetometers. We are not claiming that the 1D mirror mode method is readily applicable to MPO magnetometer; Of course, we agree that the 3-D method needs to be developed and tested for MPO; this should be done in a separate paper otherwise the paper has too many goals.

Additional comments are listed below:

Paragraph beginning at line 65: The text should also include a description of performing spacecraft rolls as a well-established method for determining offsets. This has been done with routinely with many missions, most recently including MAVEN at Mars and Parker Solar Probe.

This will be added to the text.

Please change all references to MESSENGER into the past tense: Line 100: “MESSENGER is highly” -> “MESSENGER was highly” Line 101: “altitudes ranges” -> “altitudes ranged” Line 101: “form” -> “from” Line 102: “MESSENGER crosses the magnetopause” -> “MESSENGER crossed the magnetopause” Line 107: “MESSENGER is a three-axis-stabilized” -> “MESSENGER was a three-axis-stabilized”

This will be changed in the text.

Line 150-152: Please define the mean-field-aligned coordinates system and how it is calculated.

This will be added to the text.

Line 225 – 227: “Note that, although standard deviation of the individual offsets σ_{Ozn} might be large, a larger number of samples or events helps lower the value of the

standard deviation of the mean offset O_{zn} (standard error in Table 2).” However, given the small percentage of occurrence rate showed in table 1 – will a large number of samples actually be possible?

As mentioned above, if it is really fulfilled by BepiColombo, we need further information about the final orbit of the spacecraft. At this point, we can only show that for MESSENGER the sample size for the mirror mode method is indeed large enough to reproduce the 1D offset determination which was originally obtained from the Alfvénic fluctuation method.

Line 270-273: “We find that the offset determination method proposed by Plaschke and Narita (2016) is well applicable to the data from the Hermean environment. It can hence be used for in-flight calibration of the magnetometers onboard Mio and MPO.”– While the offset analysis presented here is sound and well-described, it does not demonstrate the application of Plaschke et al (2017) to the MPO dataset, which is most important to derive calibrated vector measurements.

Accordingly, we have lowered our claims that the method developed and presented in the manuscript is stand-by for immediate applications to the MPO magnetic field data and thus will delete the sentence.

Line 274: “As is been seen in . . .” please revise wording
This will be changed in the text.

We like to thank the referee for the helpful comments to improve the quality of the paper and make it more easily comprehensible for the reader.

Anonymous Referee #2

The paper is a bit unusual in that it deals with magnetometer calibrations rather than scientific results. However other than that it is well written and could be published in Annales Geophysicae after suitable corrections. Major Comments The magnetometer offset correction techniques are applied to Alfvén waves and mirror mode waves. The general audience will not understand what these waves are and why they would be useful for calibration purposes. Thus I recommend that the authors show examples of each and give the readership some background about their generation mechanisms and properties and why they are in the solar wind and magnetosheath, respectively. The AG readership should be given some context for why the authors use these two regions of space. The average reader will not know what a mirror mode is.

The critique is well justified. We will add a paragraph about the Alfvén wave and the mirror mode, and introduce how these are used as calibration standard on an elementary level for the benefit to the readers. We add sketches of wave measurements and the use of waves for offset calibration

Abstract, lines 11 and 12. A reference should be added for the “mirror mode technique”. Line 13. A reference should be given for the “Alfvén fluctuation technique”.

We think that the Abstract should not contain references since it should be a document on its own.

Line 65 and following paragraph. Much of what is written in this paragraph could be deleted without loss. For example it is not necessary to understand the Rosetta null technique involving diamagnetic cavities.

Based on the other referee’s suggestions we decided to keep this paragraph, also because it shows that there are various other calibration techniques, which have successfully been applied to previous spacecraft missions (3-axis stabilized and spinning).

However the spin technique is necessary to discuss since you are using it to get two components of your magnetospheric spacecraft magnetometer offsets.

We agree with the referee that a more detail description of the Alfvén and mirror mode method is beneficial and thus include additional information about these calibration techniques.

Line 74. Give references for the minimum variance method applied to Alfvén waves. In Belcher (1973) the applied minimum variance method is explained in detail. The reference is given at the end of the sentence.

Line 75. Alfvén waves are not always incompressible. See JGRSP, 123, <https://doi.org/10.1002/2017JA024203>, 2018. This is a misconception in the literature and should be mentioned in this paper. When they are not incompressible, how will they affect your analyses? Please discuss.

We fully agree with the referee that Alfvén waves are not always incompressible. Only pure Alfvénic fluctuations are strictly incompressible. They are characterized by changes in the magnetic field components while the magnitude of the field stays constant. Particularly in inhomogeneous media such simple classifications are found to be impossible (see Tsurutani (2018) for a review; <https://doi.org/10.1002/2017JA024203>). In fact, oblique propagation angles to the mean magnetic field, electric field polarization in the plane perpendicular to the mean field, and finite parallel electric field make Alfvénic fluctuations of compressible character by exciting magnetic field fluctuations parallel to the mean field [Narita, 2020; <https://doi.org/10.3389/fphy.2020.00166>]. These parallel magnetic field fluctuations can be explained within the non-ideal MHD treatment where secondary effects like Hall currents and/or diamagnetic currents are also taken into consideration. These currents flow perpendicular to the mean magnetic field and can cause small-amplitude compressible perturbations. However, in the solar wind the fluctuations of the magnetic field strength (compressible part) are weak compared to the strong fluctuations of the magnetic field vector direction (see e.g. Khabibrakhmanov, 1997; <https://doi.org/10.1029/96JA03843>). By minimizing the changes of the observed total magnetic field of such fluctuations, it is therefore possible to adjust the magnetometer offsets.

To what extent the incompressibility does affect our analyses is difficult to assess, since for the in-flight offset calibration of MESSENGER additional activities had been performed (e.g. Y-axis spacecraft roll maneuver) which are hard to unravel afterwards. Moreover, to our knowledge the effect on the offset determination has so far never been studied in detail and would be an interesting aspect to look at e.g. for the upcoming BepiColombo in-flight calibration.

Line 77. Give references to the mirrormode method here again.

The reference is given at the beginning of the sentence. Plaschke and Narita (2017)

The paper is somewhat repetitive. I suggest deleting duplication and shortening the paper considerably. The readership will understand your techniques even if you express them only once.

We will go through the paper again and delete sections/sentences, which are repetitive.

Magnetometer in-flight offset accuracy for the BepiColombo spacecraft

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Abstract. Recently the two-spacecraft mission BepiColombo launched to explore the plasma and magnetic field environment of Mercury. Both spacecraft, the Mercury Planetary Orbiter (MPO) and the Mercury Magnetospheric Orbiter (MMO, also referred to as Mio), are equipped with flux-gate magnetometers, which have proven to be well-suited to measure the magnetic field in space with high precisions. Nevertheless, accurate magnetic field measurements require proper in-flight calibration. In particular the magnetometer offset, which relates relative fluxgate readings into an absolute value, needs to be determined with high accuracy. Usually, the offsets are evaluated from observations of Alfvénic fluctuations in the pristine solar wind, if those are available. ~~While Mio's orbit will indeed partially reside in the solar wind, MPO will remain within the magnetosphere at most times during the main mission phase. Therefore, we examine an alternative offset determination method, based on the observation of highly compressional fluctuations, the so-called mirror mode technique. An alternative offset determination method, which is based on the observation of highly compressional fluctuations instead of incompressible Alfvénic fluctuations, is the so-called mirror mode technique.~~ To evaluate the method performance in the Hermean environment, we analyze four years of MESSENGER magnetometer data, which are calibrated by the Alfvénic fluctuation method, and compare it with the accuracy and error of the offsets determined by the mirror mode method in different plasma environments around Mercury. We show that the mirror mode method yields the same offset estimates and thereby confirms its applicability. Furthermore, we evaluate the spacecraft observation time within different regions necessary to obtain reliable offset estimates. Although the lowest percentage of strong compressional fluctuations are observed in the solar wind, this region is

most suitable for an accurate offset determination with the mirror mode method. 132 hours of solar wind data are sufficient to determine the offset to within 0.5 nT, while thousands of hours are necessary to reach this accuracy in the magnetosheath or within the magnetosphere. We conclude that in the solar wind the mirror mode method might be a good complementary approach to the Alfvénic fluctuation method to determine the (spin-axis) offset of the Mio magnetometer. ~~However, although the mirror mode method requires considerably more data within the magnetosphere, it might also be for the MPO magnetometer one of the most valuable tools to determine the offsets accurately.~~

1 Introduction

In October 2018, BepiColombo, a two-spacecraft mission of the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA), was launched to explore Mercury (Benkhoff et al., 2010). One of the spacecraft is the Mercury Planetary Orbiter (MPO), which is a 3-axis stabilized satellite (quasi nadir pointing) to study the surface and interior of the planet (e.g. Glassmeier et al., 2010). The other is Mio (or Mercury Magnetospheric Orbiter, MMO), a spin-stabilized spacecraft (spin period of about 4 s) to investigate the magnetic field environment of Mercury (e.g. Hayakawa et al., 2004; Baumjohann et al., 2006). During the 7.2 year cruise phase, both orbiters are transported by the Mercury Transfer Module (MTM) as a single composite spacecraft. In late 2025, the composite spacecraft will approach Mercury, where the MTM separates from the other two spacecraft, which are captured into a polar orbit around the planet. As soon as Mio reaches its initial operational orbit of 590 km by 11640 km above the surface, also MPO separates and lowers its altitude to its 480 km by 1500 km orbit.

The BepiColombo Mercury Magnetometers (MERMAG) constitute a key experiment of the mission; MERMAG consists of the fluxgate magnetometers onboard both, MPO and Mio. The magnetometers will provide in-situ data for the characterization of the internal field origin as well as its dynamic interaction with the solar wind (see e.g. Wicht and Heyner, 2014, for a discussion). To achieve this goal, accurate magnetic field measurements are thus of crucial importance. Therefore, the components of a linear calibration matrix $\underline{\mathbf{M}}$ and an offset vector \mathbf{O} need to be obtained, in order to convert raw instrument outputs \mathbf{B}_{raw} to fully calibrated magnetic field measurements (see e.g. Kepko et al., 1996; Plaschke and Narita, 2016):

$$\mathbf{B} = \underline{\mathbf{M}} \cdot \mathbf{B}_{\text{raw}} - \mathbf{O}. \tag{1}$$

Here, the matrix $\underline{\mathbf{M}}$ transforms \mathbf{B}_{raw} into a spacecraft-fixed orthogonal coordinate system. It comprises 9 parameters: 3 scaling (gain) values of the sensor and an orthogonalization matrix, which is defined by the 6 angles that yield the magnetometer sensor directions with respect to the spacecraft reference frame (see e.g. Plaschke and Narita, 2016). The 3D offset vector \mathbf{O} , on the other hand, reflects the magnetometer outputs in vanishing ambient fields. These can be attributed to the instru-

ment and also to the field generated by the spacecraft at the position of the magnetometer sensor. Frequent in-flight calibration of these offsets is necessary, as they are known to change over time.

To calibrate the magnetometer, all 12 parameters need to be accurately determined. For spinning spacecraft (i.e. Mio) 8 of the calibration parameters can be determined directly by minimizing periodic signatures in the de-spun magnetic field signal at the spin frequency and/or at the second harmonic (Kepko et al., 1996). The remaining 4 parameters i.e. the absolute gain in the spin-plane and along spin-axis, the rotation angles of the sensor around the spin-axis, and the spin-axis offset need to be determined differently. It should be noted that the gains and rotation angle become important at strong fields. In the solar wind and in the Hermean environment they may play a minor role in the magnetic field measurements accuracy in comparison to the offsets.

The following methods, which can also be applied to non-spinning spacecraft (i.e. MPO), are well established for the offset determination:

(1) Cross-calibration of the magnetometer offset with independent magnetic field measurements from other instruments. The Magnetospheric Multiscale mission (MMS, Burch et al., 2016) use independent measurements from the Electron Drift Instruments (EDI, Torbert et al., 2016) to cross-calibrate the spin-axis offset of the magnetometers (Nakamura et al., 2014; Plaschke et al., 2014)).

(2) The offset may also be determined in a characteristic region where the magnetic field is known. Goetz et al. (2016) used diamagnetic cavities to determine the magnetometer offsets of the Rosetta spacecraft mission (Glassmeier et al., 2007).

(3) Spacecraft rotations about the spacecraft principal axes from time to time are also a well-established method to obtain magnetometer offsets. This has been done routinely with many missions, most recently including MAVEN (Connerney et al., 2015) at Mars and Parker Solar Probe (Bale et al., 2016).

(4) The most common way to calibrate the magnetometer offset in-flight, is to use well-known (a) (nearly-)incompressible or (b) compressible fluctuations of the magnetic field observations:

4(a) A well-established method to obtain the magnetometer offset is to minimize the variance of the total magnetic field during the passage of nearly-incompressible (Alfvénic) variations in the (pristine) solar wind (Belcher, 1973; Hedgecock, 1975). Pure Alfvénic fluctuations are strictly incompressible and circularly polarized. They are characterized by changes in the magnetic field components while the magnitude of the field stays constant. Particularly in inhomogeneous media such simple classifications are found to be impossible (see Tsurutani et al., 2018, for a review). However, in the solar wind the fluctuations of the magnetic field strength (compressible part) are weak compared to the strong fluctuations of the magnetic field vector direction (Khabibrakhmanov and Summers, 1997). By minimizing the changes of the observed total magnetic field of such fluctuations it is therefore possible to adjust the magnetometer offsets with high precision. In Figure 1(a) a schematic illustration of (nearly-)incompressible Alfvénic fluctuations is shown. The changes of

the total magnetic field, $\delta|B|$, observed by a virtual spacecraft crossing the fluctuations are minimal (shown in the bottom).

95 4(b) Recently Plaschke and Narita (2016) introduced an alternative magnetometer offset calibration technique on the basis of the observation of compressible fluctuation, the so-called mirror mode method ~~to determine the magnetometer offset on the basis of compressible fluctuations. This method,~~ which does not require pristine solar wind measurements. The idea is that for strongly compressible fluctuating fields (e.g. mirror modes) the maximum variance direction of the magnetic field
100 should be nearly parallel to the mean (background) magnetic field (Tsurutani et al., 2011). Mirror mode structures are compressional, non-propagating structures which have been observed in various space plasma environments like in the solar wind (e.g. Winterhalter et al., 1994), planetary magnetosheaths (e.g. Tsurutani et al., 1982) and even near the magnetic pileup boundaries of comets (e.g. Glassmeier et al., 1993). They are typically characterized by the anticorrelation between the
105 magnetic field strength and density fluctuations, with little or no change in the magnetic field direction across the structure (see e.g. Winterhalter et al., 1994). Figure 1(b) shows a sketch of such a mirror mode structure. A virtual spacecraft crossing the structure observes perturbations along the mean magnetic field direction, $\delta B_{||}$. Any differences between ~~these two~~ the maximum variance direction (evaluated from e.g. minimum variance analysis (MVA), Sonnerup and Scheible, 1998) of
110 the magnetic field and the mean (background) magnetic field direction can thus ~~been evaluated and~~ be used for the magnetometer offset determination. Note that although this method is called mirror mode method, observations of highly compressional waves other than mirror mode structures with strong $\delta|B|/|B|$ ratios without \mathbf{B} direction changes are sufficient for their application. An advantage of this method is that compressible waves are ubiquitous in the magnetosphere and magnetosheath.
115 Therefore this method can also be applied to calibrate the magnetometers of spacecraft which remain within the magnetosphere (like e.g. MPO).

In this paper we test the applicability of the mirror mode method in different regions (plasma environments) around Mercury, based on 4-years of MESSENGER (MERcury Surface, Space ENVi-
120 ronment, GEophysics and Ranging, Solomon et al., 2007) fluxgate magnetometer data (FGM, Anderson et al., 2007), which were calibrated using time intervals of ~~nearly~~-incompressible Alfvénic fluctuations in the solar wind. For reasons of simplicity (and because for Mio only the spin-axis offset needs to be evaluated) we apply the 1-D mirror mode method (see Plaschke and Narita, 2016) and ~~assume that two offset components are already accurately determined.~~ We test to which degree
125 the 1-D mirror mode method yields vanishing offsets as expected when using calibrated data as input. We also address the question of how much time ~~Mio and MPO a spacecraft~~ needs to spend in each individual plasma region until the magnetometer offset can be determined to a specific accuracy from intervals containing compressional magnetic field fluctuations.

The results obtained in this paper enable us to assess whether the mirror mode method would be a

130 useful tool to accurately determine the offset of BepiColombo's magnetometer.

2 Data and Methodology

We use orbital magnetic field data from the MESSENGER fluxgate magnetometer (FGM, Anderson et al., 2007) between March 2011 and April 2015. The polar orbit of MESSENGER is was highly elliptical; the initially altitude ranged between 200 km and 15000 km from Mercury's surface. With an initial orbital period of 12 hours, MESSENGER crosses the magnetopause and bow shock four times within 24 hours. We use the 1-Hz calibrated magnetic field data in spacecraft coordinates, where the Y -axis is nominally in the anti-sunward direction (radially away from the Sun), the Z -axis points towards the payload adapter ring at the bottom of the spacecraft, and the X -axis completes the right handed coordinated system. If not noted otherwise, we use the magnetic field components $\{B_x, B_y, B_z\}$ throughout this paper in these coordinates. MESSENGER is was a three-axis-stabilized spacecraft, and its magnetometer offsets are were routinely corrected using time intervals of Alfvénic fluctuations in the solar wind. We therefore use the MESSENGER magnetometer data as a calibration standard in our magnetometer offset study. To perform a test of the mirror mode method against the MESSENGER magnetometer data, we determine the 1D offset along the Z -axis, O_z , in the same way as introduced by Plaschke and Narita (2016):

145 Within strongly compressible mirror mode structures, the magnetic field variation maximum variance direction, $\ell = [l_x, l_y, l_z]$ obtained from a principal component analysis (minimum variance analysis, MVA, Sonnerup and Scheible, 1998) should be reasonably aligned with the mean field direction, $\mathbf{B} = [B_x, B_y, B_z]$. Under assumption of alignment between the maximum variance direction and the mean field direction Plaschke and Narita (2016) showed that the offset O_z can be derived by:

$$O_z = B_{xy}(\tan\theta_B - \tan\theta_\ell), \quad (2)$$

where $\theta_B = \arctan(B_z/B_{xy})$ is the elevation angle of magnetic field to the XY -plane and $\theta_\ell = \arctan(\ell_z/\ell_{xy})$ the elevation angle of the maximum variance direction to that plane. $B_{xy} = \sqrt{B_x^2 + B_y^2}$ and $\ell_{xy} = \sqrt{\ell_x^2 + \ell_y^2}$ are the magnetic field and maximum variance within the XY -plane.

155 Since a single offset estimate alone might not be very accurate, a statistically significant offset O_{zf} should be determined by finding the maximum of the probability density function P computed by the kernel density estimator (KDE) method with Gaussian kernel from a sample of individual offset estimations O_z :

$$P(O_z^*) = \frac{1}{\sqrt{2\pi}Nh} \sum_{n=1}^N \exp\left[-\frac{1}{2}\left(\frac{O_z^* - O_{z,n}}{h}\right)^2\right]. \quad (3)$$

Here N denotes the number of individual offset estimates, $O_{z,n}$, h is a smoothing parameter which denotes the bandwidth of the KDE, and O_{zf} is the offset value at which the probability P is at max-

imum, $\max(P(O_z^*)) = P(O_{zf})$. We use the method introduced by Silverman (1986), to determine
 165 an optimal bandwidth $h = c_1 \cdot \sigma(O_{z,n})N^{c_2}$, with $c_1 = 1.06$ and $c_2 = -1/5$. The symbol σ denotes
 the standard deviation of the offset-value distribution.

3 Data Analysis and Results

A basic condition for the mirror mode method, is the availability of compressional magnetic field
 fluctuations. As a first step we use the magnetometer data to estimate the occurrence rate of com-
 170 pressional fluctuations in the different plasma environments around Mercury. Then we compare the
 offset determination by the mirror mode method with the Alfvén wave method in terms of accu-
 racy. Finally, we evaluate the number of offset samples that are sufficient for in-flight calibration
 with the mirror mode method, given a minimum required accuracy. Therewith, we subsequently
 determine how many hours the spacecraft (i.e. Mio and/or MPO) need to spend in different plasma
 175 environments to obtain reliable offset values.

3.1 Occurrence rate of compressional fluctuations

Mercury’s plasma environment is highly dynamic and home to a plethora of wave modes and fluctua-
 tions (Russell, 1989; Boardsen et al., 2009, 2012; Sundberg et al., 2015). We separate the MESSEN-
 GER orbit segments into solar wind, magnetosheath and magnetospheric parts, based on an extended
 180 boundary data set (Winslow et al., 2013, and personal communication with R. Winslow and B. J. An-
 derson), in order to distinguish occurrence rates of (compressional) fluctuations and offset estimate
 accuracies by region. We characterize the observed fluctuations in the following way: The magnetic
 field data are divided into overlapping 30-s intervals shifted by 15-s. Within each sub-intervals the
 magnetic field measurements are transformed into a mean-field-aligned (MFA) coordinate system ,
 185 where the parallel component, $\hat{\mathbf{b}}_{||} = \mathbf{B}_0/|\mathbf{B}_0|$, is given by the average magnetic field within the 30-s
 interval, $\mathbf{B}_0 = [B_{x,0}, B_{y,0}, B_{z,0}]$, and the perpendicular components in this coordinate system are
 chosen to be $\hat{\mathbf{b}}_{\perp,1} = [0, -B_{z,0}, B_{y,0}]/|[0, -B_{z,0}, B_{y,0}]|$ and $\hat{\mathbf{b}}_{\perp,2} = \hat{\mathbf{b}}_{\perp,1} \times \hat{\mathbf{b}}_{||}$. Then the maximum
 variance direction, ℓ , of the transverse (perpendicular) magnetic field components is evaluated by a
 2D minimum variance analysis (MVA, Sonnerup and Scheible, 1998). The difference between the
 190 maximum and minimum values of the magnetic field in this maximum variance direction yields the
 measure for the transverse fluctuations $\delta B_{\perp,\ell} = B_{\perp,\ell}^{\max} - B_{\perp,\ell}^{\min}$. The compressional fluctuations,
 on the other hand, are essentially represented by fluctuations in the magnetic field magnitude $\delta|B|$,
 given by the difference between the maximum and minimum value of the magnetic field magnitude
 within the 30-s interval. Subsequently, to determine whether the compressional or the transverse
 195 part is dominating, we further define the compressibility index Q^{\pm} as

$$Q^{\pm} = \log_{10} \left(\frac{\delta|B|}{\delta B_{\perp,\ell}} \right), \quad (4)$$

which is positive/negative in case of dominating compressional/transverse fluctuations.

Left panel of Figure 2 displays the occurrence rate (normalized to unity when integrated over the whole domain) of fluctuations of the magnetic field magnitude (compressible sense) relative to the mean field in various plasma regions: in the solar wind (in red), in the magnetosheath (in green), and in the Hermean magnetosphere (in blue) for the MESSENGER magnetometer data for 4 years. Most of the large-amplitude fluctuations are observed in the magnetosheath. Such a result is not surprising, since the magnetosheath is characterized generally by a highly turbulent plasma with enhanced magnetic field variations. The right panel shows the normalized occurrence rate of the compressibility index Q^\pm of selected intervals with large amplitude fluctuations ($\delta|B|/\bar{B} > 0.3$). The shifts of the maximum occurrence rates to negative Q^\pm values indicate that statistically transverse fluctuations were dominating. However, there is also a significant number of time intervals with compressional fluctuations observed. The integrated occurrence rates are shown in Table 1. The first column of Table 1 shows the percentage of the sub-intervals where the magnetic field magnitude fluctuations $\delta|B|/\bar{B}$ were larger than 0.3. The percentage in the second column shows how many of the intervals with large-amplitude fluctuations ($\delta|B|/\bar{B} > 0.3$) are dominated by strongly compressional fluctuations, where $\delta|B|/\delta B_{\perp,\ell} > 2$ ($Q^\pm > 0.3$). The last column reflects the percentage of intervals that include these strongly compressional fluctuations out of all intervals of MESSENGER observations in the respective regions.

About 25 % of the time enhanced magnetic field fluctuations ($\delta B/\bar{B} > 0.3$) are observed in the magnetosheath and 10.6 % of these fluctuations had a compressional nature. That means that from the total observation time in the magnetosheath, 2.6 % of the time MESSENGER observed strongly compressional fluctuations. A smaller fraction of the MESSENGER data set represent compressible dominated time intervals of the solar wind (0.4 %) and the Hermean magnetosphere (1.7 %). This suggests that the MESSENGER magnetosheath data may be best suited for the offset calibration with the mirror mode method.

3.2 Test of the mirror mode method

Using Equation 2 we determine the offset O_z within each 30-sec time interval. To ensure reliable offset estimates, the same requirements introduced by Plaschke and Narita (2016) have to be fulfilled within each window:

$$-\frac{\delta B_{xy}}{\bar{B}_{xy}} = \frac{B_{xy}^{\max} - B_{xy}^{\min}}{B_{xy}^{\text{mean}}} > 0.3, \text{ since mirror modes are characterized by large magnetic field fluctuations (see Price et al., 1986; Schmid et al., 2014). } B_{xy}^{\max}, B_{xy}^{\min} \text{ and } B_{xy}^{\text{mean}} \text{ are the maximum, minimum and average magnetic field values in the spacecraft } XY\text{-plane, respectively.}$$

Note that we only consider the XY -plane components, because the Z -component are subject to an a-priori unknown offset O_z .

- $\phi < 20^\circ$, where ϕ is the angle between the maximum variance, ℓ , and magnetic field, \mathbf{B} , directions in the XY -plane. Note that only the XY -plane components is used. Plaschke and Narita (2016) derived this requirement and threshold from Lucek et al. (1999), who identified mirror modes ~~due to using~~ the angle between maximum variance and magnetic field direction.
- $|\theta_{\mathbf{B}}| < 30^\circ$ and $|\theta_{\ell}| < 30^\circ$, so that both, maximum variance and magnetic field directions point closer to the XY -plane.

Out of 4-years of MESSENGER data these requirements are met for 3.0 %, 2.1 % and 0.4 % of the intervals within the magnetosphere, magnetosheath and the solar wind, respectively (see also first column of Table 2). It should be noted that these numbers do not have to match the numbers shown in Table 1, since the criteria are different. The numbers in Table 1 reflect the occurrences of strongly compressional fluctuations and here they reflect the occurrences of intervals with mirror mode like characteristics. Interestingly, however, the numbers in the solar wind and the magnetosheath are similar but differ considerably in the magnetosphere.

Using Equation 3 the probability density function P is computed for each region from all determined best-estimate offset O_z in that region. Under the assumption that the data are perfectly calibrated and the mirror mode method works accurately, the offset O_{zf} should vanish and P should be highly symmetric with the peak around 0 nT.

Figure 3 shows the probability density functions P based on the magnetosphere (red), magnetosheath (green) and solar wind (blue) offset estimates. Indeed, the best estimate of the Z -component offset O_{zf} is around zero for all three regions. It is noteworthy that the standard deviation of individual offset estimates, $O_{z,n}$, is smallest in the solar wind. This is actually not surprising, since the intervals in the solar wind where the above requirements are fulfilled, are well-suited for this calibration method due to their clear compressional signature in the rather low background magnetic field. In Table 2 the total number of intervals (O_z estimates) and their best-estimate offset O_{zf} are given. Further, the arithmetic mean of the individual offsets in each interval $O_{z,n}$ with their standard deviations and error are summarized.

The average $\langle O_{z,n} \rangle$ is found to be quite close to the final offset estimate O_{zf} . Note that, although the standard deviation of the individual offsets $O_{z,n}$ might be large, a larger number of samples or events helps lower the value of the standard deviation of the mean offset $\langle O_{z,n} \rangle$ (standard error in Table 2).

3.3 Effect of sample size on offset accuracy

In the following we check how the best-estimate offset O_{zf} is affected by the number of $O_{z,n}$ estimates. Therefore, from each region, 1 to 20000 offset estimates ($N = \{x \cdot 10^y \mid x \in [1, 9], y \in [0, 4]\}$, $\max(N) = 20000$) are randomly picked and their best-estimate offset O_{zf} determined. For each

N , this sequence is repeated 1000 times (bootstrapping). The standard deviation of the 1000 O_{zf} ($\sigma(O_{zf})$) subsequently reflects the uncertainty of the determined O_{zf} . Here we use the $2\text{-}\sigma$ interval, to evaluate the uncertainty of the best-estimate offset O_{zf} with 95% confidence. The standard error ϵ of the $2\text{-}\sigma$ uncertainty of the best-estimate offset, $2\text{-}\sigma(O_{zf})$, from the bootstrapping is given by $\epsilon \simeq 2\text{-}\sigma(O_{zf})/\sqrt{2(M-1)}$ (see e.g. Squires, 2001). Here $M = 1000$ yielding a relative standard error $\epsilon = 4.3\%$ of the evaluated $2\text{-}\sigma(O_{zf})$. Figure 4 displays $2\text{-}\sigma(O_{zf})$ as a function of the number N of the offset estimates $O_{z,n}$ used.

The dashed lines in Figure 4 mark offset accuracies at 0.5 nT and 1.0 nT. It is visible that the offset accuracy increases with the number of samples following a power law. However, below ~ 0.5 nT considerably more samples are needed to improve the offset accuracy, which could indicate the lower limit of the offset accuracy of the MESSENGER magnetometer determined by the Alfvénic method. As can be seen in Figure 4, this divergence is only observed in the solar wind, because it is the only region where a significant number of $O_{zf} < 0.5$ nT are obtained. The solid lines in Figure 4 depict the regression lines of a linear least squares fit of the offset accuracies above 0.5 nT and clearly shows the power law behavior between these offset accuracies and the number of samples. Table 3 shows the fitting parameters of the regression lines of the power laws,

$$\log_{10}[2\sigma(O_{zf})] = \log_{10}[a] + k \cdot \log_{10}[N]. \quad (5)$$

Here a denotes the $2\text{-}\sigma$ confidence of the best-estimate O_{zf} determined from only one offset O_z and k represents the spectral index of the power law.

From the least squares approximation we calculate the minimum number N of $O_{z,n}$ estimates to reach an offset accuracy of 0.5 nT and 1.0 nT. These numbers are multiplied by 30 s, the sliding window time interval, yielding the time ranges from which reliable $O_{z,n}$ estimates are obtained (i.e. where the criteria from above are satisfied). These time ranges multiplied with the probability to observe these time intervals (see first column in Table 2), finally give the time lengths that a spacecraft needs to spend in the solar wind, magnetosheath or magnetosphere in order to determine the offset with an accuracy better than 0.5 nT or 1.0 nT. Table 4 shows the minimum number N of $O_{z,n}$ estimates with their corresponding time ranges and the necessary spacecraft observation time, required to reach these accuracies.

While 132 hours of solar wind data are sufficient to determine the offset at an accuracy of 0.5 nT, 4241 hours are needed in the magnetosphere and more than 6130 hours in the magnetosheath. This is an interesting result, since the magnetosheath is the region with the highest probability to observe large-amplitude compressional fluctuations and the solar wind with the lowest (see Table 1). A possible explanation might be that the solar wind data are observations in the shock-upstream region in which the shock-reflected backstreaming ions excite large-amplitude Alfvén waves that either pitch the plasma (through ponderomotive force) or develop into magnetosonic-type waves. However, the results suggests that the fluctuations in the solar wind, although observed less often, are better suited to determine the offset with the mirror mode method.

4 Discussion and Conclusions

305 We find that the offset determination method proposed by Plaschke and Narita (2016) is well applicable to the data from the Hermean environment. ~~It can hence be used for in-flight calibration of the magnetometers onboard Mio and MPO.~~ The results reveal that the solar wind is the most suitable region to accurately determine the offset by the mirror mode method, although the lowest percentage of highly compressible fluctuations are observed there (see Table 1). As ~~is can~~ been seen in Table 4, 310 offset determination with uncertainties better than 0.5 nT can be achieved with less than 132 hours of solar wind data. However, it is important to note that during this time the instrument offsets need to stay constant to within 0.5 nT, otherwise the intrinsic offset drifts over time would limit the achievable precision, independently from the the amount of solar wind data. Specifically in the magnetosheath and within the magnetosphere this might be a more important limiting factor, since 315 several thousands of hours of data in those regions are needed to ensure that the offset uncertainty is less than 0.5 nT (see Table 4). Figure 4 shows that the offset accuracies down to 0.5 nT diminish with the number of necessary O_z estimates and follows a power law. However, below 0.5 nT the power law correlation flattens (spectral index becomes smaller), which might indicate that the lower limit of the offset accuracy of the calibrated magnetometer data itself has been reached. To ensure 320 e.g. the offset uncertainty to be of the order of 1.0 nT, 60 hours of magnetic field data in the solar wind would be sufficient, but hundreds of hours of magnetosheath or magnetosphere data are would be needed.

In the following we consider possible implications of these results on the BepiColombo mission:

– **Mio (Mercury Magnetospheric Orbiter, MMO):** Since Mio’s orbit allows the spacecraft 325 encounter the solar wind (particularly near Mercury’s perihelion), the mirror mode method would serve as a reasonable complementary approach to the Alfvénic fluctuation method. Furthermore, Mio is a spin-stabilized spacecraft (with a period of about 4 s) and thus two of the three offsets in the de-spun plane can be directly determined by minimization of spin-tone in the data. Since the two spin-plane offsets can be determined very accurate (Kepko et al., 330 1996), the mirror mode method ~~presented in this study can thus be directly applied to~~ determine the remaining offset (spin-axis offset) very precisely (see, Plaschke and Narita, 2016). However, the mirror mode method assumes the time independence of the offset properties during the fluctuation measurements. Offsets drifts over time, e.g. due to temperature changes over orbital periods, will be the limiting factors for the achievable accuracies.

335

– **MPO (Mercury Planetary Orbiter):** ~~The MPO spacecraft, on the other hand, is 3-axis stabilized, which should diminish the offset determination accuracy due to the two additional degrees of freedom and the 1D mirror mode method presented in this study cannot be applied~~

340 directly. Based on the principles of the 1D mirror method, Plaschke et al. (2017) extended the
method to 3 dimensions and introduced the so-called 3D mirror mode method. This method
has successfully been tested to 3-axis stabilized spacecraft magnetic field measurements and
is able to determine the 3D offset vectors directly from observations of highly compressional
magnetic field fluctuations. Hence, the 3D mirror mode method would be more appropriate to
345 determine the MPO magnetometer offsets. However, the applicability of the 3-D mirror mode
method needs to be evaluated in detail and is beyond the scope of this paper. Nevertheless,
from the 1D mirror mode method performed in this work, it is possible to get a first idea of
how many hours of magnetic field observations are needed in order to determine the offset of
one component if the other two are well determined. The orbit of MPO will remain in the
Hermean magnetosphere for most of the time (except for cusp crossings or during events of
350 high dynamic pressure in the solar wind). Based on the results obtained from MESSENGER,
780 hours of observations are needed in order to determine the offset of one component with
an accuracy better than 1.0 nT in this region. Note that during this long observation period the
magnetometer offsets need to stay constant within 1.0 nT, as mentioned above.

From the results obtained in this work we conclude that in the solar wind the mirror mode method
355 should be an good complementary approach to the Alfvénic fluctuation method to determine the
spin-axis offset of the Mio magnetometer. In case of MPO we cannot evaluate from this study
whether the mirror mode method is sufficient to obtain reliable offset estimates. However, from the
results of the 1D mirror mode method, we find that considerably more data are needed to reach the
same offset accuracy, since the orbit nominally remains within Mercury’s magnetosphere. ~~Never-~~
360 ~~theless,~~ In a future work the 3D mirror mode method should be applied on the MESSENGER data
to asses whether the mirror mode method might still also be a valuable tool to obtain reliable offset
estimates also for the magnetometers of MPO-MAG.

Data availability The MESSENGER magnetic field (MAG) data are obtained from the NASA
Planetary Data System (PDS). All data are open access and can be retrieved on the PDS website
365 (<https://pds-ppi.igpp.ucla.edu>, NASA Planetary Date System, 2015).

Author contributions DS initiated this study, collected the data and did the analysis. FP wrote
the initial version of the Mirror Mode Method program and helped interpreting the results. YN
370 contributed Figure 1 and helped evaluating the manuscript and interpreting the results. WB, AM,
DH and JM also assisted in evaluating the manuscript. As the PI of the MESSENGER magnetometer,
BA guaranteed the quality and usability of the data.

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

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Tables

Table 1. The first column gives the percentage of the sub-intervals where the magnetic field magnitude fluctuations $\delta|B|/\bar{B}$ is larger than 0.3 in each respective region. The percentage in the second column shows how many intervals of the sub-intervals with $\delta|B|/\bar{B} > 0.3$ are dominated by compressional fluctuations ($Q^\pm > 0.3$). The last column reflects the percentage of compressional fluctuations MESSENGER observes in total in each region.

| Region | $\delta B /\bar{B} > 0.3$ | | compressible |
|---------------|---------------------------|---------------|-----------------------|
| | total | $Q^\pm > 0.3$ | fluctuations in total |
| Solar wind | 7.9 % | 5.4 % | 0.4 % |
| Magnetosheath | 24.6 % | 10.6 % | 2.6 % |
| Magnetosphere | 8.0 % | 21.6 % | 1.7 % |

Table 2. Number of samples (time intervals) used in the statistical study for the offset determination and various offset estimates in units of nT (best-estimate, mean, standard deviation, and standard error).

| Region | Number of samples (% of total) | best-estimate O_{zf} [nT] | mean $\langle O_{z,n} \rangle$ [nT] | standard deviation $\sigma(O_{z,n})$ [nT] | standard error $\sigma(O_{z,n})/\sqrt{N}$ [nT] |
|---------------|-----------------------------------|--------------------------------|--|--|---|
| Solar wind | 21200 (0.4 %) | -0.04 | -0.10 | 6.5 | 0.04 |
| Magnetosheath | 29289 (2.1 %) | -0.17 | -0.34 | 14.0 | 0.08 |
| Magnetosphere | 36652 (3.0 %) | -0.01 | -1.01 | 12.4 | 0.09 |

Table 3. Fitting parameters of Equation 5 with 95 % confidence intervals, exhibited from linear least squares fit of the offset accuracies above 0.5 nT in Figure 4. a is the 2- σ confidence of the best-estimate O_{zf} determined from only one offset O_z and k is the spectral index of the power law.

| Region | a [nT] | k |
|---------------|----------------|------------------|
| Solar wind | 18.6 ± 1.1 | -0.87 ± 0.03 |
| Magnetosheath | 34.8 ± 1.0 | -0.44 ± 0.01 |
| Magnetosphere | 25.9 ± 1.0 | -0.41 ± 0.01 |

Table 4. Minimum number of $O_{z,n}$ estimates (first row) and corresponding time ranges (second row) required to determine the offset with an accuracy of 0.5 nT or 1.0 nT in the solar wind, magnetosheath or magnetosphere. The necessary observation time of the spacecraft (third row) in each region.

| Offset accuracy | Solar Wind | | Magnetosheath | | Magnetosphere | |
|--------------------------------|------------|--------|---------------|--------|---------------|--------|
| | 0.5 nT | 1.0 nT | 0.5 nT | 1.0 nT | 0.5 nT | 1.0 nT |
| minimum number of samples | 63 | 29 | 15325 | 3173 | 15422 | 2837 |
| time to reach accuracy | 31 min | 14 min | 128 h | 26 h | 128 h | 24 h |
| necessary S/C observation time | 132 h | 60 h | 6130 h | 1269 h | 4241 h | 780 h |

Figure Captions

Fig. 1. Schematic illustration of (a) Alfvénic fluctuations and (b) mirror mode fluctuations. The bottom panels show the in-situ (a) magnetic magnitude fluctuations, $\delta|B|$ and (b) mean (background) magnetic field fluctuations $\delta|B_{||}|$ of a virtual spacecraft crossing the respective region.

Fig. 2. Left: Normalized occurrence rate of the total magnetic field fluctuations $\delta|B|/\bar{B}$ in the solar wind (blue), magnetosheath (green) and magnetosphere (red) during 4 years of MESSENGER observations. Right: Normalized occurrence rate of the compressibility index Q^\pm for magnetic fluctuations with $\delta|B|/\bar{B} > 0.3$. Positive or negative Q^\pm values indicate whether the compressional or the transverse part of the magnetic fluctuations is dominating and $Q^\pm > 0.3$ values are considered as strong compressional fluctuations.

Fig. 3. Probability density function P , estimated with the KDE method from Equation 3 from 4-years of MESSENGER observations.

Fig. 4. The relationship between $2\text{-}\sigma(O_{zf})$ as a function of the number N of the offset estimates $O_{z,n}$. $2\text{-}\sigma(O_{zf})$ is the uncertainty of the determined best-estimate offset O_{zf} with 95 % confidence. The solid lines represent the linear least squares fits of the $2\text{-}\sigma$ confidence offsets above 0.5 nT.

Figures

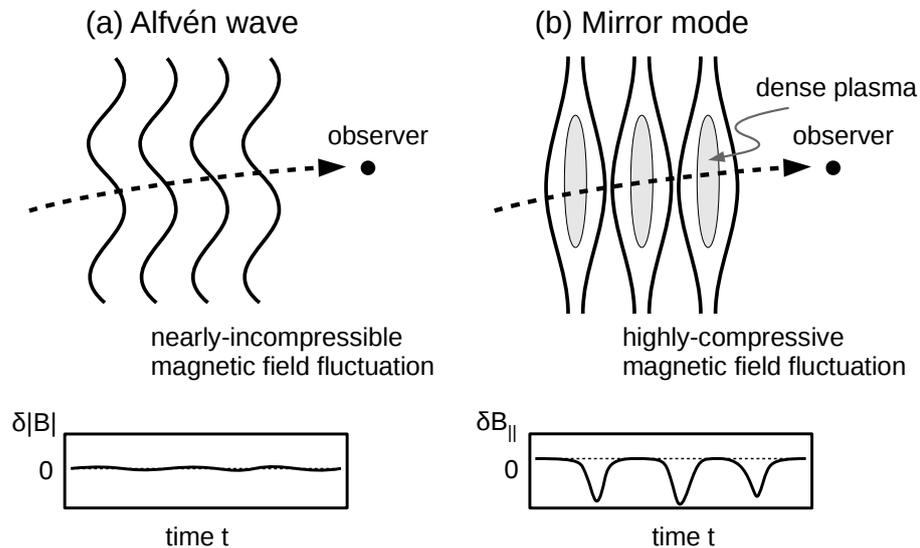


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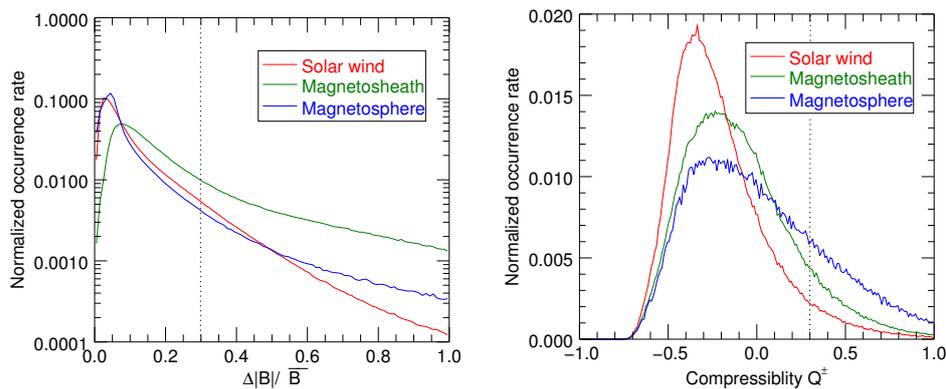


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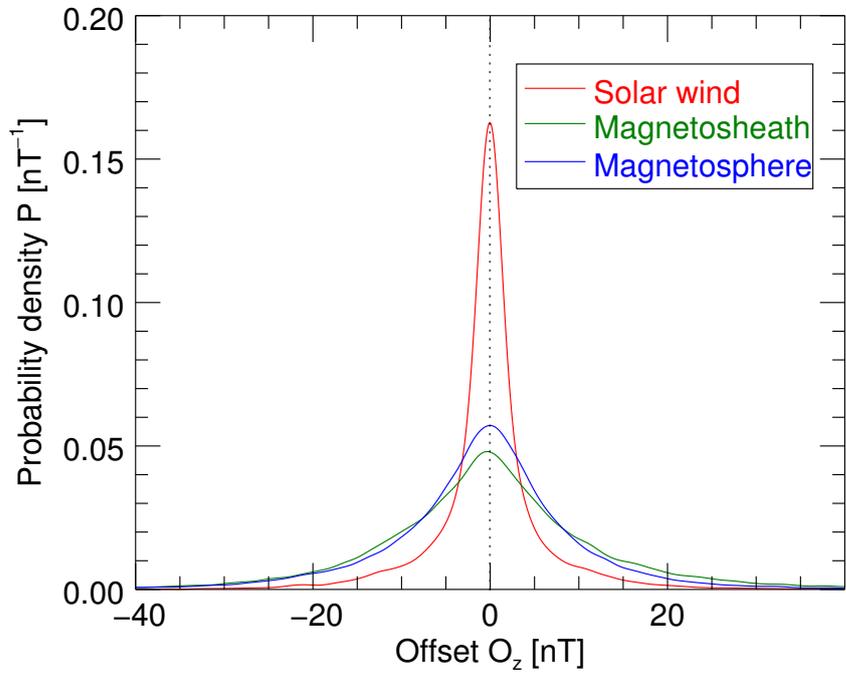


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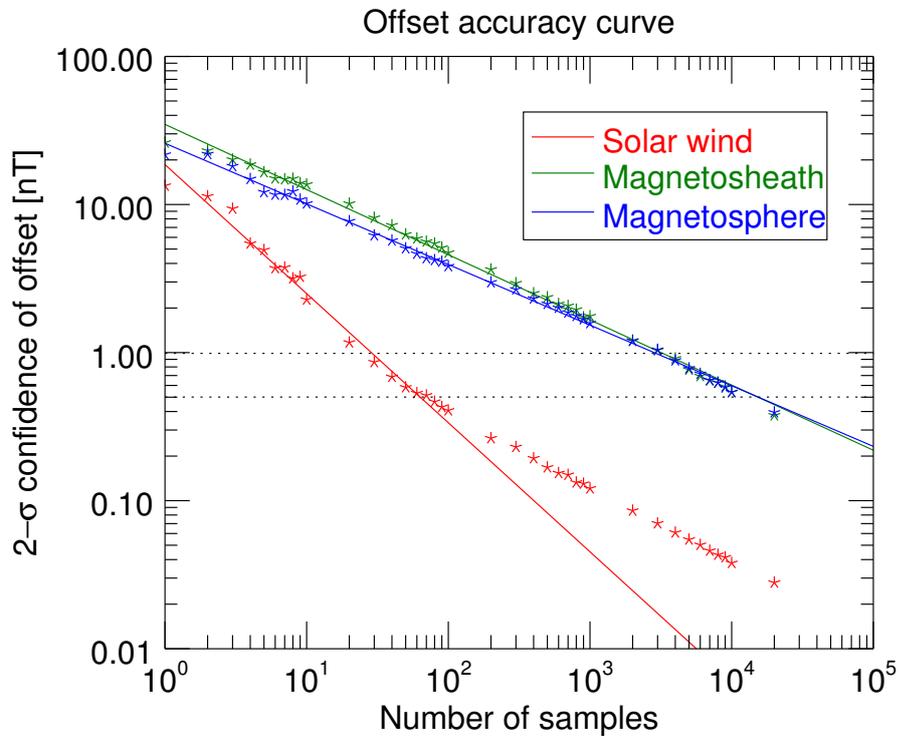


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