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Recalibration of the CHAMP Satellite Magnetic Field Measurements

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Abstract. The 8 years of continuous CHAMP operation allow us to investigate the long-term behaviours of the vector magnetometer on board the satellite. For the processing of the FGM vector magnetometer data primarily 9 instrument parameters are needed (3 offsets, 3 scale factors, 3 misalignment angles). These are determined in pre-flight calibration and routinely in the in-flight scalar calibration. A review of the temporal evolution shows that the scale factors exhibit a clear change with time. This variation of the sensitivity can well be described by a logarithmic function. The offsets and the misalignment angles show no long-term trend. The Z component offset performs medium-term variations within the range of 1nT. These have been corrected on a daily base. When processing the FGM data over the whole period with the derived parameters, the difference between the FGM and OVM readings stays below 0.5nT (corresponding to about 0.2nT standard deviation). For a further improvement the error model has to be extended beyond the scalar calibration. Dynamic spacecraft magnetic fields varying over an orbit are falsely interpreted by the scalar calibration and cause apparent variations of the instrument parameters. In the case of CHAMP magnetic field generated by the power system are responsible for most of the remaining errors. We have applied an extended error model that can account for the time-varying disturbance fields. When considering them properly the standard deviation of scalar errors less than 0.1nT can be achieved.

Keywords. Magnetic field measurements, magnetometer calibration, magnetic field satellites

1 Introduction

CHAMP (CHAllenging Minisatellite Payload) is a German small satellite mission to study the Earth's gravity field, magnetic field and upper atmosphere (Reigber et al., 2002). It was launched in

July 2000 into a near-polar, low altitude orbit. Thanks to the good condition of the satellite so far, the planned 5 years mission is extended to the year 2010. The measurements of the magnetic field are undertaken by a Flux Gate Magnetometer (FGM, vector magnetometer) and an OVerhauser Magnetometer (OVM, scalar magnetometer). In order to maintain an absolute accuracy of the magnetic field data a repeated calibration of the FGM during the mission is necessary.

Calibration of spaceborne magnetometers in orbit is a general problem. Depending on the purpose of the mission or the equipment flown many different approaches have been applied (e.g., Kepko et al., 1996; Anderson et al., 2001; Merayo et al., 2001; Kim et al., 2003; Brown et al., 2008; Leinweber et al., 2008). For Low Earth orbiting satellites (LEOs), in cases where no reference instrument is available like the Swedish micro-satellite Astrid-2, the readings of a tri-axial magnetometer was calibrated by comparing it with the field computed from a model like IGRF (Merayo et al. 2000). In case of the Argentine/USA SAC-C satellite the scalar (SHM) and vector (CSC) magnetometers are compared with their counterparts on the Danish Ørsted and German CHAMP during close encounters of the satellites (Purucker et al. 2002).

In comparison to deep space missions(e.g. Cassini with a vector/scalar helium magnetometer and a fluxgate magnetometer, ULYSSES with a vector helium magnetometer and a fluxgate magnetometer), near-earth magnetic field mapping missions Ørsted and CHAMP which both carry a vector magnetometer and a high-precision scalar magnetometer (NASA MAGSAT spacecraft had similar configurations, Langel et al., 1982) aim to modeling the global geomagnetic field and separating the different sources which contribute to it. Hence the routine in-flight calibration of the vector magnetometers is required. The scalar magnetometer serves as the magnetic reference and is mounted at the tip of a long deployable boom in order to keep the influence of the magnetic field from the spacecraft small. The scalar readings are used for checking the data of the vector magnetometer. The raw data of the vector magnetometer are processed by applying the 9 instrument parameters (scale factors, offsets and sensor non-orthogonality) that need to be updated routinely. For the applied calibration with respect to the scalar magnetometer only the scalar intensity of the magnetic field is available, therefore it is called scalar calibration (Olsen et al., 2003). The scalar calibration as a part of the in-flight calibration is performed routinely during the whole mission. It has proven to be a simple and practical method in both Ørsted (Olsen et al., 2003) and CHAMP (Rother et al., 2005) missions. Here 8 years of CHAMP operation are used to investigate the long-term behaviour of the magnetometers and the satellite systems. We present the calibration results in sections 2 and 3.

Although the scalar calibration is widely used, it is only based on a simple linear error model for a vector magnetometer. Static and long-term drifts can be detected well with it, but the method fails to invert short periodic (< 1 day) or orbit-synchronous errors like dynamic disturbance fields of the spacecraft. Primdahl et al. (2006) tried to estimate the spacecraft magnetic field from the difference in readings at the locations of the vector and the scalar magnetometer sensors near the boom tip. They assumed the field to be dipolar and the spacecraft field to vary slowly. Our studies

show that the assumptions are not applicable for CHAMP. The magnetic field created by the satellite and its electronics are complex and dynamic. We extend the initial error model by a time-variable function and associate the additional error source with the power supply system of the satellite (Yin, 2010). The dynamic disturbance fields of the spacecraft are misinterpreted in the 9-parameter scalar calibration, which causes apparent local time dependent variations of the instrument parameters. An application of the new error model is represented in section 4. In section 5 the performance of the reprocessed CHAMP magnetic field data is discussed.

2 The Routine Scalar Calibration of CHAMP Magnetometers

The scalar calibration has proven to be a useful calibration method in many satellite magnetic field mapping missions (Langel and Sabaka, 1997; Merayo et al., 2000; Olsen et al., 2003). It is based on a linear error model for the vector magnetometer. Differences between the scalar and the vector magnetometer readings are assumed to be due to inconsistencies in any of the 9 instrument parameters: scale factors, offsets and non-orthogonal angles between the sensors elements. In the CHAMP mission the scalar intensity is measured by an absolute Overhauser magnetometer and compared with the readings of the vector magnetometer. The readings of the vector magnetometer are calibrated by the 9 parameters derived from this comparison until an optimal agreement between the data of the two magnetometers is achieved.

We introduce the configuration of a sensor in Figure (1). X' , Y' , Z' denote the orientations of the three sensor axes of the fluxgate magnetometer. Ideally, they are perpendicular to each other. In reality the coordinate system based on these slightly skewed mechanical axes is non-orthogonal. We have assigned a Cartesian reference frame (X , Y , Z) to these non-orthogonal mechanical axes, where the first principal axis (Z) is fully aligned with the Z' mechanical axis. The other component X is chosen to be perpendicular to the plane defined by the axes Z' and Y' . Consequently, the axis Y is defined to be perpendicular to both axes, Z and X . Furthermore, Y lies in the plane $Z'Y'$. The relationship between this orthonormal basis and the non-orthonormal sensor system can be described as follows:

$$\begin{pmatrix} E'_x \\ E'_y \\ E'_z \end{pmatrix} = A \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} \quad (1)$$

where the vector $\mathbf{B}$ is defined by the orthogonal(X , Y , Z) and E' by the non-orthogonal(X' , Y' , Z') system. Figure (1) illustrates the geometric relation between the two coordinate systems with angles U_1, U_2, U_3 . The transformation matrix A is expressed

$$A = \begin{pmatrix} a_1 & a_2 & a_3 \\ 0 & a_4 & a_5 \\ 0 & 0 & a_6 \end{pmatrix} \quad (2)$$

where $a_1 = \frac{1}{W}$, $a_2 = \frac{\tan U_3}{W}$, $a_3 = \frac{\tan U_2}{W}$, $a_4 = \cos U_1$, $a_5 = \sin U_1$, $W = \sqrt{1 + (\tan U_2)^2 + (\tan U_3)^2}$.

90 Because Z is aligned with Z', E'_z is equal to B_z , that is, $a_6 = 1$. The angles U_1, U_2, U_3 are all close to zero. Notice that the FGM output of each component is affected also by the intrinsic offsets and scale factors of the sensor. Therefore these should be corrected first,

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{pmatrix} S_x E'_x \\ S_y E'_y \\ S_z E'_z \end{pmatrix} + \begin{pmatrix} E_{x0} \\ E_{y0} \\ E_{z0} \end{pmatrix} \quad (3)$$

where E_{x0}, E_{y0}, E_{z0} are offsets and S_x, S_y, S_z are scale factors of the components. The relationship
95 between output readings of the FGM and observed magnetic field is expressed as

$$\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{pmatrix} S_x a_1 & S_x a_2 & S_x a_3 \\ 0 & S_y a_4 & S_y a_5 \\ 0 & 0 & S_z \end{pmatrix} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} + \begin{pmatrix} E_{x0} \\ E_{y0} \\ E_{z0} \end{pmatrix} \quad (4)$$

Knowing $S_x, S_y, S_z, U_1, U_2, U_3, E_{x0}, E_{y0}, E_{z0}$ and the output of the FGM we can derive the actual magnetic field. In this sense these nine parameters fully describe the character of the tri-axial fluxgate magnetometer.

100 As we know the S_x, S_y, S_z are close to 1, and U_1, U_2, U_3 are close to zero. For efficiency reasons Eq. (4) can be written in a simplified inverse form

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} = \begin{pmatrix} l_x \cos a_{xy} \cos a_{xz} \\ 0 & l_y \cos a_{yz} \\ 0 & 0 & l_z \end{pmatrix} \left[\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} - \begin{pmatrix} E_{x0} \\ E_{y0} \\ E_{z0} \end{pmatrix} \right] \quad (5)$$

where l_x, l_y, l_z represent approximately the scale factors, and a_{xy}, a_{xz}, a_{yz} represent the angles between any two axes of the three sensor elements.

105 With the error propagation function the error of the scalar value can be expressed

$$\Delta B = |E_{fgm}| - |B_{ovm}| = \frac{B_x}{|B|} \Delta B_x + \frac{B_y}{|B|} \Delta B_y + \frac{B_z}{|B|} \Delta B_z, \quad \frac{B_{x,y,z}}{|B|} \approx \frac{E_{x,y,z}}{|E|} \quad (6)$$

where $|E_{fgm}| = \sqrt{(E_x)^2 + (E_y)^2 + (E_z)^2}$, $|E|$ for short; $|B_{ovm}|$ is the scalar reading from the Overhauser magnetometer. And the three component errors are given

$$\begin{pmatrix} \Delta B_x \\ \Delta B_y \\ \Delta B_z \end{pmatrix} = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} - \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix} \approx \begin{pmatrix} (1 - l_x) E_x \\ (1 - l_y) E_y \\ (1 - l_z) E_z \end{pmatrix} + \begin{pmatrix} -\cos a_{xy} E_y - \cos a_{xz} E_z \\ -\cos a_{yz} E_z \\ 0 \end{pmatrix} + \begin{pmatrix} l_x E_{x0} \\ l_y E_{y0} \\ l_z E_{z0} \end{pmatrix} \quad (7)$$

110 Therefore we have this linear error model,

$$\Delta B = |E_{fgm}| - |B_{ovm}| = \mathbf{M} \bullet \mathbf{P} \quad (8)$$

where the parameter vector is

$$\mathbf{P} \approx (1 - l_x, 1 - l_y, 1 - l_z, -\cos a_{xy}, -\cos a_{xz}, -\cos a_{yz}, E_{x0}, E_{y0}, E_{z0})'$$

and the design matrix $M = (\frac{E_x^2}{|E|}, \frac{E_y^2}{|E|}, \frac{E_z^2}{|E|}, \frac{E_x E_y}{|E|}, \frac{E_x E_z}{|E|}, \frac{E_y E_z}{|E|}, \frac{E_x}{|E|}, \frac{E_y}{|E|}, \frac{E_z}{|E|})$ consists only of
 115 observables.

We establish the design matrix M and solve for the parameter vector $\mathbf{P}$. A linear least-squares procedure can be used to estimate the nine parameters in vector $\mathbf{P}$ which are needed to minimize the difference between the OVM output and the modulus of the FGM outputs, i.e. $\mathbf{P} = (M^T M)^{-1} M^T \Delta \mathbf{B}$ provides the solution in the least squares sense. If we have the parameter vector
 120 $\mathbf{P}$ then the raw FGM readings can be processed. In practice we use the FGM and OVM data of one day (sampling rate 1Hz, giving 86400 equations for $\Delta B_i = M_i \bullet \mathbf{P}, i = 1, \dots, 86400$, then $\Delta \mathbf{B}$ is an 86400-by-1 vector and M is an 86400-by-9 matrix) to solve the over-determined problem. The orbit of the CHAMP satellite is near-polar and the orbital period is about 93min. The sensor axis Z points roughly to the Earth's center, X points in the flight direction of the satellite, and Y points
 125 to the east or west. At the altitude of CHAMP the ranges of the measurements span $X: \pm 40000\text{nT}$; $Y: \pm 15000\text{nT}$; $Z: \pm 60000\text{nT}$. The data of one day provide a rather uniform global distribution of the measurements. However, the parameters for the Y component are not as accurately estimated as for the other components since Y covers the smallest range. Another limitation of the method is that the short-term (shorter than one day) variations of the parameters cannot be resolved. The derived 9
 130 parameters are mean values over one day.

The experience of the CHAMP mission shows that the parameters are reasonably constant for about two weeks. If we don't update the parameter $\mathbf{P}$, the scalar error $\Delta B = |E_{fgm}^{(P_0)}| - |B_{ovm}|$ ($E_{fgm}^{(P_0)}$ means E_{fgm} calibrated by the parameter vector $\mathbf{P}_0$) will become larger and larger. Consequently, the scalar calibration of vector field measurements is performed for CHAMP every 15 days. Figure (2)
 135 and Figure (3) show the temporal evolution of the 9 instrument parameters over the whole mission, where MJD stands for Modified Julian Day starting on 1.Jan 2000 at 00:00 UT.

3 Applying Continuous Instrument Parameters

From the result of the routine scalar calibration over the CHAMP mission period, we can see that the instrument parameters show some systematic features:

- 140 – the scale factors of the 3 components show long-term trends.
- the offsets and misalignment angles show no long-term drift.
- all the parameters show some local time-related variations.

Rother et al. (2005) had used a linear function to fit the change of the scale factors. Olsen et al. (2003) had used a parabolic function to describe the time dependence of the scale factors of the
 145 FGM on Ørsted, $S_0 = S_a + S_b(t - t_{01}) + S_c(t - t_{02})^2$.

But their function is based on the variation of the scale factors only over several months. The

CHAMP data covering eight years show that the long-term dependence of the scale factor can be described much better by a logarithm function than by any other function. Figure (2) shows the fit of our function to the variation of the scale factors of the FGM on CHAMP. We have considered a function of the form, $S_0 = S_a + S_b \ln(t - t_0)$. We determine the coefficients of the function by fitting to the time dependence of scale factors over the eight years. The reason for this time dependence is probably related to aging of the electronic devices, e.g. radiation effects. The logarithmic trend indicates a long-term drift of the reference voltage in the Analog-to-Digital Converter according to the instrument provider (Technical University of Denmark, Nielsen et al., 1995; Merayo et al., 2005). They have found radiation induced voltage changes (Merayo, personal communication, 2009).

We propose another way of processing the FGM data. Rather than applying a new set of parameters every 15 days, as is done in the standard processing, we give continuous functions for the instrument parameters. The temporal change of the scale factor can be described by a logarithm function. We apply constant values for the misalignment angles and the offsets over the whole period. The applied function for the scale factors has the following form

$$S_0 = S_a + S_b \ln(MJD - MJD_0), \quad MJD_0 = 150 \quad (9)$$

The average values derived from the calibration for the offsets and misalignment angles are good estimates for the fixed values. Actual numbers for all the instrument parameters are listed in Table (1).

Subsequently we applied the continuous calibration parameters to the FGM data of all eight years. This gives us the chance to investigate statistical properties of the newly processed data, e.g. to see the local time-related variations of the residuals and to trace the systematic errors back to their sources.

As an indicator for the quality of the agreement between the OVM and FGM data we use the difference in total fields, $\Delta B = |E_{fgm}^{(P)}| - |B_{ovm}|$. The two important quantities for characterizing ΔB are the standard deviation (std) and the median value. Both are calculated for every day. Figure (4) shows the standard deviations and medians of the residuals from the routinely processed data of year 2007 in red and blue curves. Quite evident is the 15-day periodicity in some parts of the blue curve. This is the update rate of the FGM parameters. For test purposes the scalar calibration has been repeated and the nine parameters are updated on a daily base. After that the std of ΔB is markedly reduced (cyan) and the median of ΔB is practically zero (magenta). Alternatively, we applied the new processing to the data of year 2007. Figure (5) shows the results corresponding to those of Figure (4). Although we are using pre-determined functions or constant values for the FGM parameters, the sizes of the standard deviation and median values of ΔB are not significantly larger. The absence of any long-term trend confirms the choice of functions for the parameters. We repeat the scalar calibration on a daily base and obtain again a constantly small std of ΔB (cyan) and a zero median (magenta). Very small differences between two cyan and two magenta lines are due to the

different processing codes and a improvement of the averaging routine in standard processing after April 2007.

185 Since we want to avoid the daily scalar calibration in the new processing approach, we try to identify the reason for the temporal variations of the standard variation (red curve in Figure (5)). In Figure (6) we repeat the std of ΔB as a red curve. The Z component offset, as determined in the daily scalar calibration, is plotted in green. For a better comparison the absolute value of the offset is added in blue. The synchronous variation of the red and blue curves provides strong evidence for
190 the close relationship between the Z offset and the standard deviation of ΔB in Figure(6).

For obtaining a more quantitative expression of the relation between the two quantities we assumed the following linear function.

$$std^2(\Delta B) = aZ_0^2 + noise^2 \quad (10)$$

In order to test this assumption we made use of the daily results of these two quantities for the
195 years 2001 through 2008. Figure (7) shows a scatter plot of all the data points. As expected, a nice linear relation emerges. From a linear regression we obtain the coefficients and can write,

$$std^2(\Delta B) = 0.6655Z_0^2 + 0.0390nT^2 \quad (11)$$

For the physical interpretation of this result we make a short model calculation. The Earth's magnetic field can be approximated by a dipole with the components,

200 $X = B_0 \sin \theta, Y = 0, Z = 2B_0 \cos \theta$

where B_0 is the field strength at the equator and θ the angle of colatitude ($\theta = 0^\circ$ at North Pole). The effect of a small disturbance field, $\mathbf{b} = (0, 0, Z_0)$, on the field magnitude can be expressed in the form of a dot product.

$$\Delta B = \frac{\mathbf{b} \cdot \mathbf{B}}{|\mathbf{B}|} = \frac{Z_0 2B_0 \cos \theta}{B_0 \sqrt{1+3 \cos^2 \theta}}$$

205 For the average over an orbit of the squared function we obtain

$$\langle \Delta B^2 \rangle = \left\langle \frac{4Z_0^2 \cos^2 \theta}{1+3 \cos^2 \theta} \right\rangle = \frac{2}{3} Z_0^2$$

The obtained orbital average can be compared with the squared standard deviation of ΔB in Eq. (11).

It is interesting to note, that the proportionality factor of Z_0^2 obtained in the correlation analysis is very close to the predicted effect of an offset in our simple dipole model (0.6655 vs. 0.6667). This

210 confirms the role of the Z offset for the std of ΔB and that daily Z offset correction based on the scalar calibration is reliable. The imperfection of all the other parameters contributes to the noise floor of ΔB , which amounts to $\sqrt{0.039} \approx 0.2nT$ (see also Figure (6)). Based on the analysis above we can use Eq. (11) combined with the scalar calibration to confirm the Z offset correction without knowing the reason for the offset variation. On the other hand, the median value of ΔB depends on
215 the imperfection of the scale factors.

From Figure (4) and Figure (5) we can see, if we apply a daily scalar calibration, the standard deviation of the residual between FGM and OVM outputs can be reduced to about 0.1 nT (cyan

curves). We may ask why we don't do that. The answer depends on the reliability of the results. The agreement between scalar values from FGM and OVM, is not sufficient as quality criteria. Our 9-parameter scalar calibration is based on the linear model described by Eq. (8). Any discrepancy between FGM and OVM readings is attributed solely to the instrument parameters. In the presence of other error sources effects leak into the instrument parameters and make the results less reliable. The measurements of FGM on CHAMP are performed along near-polar orbits. Consequently, the sensitivity of the components to external disturbances varies along the orbit. Any systematically varying scalar error will be folded by the ambient field distribution and misinterpreted by the scalar calibration as a changing parameter vector $\mathbf{P}$. An important indication of such an error leakage is the 260-day variation of the misalignment angles as evident in Figure (8).

4 Orbit synchronous satellite magnetic fields

The instrument parameters show after recalibration some local time-related variations. Such variation may be caused by environmental influences e.g. temperature or solar illumination. In many cases the different factors are coupled. We have found a direct relationship between the temperature and scale factor changes as well as some indications for influences on the offsets. These are taken care of in the recalibration. The misalignment angles, however, do not seem to be affected by temperature.

The axes of the FGM sensor seem to be very stable. The mean values of the misalignment angles over the 8 years mission period agree within arcseconds with the angles determined in pre-flight tests. In spite of these favourable observations our in-flight recalibration reveals some systematic variation of the angles with a period of 260 days (see Figure (8)). This time period is just needed for the orbital plane to sweep through all local times. Interestingly, maximum deflections of the angles seem to occur during 12/24 local time orbits. As the local time changes, the satellite is subjected to the different conditions of sun illumination, which causes different temperatures inside the satellite (see top curves in Figure (8) and Figure (9)). These may lead to the variation of the sensor misalignment angles. However, the temperature varies with a period of 130d not 260d (from Figure (9) we can see that at 12:00 and 24:00 the sensor gets light from the same direction no matter if it is flying up or down. Correspondingly, the sensor temperature is lowest.). We take this as an indication that the apparent local time dependent change of the misalignment angles is misinterpreted by the scalar calibration.

Our simple 9-parameter scalar calibration model is somewhat unsuitable to account for the errors when there are several sources. Especially, the apparent variations of the misalignment angles imply that there must be some mixture of the different errors entering the scalar calibration. We review our

scalar error equation,

$$\begin{aligned}\Delta B &= |E_{fgm}| - |B_{ovm}| \\ &= \frac{B_x}{|B|}(f_{insx} + f_{satx}) + \frac{B_y}{|B|}(f_{insy} + f_{saty}) + \frac{B_z}{|B|}(f_{insz} + f_{satz}) + f_{ovm}\end{aligned}\quad (12)$$

Function f_{ins} gives the errors of the FGM itself and represents its characteristics. So f_{ins} is a function of the measured signal amplitude and the characteristic parameters, p .

$$f_{ins} = f_{ins}(B_x, B_y, B_z, p)$$

Parameters p may be influenced by the environmental conditions, but they are assumed to be constant over a day. In the 9-parameter scalar calibration we consider an error function $f_{ins}(B_{fgmx,y,z})$ in the form (taking the X component as an example),

$$\Delta E_x = f_{insx}(B_{fgmx,y,z}) = O_x + S_x B_{fgmx} + \cos(A_{xy}) B_{fgmy} + \cos(A_{xz}) B_{fgmz}$$

where O is the offset of the component, S the scale factor, and A the non-orthonormal angles between the components. These parameters are all represented in the error model described in Eq. (8). Obviously, the scalar errors are dependent on the measured value but independent of the time sequence of the measurements. Suppose that function f_{sat} is more probably a function of orbital local time t and it represents a disturbance from the satellite body.

$$f_{sat} = f_{sat}(t - t_0)$$

Because the OVM is expected to show little error, and the Y component is always much smaller than the other two, we simplify Eq. (12) as follows,

$$\Delta B = |E_{fgm}| - |B_{ovm}| = \frac{B_x}{|B|}(f_{insx} + f_{satx}) + \frac{B_z}{|B|}(f_{insz} + f_{satz}) \quad (13)$$

However, our measurements of the magnetometer (B_x, B_y, B_z) are not independent of the time t in orbit. The measurements are taken along the orbit of the satellite. The weight of the component $\frac{B_x, B_z}{|B|}$ in Eq. (13) can be a function of (B_x, B_y, B_z) as well as of t . But if f_{sat} is absent, the ΔB can be seen as a function of only (B_x, B_y, B_z, p). We can test whether there is an f_{sat} or not. As an example we choose the data of MJD2852 (LT, 10:54) and MJD2979 (LT, 23:10) which both are in the cold local time phase and where the average sensor temperature is $3^\circ C$, so the parameters in p should be the same. However, the misalignment angles after recalibration show differences (0.000534° for MJD2852 and -0.000649° for MJD2979) and correspond in the variation curve to the maximum and minimum, respectively. So we need an extra f_{sat} to explain ΔB , and this error $f_{sat}(t - t_0)$ is misinterpreted as misalignment angle change in the recalibration. Another hint, if we draw a plot of ΔB versus $\frac{B_z}{|B|}$, we can see clearly two straight lines (see Figure (10)). Here we have used the conclusion of chapter 3, namely, the Z offset plays an important role in the disagreement between OVM and FGM readings.

It seems the function $f_{sat}(t - t_0)$ has a simple square wave form,

$$f_{sat}(t - t_0) = \begin{cases} O_{sat_d} , & t \in \text{daytime in orbit} \\ O_{sat_n} , & t \in \text{nighttime in orbit} \end{cases} \quad (14)$$

where O_{sat_d} and O_{sat_n} are constant. Therefore function $f_{sat}(\tau)$, $\tau = t - t_0$ is an even function

285 if t_0 is chosen to be the time the satellite crosses the equator. It is assumed a square wave signal due to the daytime and night time alternation with duty cycle

$$D = \frac{d}{T}$$

where d is the duration of the orbit in sunlight and T is the orbital period of the satellite. We simply use the group of cosine functions for the simulation,

$$290 \quad f_{satx,y,z}(t - t_0) = a_{0x,y,z} + \sum_{k=1}^N a_{kx,y,z} \cos[k \frac{2\pi}{T}(t - t_0)] \quad (15)$$

where N is maximum harmonics up to 8 or 9. This means that we do not allow the signal to vary much along the orbit. The error model turns to be,

$$\triangle B(t - t_0) \approx \frac{E_x(t - t_0)}{|E(t - t_0)|} f_{satx} + \frac{E_y(t - t_0)}{|E(t - t_0)|} f_{saty} + \frac{E_z(t - t_0)}{|E(t - t_0)|} f_{satz} \quad (16)$$

A linear least-squares procedure is again used to estimate the parameters. The decomposition of

295 error sources confirms our assumption about f_{sat} . Obtained results are shown in the left panel of

Figure (11). We can see that the curves of f_{satx} and f_{satz} show the same variation relative to the day-night alternation. All the results around 12:00 and 24:00 local time show the same signature.

The second and fourth frame of Figure (11) confirm how small the residuals get when the f_{satx} and f_{satz} are considered properly. We may imagine, that f_{saty} shows similar variations, but we cannot

300 resolve them due to the small range of the Y component. The right panel of Figure (11) shows the

corresponding error propagation terms $\frac{B_x}{|B|}$, $\frac{B_z}{|B|}$. Here we present them as a function of time, centered at the daytime equator crossing. Intuitively it explains why around local times 24:00 and 12:00 the misalignment angles show, respectively, minima and maxima. In the cold phase, $D = \frac{d}{T} \approx 0.4$, the sunlight period is shortest. The dynamic part of the disturbance signal, f_{sat} , shows a similar wave

305 form as $\frac{B_x}{|B|}$ with positive and negative correlation during 24 and 12 LT orbits, respectively. The error

model described by Eq. (16) is more general than the error model of Eq. (8). For example, the error $\frac{B_z}{|B|} f_{satz}$ is strongly absorbed in the 9-parameter calibration by the term $\frac{B_x B_z}{|B|}$ and misinterpreted as change in the angle between X and Z components.

Obviously, in the hot phases of the mission, around local times 06:00 and 18:00, the satellite

310 flies mostly in the sun and D is 1. The dynamic part of the disturbance signal is small here since

the satellite is supplied continuously by the solar current. There is no change in the power system.

The disturbance signal f_{sat} appears to be a constant offset and has no influence on the variation of

$\frac{B_x B_z}{|B|}$. Such a misinterpretation of dynamic spacecraft fields causes the regular 260d periodical signal with extrema in the variation of misalignment angles at 12:00/24:00 LT orbits and zero crossings at 06:00/18:00 LT. Due to the same reason, during 12/24 LT orbits the $\frac{B_x}{|B|} f_{satx}$ effect is prone to be compensated by $\frac{B_x B_x}{|B|}$ thus causing an apparent variation of the X component scale factor. However, we have not investigated it in detail due to the absence of extra information about the disturbance field.

Physically and technically this dynamic part of f_{sat} is easy to explain. The day to night time alternation causes the switch of the power supply system from solar cell to battery supply or vice versa, which leads to changing disturbance magnetic fields from the different current circuits inside of the satellite in sunlight and darkness.

In summary, if Z_0 and f_{sat} corrections are fully exploited, the standard deviation of the scalar difference, ΔB , between FGM and OVM stays below 0.1nT (see Figure (11)). In the case of CHAMP this power system related f_{sat} cannot be accounted for deterministically because of missing house-keeping information. There is only one reading for the total solar current intensity. Separate measurements for the different panels would have been needed since each of the three panels has a different disturbance signature ranging from zero to 0.6 nT at the location of FGM. With our developed disturbance model for the solar panels we can solve the problem only partly.

5 Discussion and Conclusion

In the CHAMP mission the OVM readings are used as the magnetic standard for calibrating the FGM data. The difference between OVM and FGM readings indicates how much uncertainty is in the FGM data. However, this disagreement shows a temporal variation, which discloses that the instrument parameters have a time dependence. For this reason, a frequent scalar calibration is needed during the mission to update the instrument parameters of the FGM. In particular the long-term change of the scale factors of the CHAMP FGM is significant. We have proposed a suitable function (logarithmic evolution of scale factors) to describe the long-term behaviours of this parameter. Applying this function to the CHAMP vector magnetic field data from the past 8 years and using constant values for the offsets and misalignment angles (see Table (1)) the difference between FGM and OVM readings stays below $\pm 1nT$. This demonstrates the excellent stability of the CHAMP magnetometers.

We have found that the Z component offset of the FGM is a particularly variable parameter. Although many effects have an influence on the offset, we show the relationship between Z offset and standard deviation of ΔB . This confirms that we can, regardless of other effects, estimate the daily Z offset corrections from the standard deviation of ΔB . After this correction procedure ΔB is limited to $\pm 0.5nT$ (corresponding to std $0.2nT$). This demonstrates that all remaining uncertainty or the errors of the FGM vector data amount to less than $0.5nT$ after our calibration.

The dynamic disturbance fields from the satellite body are the main source of the remaining errors in the FGM data. The day to night time alternation results in the switch of the power supply system of the satellite from solar cell to battery or from battery to solar cell, which leads to changing disturbance fields from the currents inside of the satellite. Such disturbance fields are erroneously absorbed in the 9-parameter calibration, which causes false local time-related variations of the calibration parameters. If the disturbance fields from the power system are fully corrected, the standard deviation of the scalar difference, ΔB between FGM and OVM, stays below 0.1nT.

From the experience with CHAMP some suggestions for future satellite magnetic field missions can be made. If scientists want high precision measurement of the Earth's magnetic field (system error $< 0.5nT$), a stringent design is desired to keep the FGM away from the disturbance sources of the satellite body or to reduce the disturbance to a low level. Very helpful is a good and detailed monitoring of the currents in the various loops of the power system and a close temperature tracking of the relevant units. These are essential for parameterizing the extended error model going beyond scalar calibration. A lack of sufficient housekeeping information has impeded the correction of CHAMP vector magnetic field data to full extend. For the calibration a highly precise ($1ms$) time synchronization is needed for the comparison of FGM and OVM measurements. The essential parts of these suggestions are considered in ESA's upcoming Swarm mission.

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	X	Y	Z
S_a	1.00025304	1.00111601	1.00102659
S_b	0.00028960	0.00029990	0.00029850
Offsets	26.970 nT	19.843 nT	21.625 nT
Misalign angles	$XY : 90.02613^\circ$	$XZ : 90.05986^\circ$	$YZ : 90.03873^\circ$

Table 1. Suggested instrument parameters for the processing of the 8 years of CHAMP FGM data

Figures

Fig. 1. The orthogonal coordinate is defined from the non-orthogonal mechanical axes.

Fig. 2. Temporal variation of the FGM scale factors. The thin black lines are logarithmic fit to the measured changes.

Fig. 3. Temporal variations of the other 6 calibration parameters

Fig. 4. Daily standard deviations and medians of the residuals for year 2007. Results of the standard processing with 15-day updated parameters.

Fig. 5. Daily standard deviations and medians of the residuals for year 2007. Results of the new processing with pre-determined logarithmic or constant parameters.

Fig. 6. Comparison of the ΔB standard deviation with the Zcomponent offset

Fig. 7. Linear correlation between the variance of ΔB and the squared Z offset

Fig. 8. Apparent variations of the FGM sensor misalignment angles. The vertical lines indicate an ascending orbit at 12:00 LT. The magenta indicates the sensor temperature and the cyan the ratio of the duration of the sunshine in orbit to the period of the satellite orbit. Black circles mark MJD2852 and MJD2979.

Fig. 9. This scheme shows substantially that the attitude of the satellite and the conditions of sun illumination at different local time of the orbital plane when the satellite crosses the equator. The eye point is above the north pole of the earth (the filled large circle). Trapeziums with small circle indicate that the satellite flies from south to north; Ones with cross indicate from north to south. S_1 marks one side of the satellite and S_2 marks the other.

Fig. 10. Dependence of ΔB on the ambient magnetic field and battery discharge current. upper left panel: the slope of the red line is -0.47nT and of green is 0.18nT ; lower left: scalar error due to the f_{sat-z} with different values (-0.47nT or 0.18nT) at different t ; upper right: the errors mostly occur where $B_x < 0$; lower right: $B_x < 0$ is in the daytime.

Fig. 11. Black: Battery discharge current indicates the daytime and nighttime; Magenta: solution of f_{satx} ; Cyan: solution of f_{satz} ; Red on the left panel: the measured avg. scalar error; Green: the simulated scalar error with the solution; right panel: error propagation term of the components