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Interactive comment on "Principal Component Gradiometer technique for removal of spacecraft-generated disturbances from magnetic field data" *by* Ovidiu Dragoş Constantinescu et al.

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We thank the Reviewer for the useful comments on our manuscript. We answer bellow to the points raised and we are going to change the manuscript accordingly.

This material is fully worth publishing as a working record of the cleaning of SOMAG magnetic field data. As an academic paper to discuss the technique which contributes to the better scientific results, I think, the authors have to revise it, at first, to distinguish the matter particular to the SOMAG case from the general matter.

Major comments :

1) *The descriptions in section 2 should be considered, because they would be inadequate to explain the basics of the method proposed by the authors. The authors start with expressing the disturbances as the productions of dipole and quadrupole magnetic moments. However, the disturbance characteristic which makes the method described in section 3 applicable is the linear independence at two sensor positions, and therefore disturbances are not necessary to be expressed by the magnetic moments. Although the magnetic moment model would be very useful to optimize the sensor positions and estimate the error, as author did in section 5 and Ness (1971) did, it is not essential to describe the principle of the method proposed by the authors.*

(1) In section 2.1 we demonstrate that for single dipole/quadrupole disturbance sources the problem of deriving the magnetic field produced by a disturber at one location using only the magnetic field measured at another location, has a solution and the solution is unique (equations (2),(3) and (5),(6) on page 3). This allows expressing the disturbance magnetic field as a linear combination of the difference between the measurements (equation (7) on page 4, valid for both dipole and quadrupole disturbances). This in turn is the justification for equation (10) in section 3 (see first sentence on page 6) on which the proposed cleaning algorithm is based. We believe that this justification is essential for the proposed method and therefore the dipole/quadrupole description of the disturbing sources is necessary.

... the disturbance characteristic which makes the method described in section 3 applicable is the linear independence at two sensor positions ...

On the contrary, equations (2) and (5) show that the disturbing magnetic field at one position is a linear combination of the components of the disturbing magnetic field at another position, therefore they are not linearly independent. The most general needed characteristic for gradiometer-based methods is equation (7), i.e. the linear relation between the contribution of the disturbance at one point in space and the difference between the measurements taken at that point and those taken at another point. In the particular case of our proposed PiCoG method, an additional necessary property is the linear polarization (i.e. one dimensional character) of the disturbance.

2) *Descriptions about general rule and requirements are mixed with those about specific conditions to SOMAG and author's assumptions. It makes the readers confuse what is universal to all magnetic field measurement with what is specific to author's case.*

(2)

We agree that the text is misleading. We have to distinguish between two types of disturbance sources. The first one (the one we mentioned in the text) is caused by time variable currents. The field signature caused by this type of disturbance is identical at any measurement position and direction. Only the sign and amplitude depend on position and direction. One can rotate the field measured by a three axes sensor in a (principal axes) coordinate system in which the disturbance is present in one component only. This scalar type of disturbance needs 1 degree of freedom of a sensor difference signal for correction.

In contrast, a rotating magnet (at a sufficient large distance assumed as a rotating dipole) will produce a signature in two directions in a coordinate system aligned to the disturbance signal. We are not treating this type of disturbance in the present work.

We did our best to formulate the cleaning algorithm in its most general form. For single disturbance sources the most general approach is the gradiometer approach, expressed by equation (7). However, for the algorithm to work when multiple disturbers are present, there are several conditions to be met, which reduce the generality. The most important condition required by the PiCoG technique is that the disturbances to be cleaned vary only in magnitude and keep their direction constant. From the points (2.1), (2.2), (2.3) raised below, we conclude that by “specific conditions to SOMAG and author's assumptions” the Reviewer refers exactly to this constant direction requirement. This condition is essential for the proposed algorithm. We state in the first paragraph of section 2.2 (lines 98-101) that the universal case of multiple arbitrary disturbers cannot be treated by the proposed algorithm. Next, on page 5 lines 121-122 we clearly state that “The PiCoG cleaning method assumes this type of linearly polarized disturbances”. The next sentence allowing for “non-linearly polarized disturbances” is indeed an oversight on our part, confusing for the reader. We will remove this from the manuscript.

2-1) *page 2 line 47, 'In many cases the direction of ...' I do not think it is often the case.*

(2.1) We will change the text to make clear we refer to the disturbances due to time variable currents

2-2) *page 5 line 117, 'but does not change its direction' I do not think it is often the case.*

(2.2) We will change the text to make clear we refer to the disturbances due to time variable currents

2-3) *page 6, line 157, 'For many spacecraft, including GK2A, artificial disturbances keep their direction fixed ...' I do not think it is often the case.*

(2.3) We will change the text to make clear we refer to the disturbances due to time variable currents

3) *Many of equations in this paper are derived without enough explanation, and some of them seem to be incorrect.*

(3) Please see the answers (3.2) to (3.7)

3-1) *page 3 lines from 70 to equation (8), this part is not understandable due to the shortage of the explanations.*

(3.1) Please see the answers (3.2), (3.3) and (3.4)

3-2) *page 3 line 73, what are k and l ?*

(3.2) As stated in lines 73-74, subscripts stand for components, superscripts stand for positions. We will explain this more clear in the manuscript. k and l are the indices for the Cartesian components. $\hat{r}_k$ is the component k of the unit vector $\hat{r}$.

3-3) *page 3 line 79. 'The inverse ... ' Please explain the process to derive it. If (3X-I)^(-1) = (3/2 X-I), as authors say, (3X-I)(3/2X-I) = I. The left is 9/2 X^2 - 9/2 X + I, so it leads X^2 = X. Is it correct ?*

(3.3) We do indeed make use of the fact that $\mathcal{X}$ is an indempotent matrix, $\mathcal{X}^2 = \mathcal{X}$. On components, using the Einstein notation (summation over repeating indices):

$$(\mathcal{X}^2)_{ij} = X_{ik}X_{kj} = \hat{r}_i\hat{r}_k\hat{r}_k\hat{r}_j = \hat{r}_i|\hat{r}|^2\hat{r}_j = \hat{r}_i\hat{r}_j = X_{ij} \tag{1}$$

Now we find a and b such as $(3\mathcal{X} - \mathcal{I})(a\mathcal{X} + b\mathcal{I}) = \mathcal{I}$

$$\Rightarrow (2a + 3b)\mathcal{X} - (1 + b)\mathcal{I} = 0 \quad \forall\mathcal{X} \quad \Rightarrow \quad a\ = 3/2b = -1$$

Using the idempotency of $\mathcal{X}$ it is easy to check that indeed $(3\mathcal{X} - \mathcal{I})(3\mathcal{X}/2 - \mathcal{I}) = \mathcal{I}$

3-4) *page 4 line 84, 'and(5X-2I)^(-1) is equal to (5/6X-1/2I)' if so, again, X^2 = X. Is it correct ?*

(3.4) The inverse of $(5\mathcal{X} - 2\mathcal{I})$ is derived using a similar approach as detailed in (3.3). As proved above, $\mathcal{X}^2 = \mathcal{X}$.

3-5) *page 7, line 196, 'To eliminate the disturbance ...' this sentence is difficult to understand. Please make it easy to understand.*

(3.5) We change the formulation in the manuscript from
"To eliminate the disturbance b_x^j, the factor in front of it must vanish, therefore"
to
"Since the corrected magnetic field should be independent on the disturbing magnetic field b_x^j, results that the factors multiplying b_x^j in Eqs. (18) must be zero, therefore"

3-6) *page 17, equations (29a)(29b)(29c), Please explain how these equations are derived*

(3.6) To derive the expressions for the matrices $\mathcal{M}$ in Eq. (28) we start by writing the third order correction of the AMR-corrected outboard sensor measurements ($B^{1,sa}$) using the AMR-corrected inboard sensor measurements ($B^{1,ta}$) as given by Eq. (26) ($i = s,\ j = t$):

$$B^{c,s} = B^{1,sa} + \mathcal{C}^s(B^{1,sa} - B^{1,ta})$$

with $\mathcal{C}^s$ given by Eq. (30) being the factor in front of $\Delta B^{0,ij}$ in Eq. (26). We then replace the first order AMR corrected inboard and outboard measurements $B^{1,sa}$ and $B^{1,ta}$ in the expression of $B^{c,s}$ above using Eqs. (27) and after some algebra we arrive at

$$B^{c,s} = \mathcal{M}^s B^{0,s} + \mathcal{M}^t B^{0,t} + \mathcal{M}^a B^{0,a}$$

with $\mathcal{M}^s, \mathcal{M}^t, \mathcal{M}^a$ given by Eqs. (29). Because the DC part of the disturbances is also removed, this form of $B^{c,s}$ does include implicitly the DC offset G^s introduced by the correction.

3-7) *page 17, lines 388-399, It is not clear what G^s expresses (it cannot be the absolute offset), and how equation (31) is derived.*

(3.7) Eq. (31) is the definition of G^s. As the temporal average is taken over the entire time interval used to determine the correction matrices $\mathcal{M}$, G^s represents the difference between the mean values before correction and the mean values after the correction, i.e. a constant offset between the original measurements of the outboard sensor, $B^{0,s}$, and the corrected field. To reduce the correction to a purely AC correction we must subtract this offset from from the corrected field, hence the correction which does not introduce a DC offset (defined as the difference between the mean values before and after the correction) is given by Eq. (28). We will revise the formulation in the manuscript to avoid the confusion between the corrected measurements which include the DC offset change due to the AC correction and $B^{c,s}$ in Eq. (28) for which the DC offset change due to the AC correction is eliminated.

***4)** page 3 line 66, 'Because higher multipole moment ...' Here authors say that they can ignore the contribution by higher degree moments. However, later they discuss under the assumption that one of the sensor pair is very closely located to the disturbance source, and therefore the contribution by higher degree moments cannot be negligible. Please make the descriptions consistent.*

(4)

While in theory one could place a sensor so close to a disturber such that the octopole (or higher) contribution becomes significant, it is difficult to imagine a real life scenario where the dipole and quadrupole contributions of the disturber do not vastly overwhelm the octopole (or higher) contribution. We are indeed assuming in section 3.1 lines 151-153 that the distance from one sensor to the disturber being currently cleaned is small *relative* to the distance to the other disturbers. This does not imply a distance small enough to make octopole and higher orders visible. It merely means that the disturbers are not equally distanced from the sensor in question. On page 4 lines 106-110 we state that the dipole and quadrupole contributions should not have comparable strengths at the sensor location. We will change this sentence to clarify that also higher multipoles should be weak compared with the dominant dipole or quadrupole being cleaned.

***5)** The proposed strategy to remove the noise argued in this paper seems to be inconsistent. In page 6, line 151, 'We now assume that one of the terms in Eq. (9) is much larger than the others. ...' In page 10 line 2, 'the placement of the AMRs close to the disturbances sources.' To do it, the authors should know the positions of the disturbance sources to locate the sensors nearby. It is inconsistent with the advantage of this method, 'allows the separation of disturbances generated by the spacecraft ... without prior knowledge about the positions of the disturbances sources. (page 5, line 134)' Please make it consistent.*

(5)

The observation is correct, of course some knowledge about the disturbers positions is necessary. For instance if a disturber is placed at equal distances from two sensors, the proposed procedure using those two sensors cannot work. It is also assumed that the boom-tip placed sensor is further away from disturbers than the other sensors, and that when the body-mounted sensors accommodations were decided at least some minimum information about the locations of major disturbers was available so sensors could be placed in their vicinity. However, apart from that, the positions of the disturbers do not enter in any way in the cleaning procedure, hence the statement in line 134. We will clarify this in the manuscript.

***6)** page 9, line 232, '3-axis Flux Gate Magnetometer (FGM)...' Is the outboard sensor built based on the design by Primdahl (1979) and inboard one is based on Acuna (2002) ? If not, please refer the papers more adequately.*

(6)

Both sensors are neither designed similar to the sensors described in the early Acuna or in the Primdahl papers. The reference refers to the fluxgate principle only. The Mario Acuna design consist of three single component sensors accommodated next to each other. The disadvantage of these sensors is that the axes directions are determined by the ringcores and the pickup windings and thus they are not stabilised by the more robust feedback coils. At low field conditions (e.g. for the Voyager spacecraft) this is not of importance, however for e.g. MAGSAT it causes a significant uncertainty. Fritz Primdahl has therefore developed a vector compensated sensor in which a sensor similar to the sensors developed by Acuna has been placed in a sophisticated feedback coil system compensating the field for all three single sensors in all directions. Xavier Lalanne developed a very nice sensor in which 6 ringcores are placed on the sides of a cube inside a Helmholtz coil system. This is a great design because it is fully symmetric, however very elaborated. Our design is based on two crossed ringcores in the centre of a Helmholtz system. It is described in detail in the Themis Magnetometer paper by Auster at al. which has been added to the list of references.

***7)** page 10, lines 263-268, I suppose that the sensing alignment relationship between the FGM and AMR sensors would significantly affect the result of the removal of the magnetic disturbances. Please describe the knowledge about the alignment relationship and its accuracy.*

(7) Actually the alignment between the FGM and AMR sensors plays no role in the PiCoG method. This is because the cleaning is performed only on the maximum variance components of the measurements which are independent on alignment.

***8)** As for the March 4 case presented in this paper, magnetic disturbances are caused by multiple sources and they can be discriminated because the repetition periods are very different one another. The authors should discuss the condition regarding the repetition periods of the disturbances when the proposed method works well and when it does not.*

(8)

That is correct. The proposed method works well when the polarization direction of the targeted disturbance is determined by the maximum variance direction. If the disturbances are in the same frequency range and therefore cannot be decoupled by using

different window lengths one must either find their polarization direction using other means, or they must have magnitudes different enough such that the dominant disturbance – being currently cleaned – determines the maximum variance direction. We will introduce a paragraph clarifying this in section 5.

***9)** The order of Figure 2 and Figure 3 should be changed since Figure 3 appears earlier in the text.*

(9) This is correct, it will be fixed in the manuscript.

***10)** The meaning of the word 'orthogonality' in this paper is not clear. If it means linear independence, 'up to three independent, mutually orthogonal, simultaneously active disturbances can be separated using two sensors. (page 5, line 118)' would not be correct. More than three disturbances may be separated if they are linearly independent. The statement in page 14, lines 323-332 should be revised.*

(10) In the manuscript, the word "orthogonal" has the common geometrical meaning: Two directions are called orthogonal if they form a right angle. We say that two disturbances are orthogonal if their maximum variance directions are orthogonal to each other. We will explain this better in the manuscript.

***11)** Page 17, section 4.3, What is the advantage to remove the disturbances by the onboard processor ? Because it cannot be guaranteed that the coefficients do not change for long period, it would be much better to determine the coefficients from the raw data on the ground.*

(11) The coefficients were determined from raw data on the ground. Monitoring the magnetic field at geostationary orbit supplies important information about the space weather events reaching the Earth. On-board data cleaning provides near real-time accurate magnetic field data which is essential in this context. An added benefit is a four fold increase in the time resolution achieved by changing the telemetry from raw data from four sensors at one vector per second to cleaned data at four vectors per second. We will include this information in the manuscript.

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