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Geoscientific Instrumentation Methods and Data Systems Discussions

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 constructive remarks and critics.

... The presented method needs the disturbing sources to change with time (variance analysis). In spacecraft magnetical cleanliness DC magnetic disturbers play a big role. On the other hand the offset drift of fluxgate magnetometer is a known problem. Is the method valid for DC calibration? Otherwise write "AC disturbance" in line 5 (Abstract) and in line 496 (Summary and Conclusion). ...

• If the mean field produced by a disturber is different from zero, i.e. there is a non-zero

DC disturbance due to the targeted disturber – which is most of the times the case, the proposed method will automatically correct this DC disturbance if it depends in the same way on the distance to the source as the cleaned AC term (dipole/quadrupole). The total DC shift introduced by the final correction is contained in the G^s vector given by equation (31). However, even if the above condition is true, the method presented here does not provide the DC offset produced by completely time independent disturbers, therefore it cannot be used for the DC correction. Moreover, the internal offset drift of the sensors cannot be treated using the PiCoG technique. We will make this clear in the Abstract and in the Conclusions.

... The authors call their method to deal with the SOSMAG data "PiCoG algorithm". It is more of a methodology than an algorithm that could be coded as is.

• That is correct. We abused the word "algorithm". We will replace "algorithm" with "technique/method" throughout the manuscript.

In chapter 2.1 interesting formulas are deduced for dipole and quadruple fields. They are used to show, that the magnetic field of a low frequency source can be factorized in a time-dependant and a geometry part. But is not that clear anyway for quasi DC magnetic sources?

• Indeed, equations (1) and (4), which are just the expressions for the magnetic field produced by a dipole/quadrupole show the trivial fact that in this case the space dependence can be separated by the time dependence as a factor. The key relations here are equations (2) and (5) which show that the magnetic field produced by a time-dependent dipole/quadrupole at a given location can be obtained using a *time independent* transformation of the magnetic field measured at a different location. This proves that it is in principle possible to use the measurements from one sensor to correct the measurements delivered by another sensor at different location. This is the foundation of our approach.

Do the formulas for the geometry factors enter the evaluation?

• No, the $\mathcal{T}$ matrices given by equations (3) and (6) are not used as such by the PiCoG technique. They might be used perhaps in a very controlled environment when the positions of the sensors and disturbers, as well as the decay law (dipole/quadrupole) of the disturber are precisely known. This work's goal is to provide a technique which does not require this information. However, the correction matrix $\mathcal{A}$ is related to the $\mathcal{T}$ matrix by the relation in line 146. This means that – once the $\mathcal{A}$ is computed using the PiCoG method – one could derive the corresponding $\mathcal{T}$ matrix. This is beyond the scope of the present work.

In chapter 3.1. it is assumed, that one of the magnetometers is very close to a disturber. Does the method also work, if that is not the case?

• This depends on the specific sensors-disturbers configuration. E.g. if more disturbers of the same type occupy a volume which is small compared to the distance to the closest sensor, the method works even if the sensor is not closer to one of the disturbers than to the others. If the directions of maximum variance of two disturbers are orthogonal to each other, again the method works even if the strength of the two disturbances are the same / disturbers placed at similar distances to the sensor. There are however situations in which the method does not work, as detailed in section 5.

Unfortunately none of modern methods for analysis of multivariate time series is used. Principal component analysis is one of them. It uses spectral analysis of the cross-covariance matrix of all additional measured magnetometer components with respect to the reference magnetometer. ...

• We are not sure we understand the point raised by the Reviewer. We *do* use Principal Component Analysis (PCA) as a key method employed by PiCoG. We state this e.g. in lines 119-120, 164-166, 496-497. We indeed determine the direction of maximum variance from the eigenvectors of the covariance matrix as described e.g. in section

1.4 of *Time Series Data Analyses in Space Physics, Song and Russell, SSR (1999)* or in *Analysis methods for multi-spacecraft data, Sonnerup and Scheible, ISSI Sci. Rep. SR-001, p185-220, Ed Paschmann and Daly, (1998)*. We do not perform a spectral analysis though because it was not necessary for our specific problem. Of course, if one knows – or determines – in advance that the disturbance to be removed is confined in a specific frequency band, one may perform the PCA in the frequency domain and select the eigenvectors corresponding to the frequency band of the disturbance. We will comment on this possibility in the revised text.

... The results of sec. 2.1, that means the known geometry factors, add information not been used in standard methods. Using for example the geometry factors for better identifying disturbing time series in the data, or for better determining the distribution of disturbing signal to the different magnetometers would render this paper interesting to a broader public.

• It is true that in this work we did not directly exploit equations (3) and (6) which give the exact expression of the "propagator" matrix $\mathcal{T}$ which allows computing the disturbance at one point in space once the disturbance at another point is known. This would allow cleaning the disturbances using a precise model representing the disturbance sources and the sensors positions. However, this is not the goal of the present work. Here we determine the correction matrices $\mathcal{A}$ – which are equivalent with the $\mathcal{T}$ matrices – solely from the available measurements. Of course, it might be possible to develop an entirely different method using the $\mathcal{T}$ matrices. However, making more intensive use of the $\mathcal{T}$ matrices is not necessary in the context of the present work.

The time dependence of the disturbing signal is not at all used in chapter 3, where the PiCoG Algorithme is defined.

• The time dependence is implicitly used through the fact that the correction is applied to the principal variance component.

... Nevertheless during the actual data evaluation the authors implicitly use the time dependence by looking at different time periods, with different sources active. Fig. 2 shows the distribution of directions on a sliding window. Later on, in chapter 4. ramps and spikes are used to validate the result. These tricks should be included in the PiCoG algorithm.

• We made efforts to keep the PiCoG method described in section 3 as general as possible. Including procedures specific to our particular application of the method to the SOSMAG data would in our opinion induce confusion to the reader. Presenting these procedures in the application section on the other hand, lets the reader decide for him/herself if these procedures are appropriate or not for his/her problem at hand. Even for our specific problem we did not used the same procedures from the beginning to the end: For the AMR correction we determined the maximum variance direction using just one step-like disturbance, while for the FGM-FGM correction we decided for a statistical approach using a sliding window.

The variance of measured date is used. That means field sources (ambient andmdisturbing fields) are understood as random processes. The motivation is not clear.

• It is true that variance normally refers to the the deviation of a random variable from its mean value. A certain randomness is introduced by the ambient field. However, in the context of the present work, the random/non-random character of the disturbance plays no role. We use the variance only as a measure of how strong the AC disturbance is in each direction, and through PCA we determine the direction in which the variance is largest therefore the disturbance is strongest.

...The step amplitudes in all components could directly be used to deduce the geometry factors (Component of Matrix A in formula 10) between different magnetometers.

• The correction matrix $\mathcal{A}$ is composed from a rotation and a scaling. We don't see a direct way to deduce the $\mathcal{A}$ matrix from step amplitudes. After the rotation in the VPS

one could indeed determine the amplitude of the steps as we did in section 5 and from them derive the α factor in equation (13a). We think however that equation (14) gives a more general solution. Both estimates of the α factor are susceptible to improvements anyway as mentioned in lines 273-274.

Fig. 4. Shows magnetometer values in the coordinate system orientated along the main axes of the data variances ellipsoid (VPS system). The figure shows, that the spike signal is still present in the z- and in the y-direction. Accordingly the VPS x-direction does not point along the spike disturbance.

• This is correct. The x-axis of the VPS in Figure 4 is aligned with the variance direction of the highest frequency disturbance (first to be cleaned), distinct from the direction of the spikes. The VPS in which the data in Figure 5 is represented has its x-axis aligned with the direction of the spikes.

L39: The PiCoG Process also is not running on the SC.

• The PiCoG technique delivers the correction matrices $\mathcal{M}$ which are uploaded to the spacecraft and used for onboard data cleaning. As far as we understand, the *Poppe et al. (2011)* procedure cannot be reduced to a simple linear combination which can easily be implemented onboard.

L48: This is the case if only variances are looked at. But the authors look later at ramps and spikes. They can even be identified, if they point along the ambient field.

• We use the PCA also for the ramps and for the spikes. One could use other methods to determine the direction of the rams or spikes disturbances (even manually perhaps), but the PCA delivers the correct directions and the scale factors in an automatic fashion. We will emphasize in the text the use of PCA for spikes and ramps.

L48: The term "principal component" is misleading. It usually refers to direction of a main axe of the stray ellipse in a multivariate random process.

• The term “principal component” in the text does indeed refer to the main axis of the variance ellipsoid. The fact that the disturbance is not a random process does not affect neither the application of the PCA nor its results. We will comment in the text on the non-randomness of the the disturbances in order to prevent possible confusion.

L107: Perhaps better: “a collection of dipoles will in general generate multipole moments”

• The suggested formulation is indeed better. Thank you, we will use it in the text.

L 151: Which term is much larger? Would a strong disturber really make only one term large?

• Since the summation index q in equation (9) refers to the disturbance sources – as detailed in line 137, the term corresponding to the strong/close disturber will be larger. A strong disturber will only affect the corresponding term in the sum.

L137 this sentence would be more readable, if the summation symbol was omitted.

• We will re-phrase this sentence to make it more readable.

L157: Do you mean: “disturbing magnetic moments are fixed in direction with moments changing with time”?

• Yes, this is what we mean. We will adapt the text to follow the Reviewer’s suggestion.

L158: The stray field of one disturber has a constant direction in the magnetometer system. No need for a new coordinate system.

• The stray field of one disturber has indeed a constant direction in the magnetometer system. However, a new coordinate system is needed to align this direction with one of the coordinate system axes (in our case the x-axis).

L166: Using this VPS suggests, that the disturber itself is a multivariate random process. But that is not the case. The VPS-x direction can be calculated by correlating the disturbing field strength with the measured x-, y- ,z- components. The term “variance principle system” is misleading. The reader could get the impression, that principal component analysis was done.

• PCA was in fact done in order to obtain the disturbance direction. As stated before, the non-random character of the disturbing field is not relevant in this context. One could probably obtain the disturbance direction by minimizing the correlation between the disturbing field strength and the measured y and z components using as free parameters the angles of rotation for the new system. We do not see the advantage in using this alternative method.

L167: Are the alpha i,j in Eq. 13a the same as the A i,j in Eq. 10? Than please use the same denomination.

• They are not the same. $\mathcal{A}^{ij}$ in equation (10) is the matrix used to correct sensor i measurements using sensor j measurements. $\alpha^{0,ij}$ in equation (13) is a scalar scale factor given by equation (14) for the first order correction.

L191: It is not clear to me if the b’s are known at this point and if yes, where they are calculated.

• The disturbance b at the sensor position is not known at this point. We only make use of the dependence on the distance of b as stated in lines 193-195.

L211: Do you mean “if stray fields of different disturbers are not coincident at the magnetometer location”?

• We mean “if stray fields of different disturbers do not share the same direction at the magnetometer location”. We will adapt the text.

I quit following the text here because the authors use a matrix notation, where I guess vectors of stray fields are sufficient.

• We do not see how to concisely write the relations without using matrix notation.

Conclusion: The paper is an excellent report on how the authors achieved to clean and calibrate SOSMAG data. However the term "principal component technique" in the title is misleading. The authors should revise the method and try to use or at least refer to standard methods for multivariate data analysis and, if possible, expand them to produce a paper of more general interest.

• We thank the Reviewer for the appreciative comment. However, as explained above on several occasions, PiCoG *is* using principal component analysis as a essential tool, therefore we believe the title is appropriate. We will revise the paper nevertheless to emphasise the use of this standard analysis method.