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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 reaction to our response. We hope that our answers below will clarify the issues pointed out.

"PiCoG algorithm" *: Would you think that the following procedure is in line with what you did. Could this be a line out of an algorithm?*

1. Define one of the N instruments as "reference instrument".

2. Calculate the differences of all instruments and the reference instrument.

3. In all difference signals, identify the instrument j showing the strongest disturbance.

4. Use this difference to correct all instrument readings using Eg. 13

5. For the next iteration start over with 2. disregarding instrument j.

• No, we use a different procedure:

Assume three magnetometers, m_0, m_1 and m_2 and two disturbance sources, d_1 and d_2. Assume we define instrument m_0 as reference instrument. Assume the dominant disturbance at the instrument m_1 location comes from the source d_1 and the dominant disturbance at the instrument m_2 location comes from the source d_2.

Assume the difference is largest for the instrument m_1, i.e. $|var(\Delta B^{01})| > |var(\Delta B^{02})|$. In these conditions equations (13) will work correctly to clean the disturbance d_1 from the measurements taken by the reference instrument m_0 and – if desired – also from the measurements taken by the instrument m_1.

However, as explained in lines 170-173 of the original manuscript, beside the $(\Delta B)_x$ term, which is written in the VPS of the difference ΔB, all other terms in equations (13) are written in the VPS of the measurements at the respective instruments. The maximum variance x-axis computed for the instrument m_2 will be aligned with the direction of the disturbance d_2 at the location of the instrument m_2 which in general will be different from the direction of the disturbance d_1 at the location of the instrument m_2. Therefore equations (13) used as suggested by point 4 above, would apply the correction for the disturbance d_1 to the wrong component of the measurements taken by the instrument m_2. Moreover, the scaling factor computed using the variance of the measurements from the instrument m_2 will also be wrong.

In contrast, the PiCoG technique uses one instrument pair at a time: After points 1-3 above, we clean the (strongest) disturbance d_1 from the measurements of the reference instrument m_0. Afterwards we compute the difference between the cleaned measurements from the reference instrument m_0 and the measurements from the instrument m_2. This difference will now reflect the disturbance d_2. We determine the VPS of the difference and of the measurements from the instrument m_2 and we finally apply again equations (13) to clean the disturbance d_2 from the cleaned measurements taken by the reference instrument m_0.

Note that the method works without knowledge about the exact positions of the sources and – after the correction matrices are determined on ground – it works with simple multiplications and additions, which can be done in real time by the onboard software.

PCA: *You determine the main axes in the 3D distribution of magnetometer measurements and in the distribution of differences between two different magnetometers. Then you assume that your α can be calculated based on the quotient of variances along these main axes (Eq. 14). This is a very bold assumption and you named quite some requirement for this assumption.*

• Up to a constant factor, the difference ΔB is the same as the disturbance at the sensor to be cleaned (same time dependence). The factor is the ratio between the amplitude of the difference and the amplitude of the disturbance at the sensor to be cleaned. This can be directly derived from the variances. As mentioned on line 174 of the original manuscript, equation (14) gives a first order estimation of the scaling factor α. This estimation may deviate from the exact scaling factor due to large ambient field fluctuations or due to additional disturbances with the same polarization direction as the disturbance to be cleaned. To improve this value one may for instance minimize the correlation between the corrected measurements and the disturbance represented by the difference ΔB as we note on lines 271-274 of the original manuscript. However, in our case this proved not to be necessary.

Asking for PCA, I meant to use PCA in the 3N dimensions of all available measured time series. If PCA is referred to in the title the reader will expect it to be used on the

multivariate time series
$(X_1(t), Y_1(t), Z_1(t), \Delta X_{21}(t), \Delta Y_{21}(t), \Delta Z_{21}(t), \Delta X_{31}(t), \Delta Y_{31}(t), \Delta Z_{31}(t), ...)$.
"1" being the reference magnetometer. This automatically produces what you call VPS-x directions (as components of the largest eigenvector).

• PCA done in 3 dimensions is not something unusual in space physics data analysis, see e.g. section 1.4 "Principal Axis Analysis" of *Time Series Data Analyses in Space Physics, Song and Russell, SSR (1999).* There might be a way to use PCA in $3N$ dimensions for cleaning multi-sensor data, but the exact implementation of this is not obvious to us. The maximum eigenvalue and the corresponding eigenvector derived for the multivariate time series suggested by the Reviewer would somehow mix the reference instrument measurements with the differences between those measurements and the measurements from all other instruments. Moreover, as explained above, if different disturbances affect different sensors, they will also be mixed together, even if initially they were decoupled from one another. This is exactly what we are trying to avoid. Even if perhaps possible, at the moment we do not see how a technique based on PCA in $3N$ dimensions can be implemented for cleaning multi-sensor data. As we showed by applying it to SOSMAG data, the (3D PCA) procedure proposed by us works well to decouple and clean spacecraft disturbances, and, in our opinion, is general enough to be easily adapted to other multi-sensor configurations.

... Please judge for yourself whether the reference to PCA in the title is really justified.

• We realise that some readers might expect a treatment along the lines suggested by the Reviewer, therefore we change the title to "Maximum Variance Gradiometer technique for removal of spacecraft-generated disturbances from magnetic field data".

But even PCA and factor analysis do not deliver unique results. In PCA geometry factors are completely ignored. Therefore exploitation of Eg. 3 and Eq. 6 would introduce a completely new idea going further than what can be done by PCA.

• Using the equations (3) and (6) would be indeed a very different approach from the one presented by us. It is definitely worth exploring ways to use these relations to develop new methods – perhaps model-based – for cleaning multi-sensor data. Once developed, such methods could be combined with the PiCoG technique to improve the results, but this should be the focus of another study.

On page 6 between line 157 and line 180 you argue very intuitively. This lack of mathematical rigor should be mitigated using PCA in the way I proposed.

• As explained above, a direct application of PCA in $3N$ dimensions is not a solution for our problem. On page 6 we write down the expressions of the corrected measurements under the stated assumptions. We do not see where the lack of mathematical rigour lies.

It is absolutely not clear how Eq. 10 follows from Eq. 9. I even doubt, that a linear relation between the correction value for B^i and the $\Delta B^{i,j}$ exists. This is only true if only one single disturber is on. I guess Eq.10 is the first order approach assuming that a certain disturber is very prominent (at a certain time span) in the difference $\Delta B^{i,j}$. Please clarify and explain that in the text.

• Equation (10) does indeed not follow equation (9) in the general multiple disturber case. We will reformulate the text to better explain that equation (10) is valid for single disturber case.

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