Cleaning magnetometer data using multi sensor configuration

Application to GEO-KOMPSAT-2A

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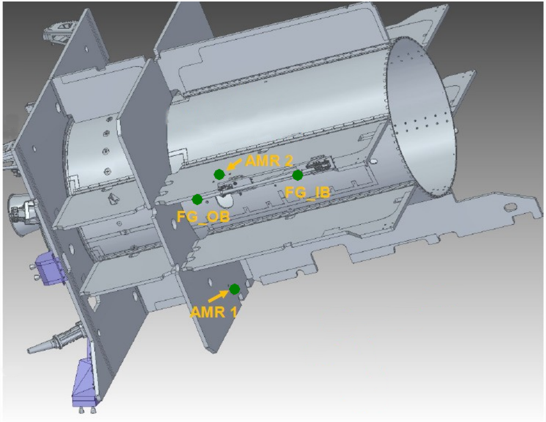
Outline

Variance analysis · (Principal Component Analysis)

It is a simple technique which identifies a more meaningful basis to represent the measured data

- assume N measured quantities, $q_i(t)\,;\ i = 1, \ldots, N$ (e.g. $B_x(t), B_y(t), B_z(t)$)
- Covariance matrix elements: $C_{ij} = \langle q_i q_j \rangle - \langle q_i \rangle \langle q_j \rangle$
  - diagonal elements represent the standard deviation σ^2 for each components
  - off-diagonal elements represent the correlation between different componentss

- compute the eigenvalues / eigenvectors: $\mathcal{C}\mathbf{v}_j = \lambda_j \mathbf{v}_j\,;\ j = 1, \ldots, N\,;$ $\lambda_1 > \lambda_2 > \cdots > \lambda_N$
- construct the transformation matrix to the new basis: $\mathcal{R} = (\mathbf{v}_1, \ldots, \mathbf{v}_N)$
- the transformed covariance matrix $\mathcal{C}' = \mathcal{R}^T \mathcal{C} \mathcal{R}$ is diagonal
  - most of the variation is in the first new component
  - correlations between the new components are minimized



- Korean meteo / space weather satellite
- launched on Dec 4 2018
- geostationary orbit 128.2° E
- no magnetic cleanliness
- 2 FGM sensors on a 1 m long boom
- 2 AMR sensors on the spacecraft body

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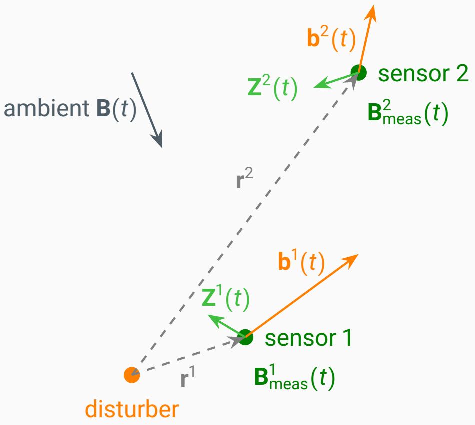
task:

- to remove the sc generated AC disturbances

Service Oriented Spacecraft Magnetometer (SOSMAG) concept



- Magnetic field measured at sensor *i*:

$$\mathbf{B}^i_{\text{meas}}(t) = \mathbf{B}(t) + \mathbf{b}^i(t) + \mathbf{Z}^i(t)$$

  - $\mathbf{B}(t)$ $\rightarrow$ ambient field
  - $\mathbf{b}^i(t)$ $\rightarrow$ disturbance at $\mathbf{r}^i$
  - $\mathbf{Z}^i(t)$ $\rightarrow$ sensor specific noise and offset

- Difference between measurements:

$$\Delta\mathbf{B}^{ij}_{\text{meas}}(t) = \Delta\mathbf{b}^{ij}(t) + \Delta\mathbf{Z}^{ij}(t)$$

- Corrected measurement:

$$\mathbf{B}^i_{\text{corr}} = \mathbf{B}^i_{\text{meas}} + \mathcal{A}^{ij}(\Delta\mathbf{B}^{ij}_{\text{meas}}), \quad \mathcal{A}^{ij} = \alpha^{ij}\mathcal{R}(t)$$

Variance driven SOSMAG cleaning algorithm

Polarized disturbance: $\mathcal{R} =$ constant in time $\Rightarrow$

- Transform to the **V**ariance **P**rincipal **S**ystem (x-axis aligned with the maximum variance direction)
- Only the maximum variance component needs correction: $(B^i_{\text{corr}})_x = (B^i_{\text{meas}})_x - \alpha^{ij}(\Delta \mathbf{B}^{ij}_{\text{meas}})_x$

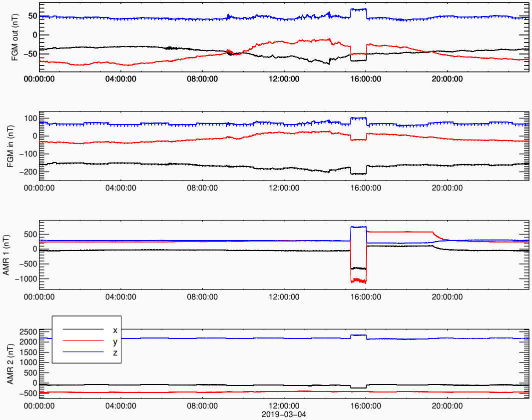
$\Rightarrow$ $\mathcal{A}^{ij}$ is completely determined by the scalar coefficient α^{ij} and by the maximum variance directions:

$$\mathcal{A}^{ij}_{kl} = -\alpha^{ij}\left(\left(\mathcal{R}^i\right)^{-1}\right)_{kx}\left(\mathcal{R}^{ij}\right)_{xl}, \qquad \alpha^{ij} \text{ is estimated from the variance ratio}$$

- Disturbance is removed but sensor specific is noise added: $(B^i_{\text{corr}})_x = B_x + 0 + Z^i_x - \alpha^{ij}(Z^i_x - Z^j_x)$
- Corrected measurements for the two sensors are identical: $(B^i_{\text{corr}})_x \equiv (B^j_{\text{corr}})_x$

Higher order corrections:

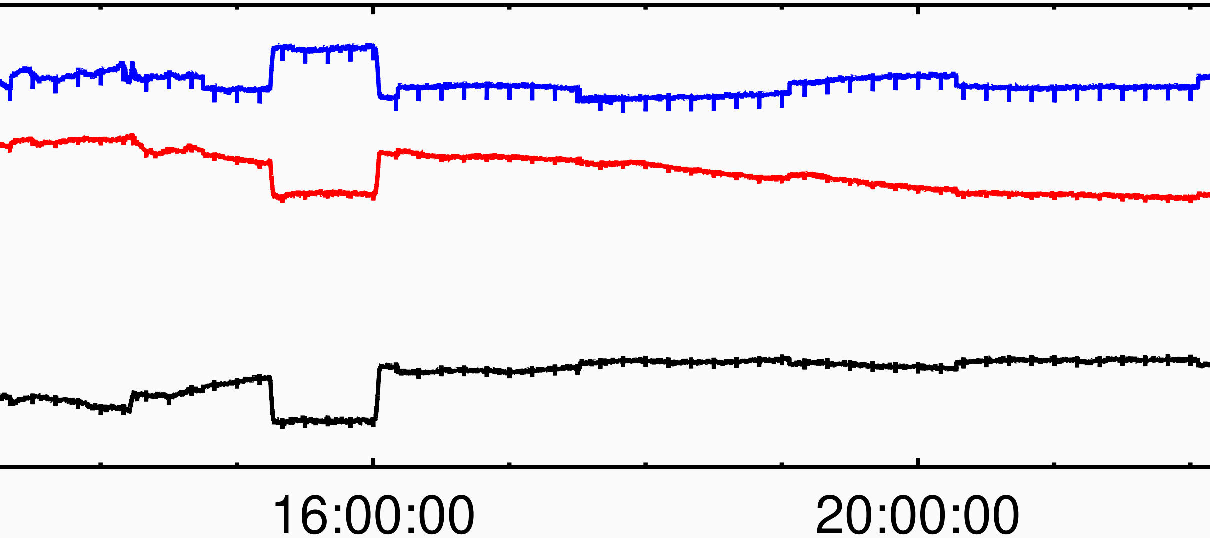
$$\mathbf{B}^{n,ij} = \mathbf{B}^{n-1,i} + \mathcal{A}^{n-1,ij}\Delta\mathbf{B}^{n-1,ij}, \qquad \mathcal{A}^{n-1,ij}_{kl} = -\alpha^{n-1,ij}\left(\left(\mathcal{R}^{n-1,i}\right)^{-1}\right)_{kx}\left(\mathcal{R}^{n-1,ij}\right)_{xl}$$



- Representative for the routine operations
- 16:00 disturbance seen by all sensors
- AMR/FGM amplitude ratios:
  - 40 for AMR 1
  - 5 for AMR 2

Strategy:

- Do not use the AMR2 data for AC cleaning
- 1st step: clean both FGMs using AMR1
- 2nd step: clean resulted FGMI/O using FGMO/I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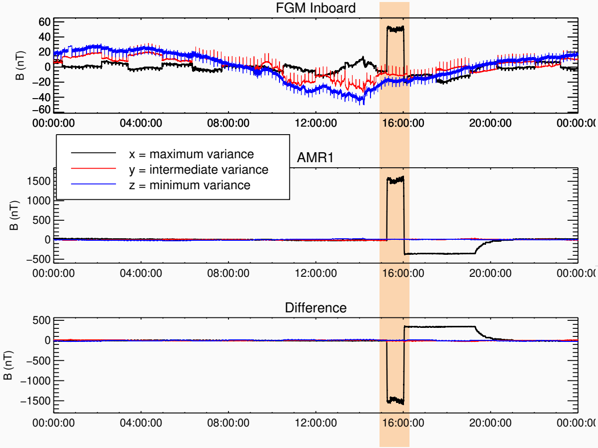
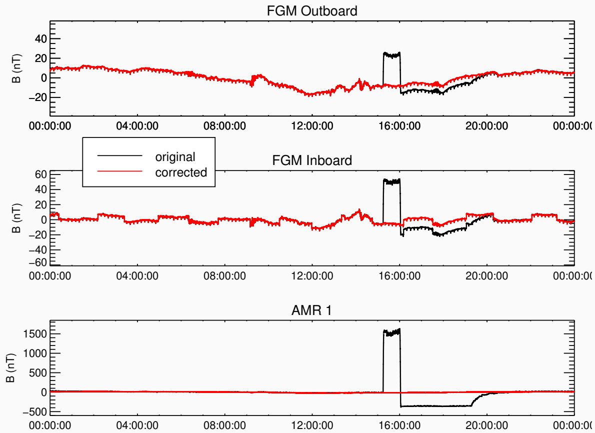


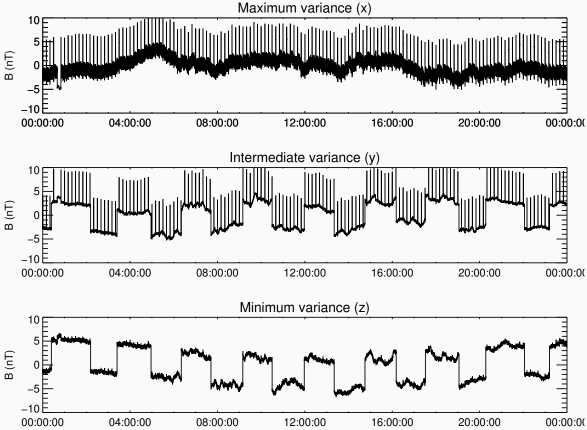
- find the VPS for the [15:10,16:15] interval
- distinct coordinate systems
- rotate the entire day to the found VPS

- main disturbance only in *x*-component
- no steps in the *z*-component



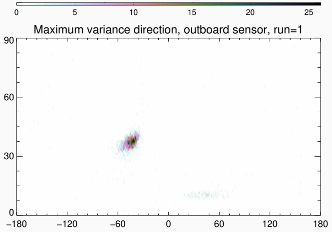
- scaling and rotation parameters:
  - FGM Out $\alpha = 48$ $\theta = 51°$ $\phi = 126°$
  - FGM In $\alpha = 27$ $\theta = 54°$ $\phi = 141°$
  - AMR 1 $\alpha = 0.97$ $\theta = 73°$ $\phi = 114°$

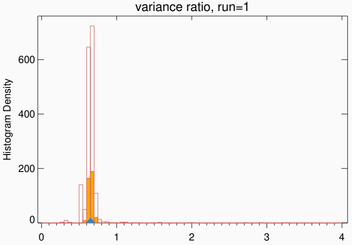
- targeted disturbance removed
- corrected FGM $\Rightarrow$ 2nd step initial data



Disturbances decouple on components:

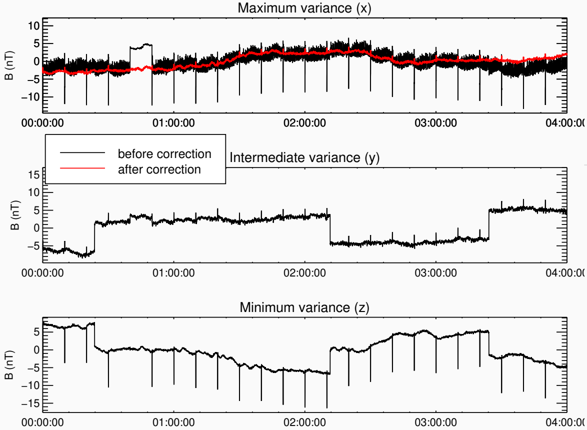
- high frequency noise on *x*
- spikes on *x* and *y*
- steps on *y* and *z*





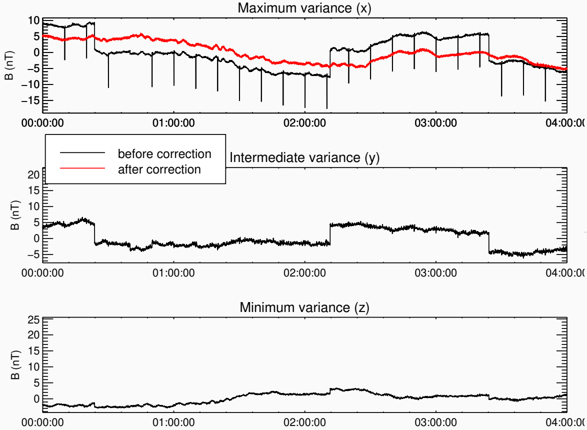
- use sliding windows to determine the variance direction
- determine the most probable variance direction
- select the corresponding α scale factors
- compute the mean scale factor

- window size selects the disturbance to be removed
- first order correction:
  - window size: 100 s (high frequency disturbance)
  - maximum variance direction: out $(-42^\circ, 37^\circ)$; in $(-38^\circ, 52^\circ)$
  - scale factor: out 0.653; in 1.620



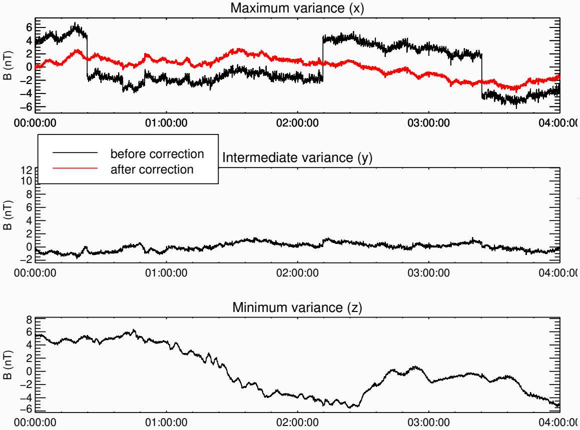
- window size $w = 100\,s$
- scale factor $\alpha = 1.6$

- the HF noise is substantially reduced
- the spikes are also reduced $\Rightarrow$
- similar scale factors $\rightarrow$ close sources
- y-component noisier then z-component



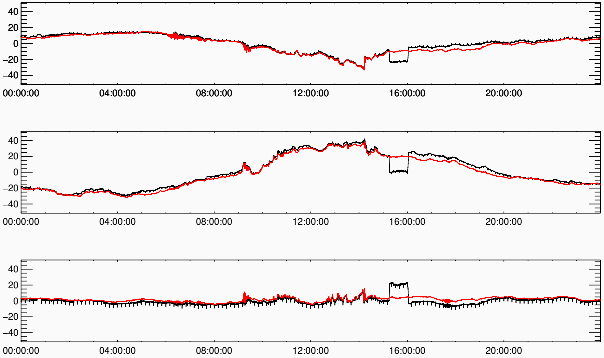
- window size $w = 700\,s$
- scale factor $\alpha = 1.4$

- the spikes are removed
- the steps are also removed



- window size $w = 16\,000\,s$
- scale factor $\alpha = 1.1$

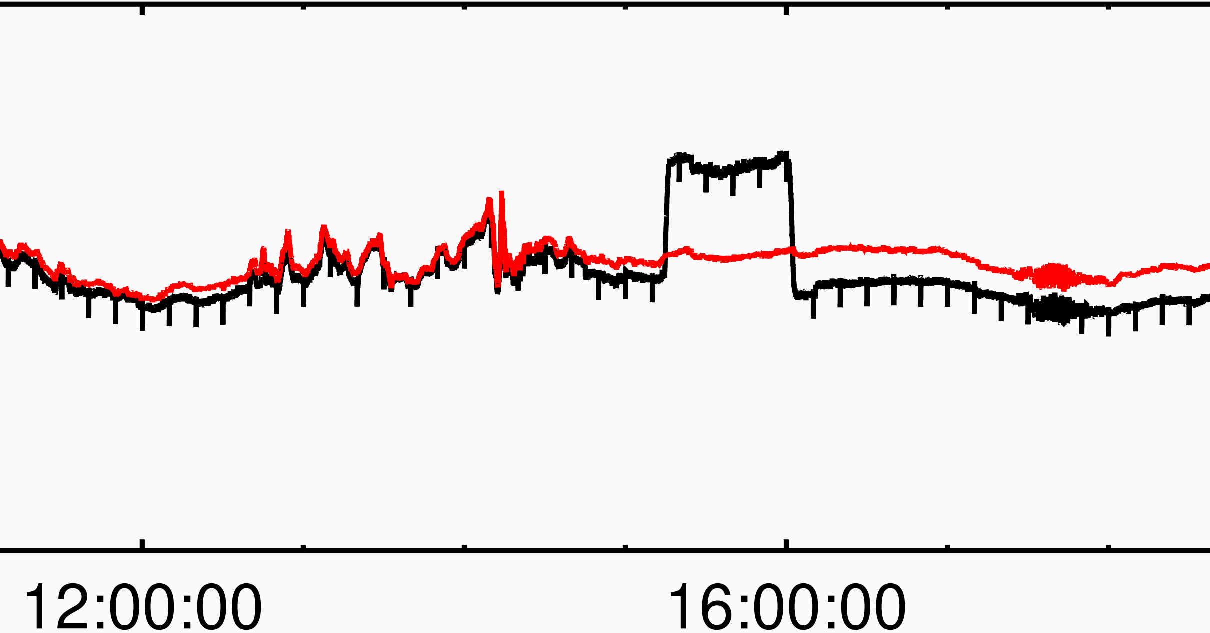
- the steps are removed
- remaining HF noise and spikes reduced
- remnants of steps and spikes on y



- combined single step correction:

$$\mathbf{B}^{\mathrm{O}}_{\mathrm{corr}} = \mathcal{M}^{\mathrm{O}}\mathbf{B}^{\mathrm{O}}_{\mathrm{meas}} + \mathcal{M}^{\mathrm{I}}\mathbf{B}^{\mathrm{I}}_{\mathrm{meas}} + \mathcal{M}^{\mathrm{AMR}}\mathbf{B}^{\mathrm{AMR}}_{\mathrm{meas}}$$

- parameters uploaded to the spacecraft
- cleaning is done now onboard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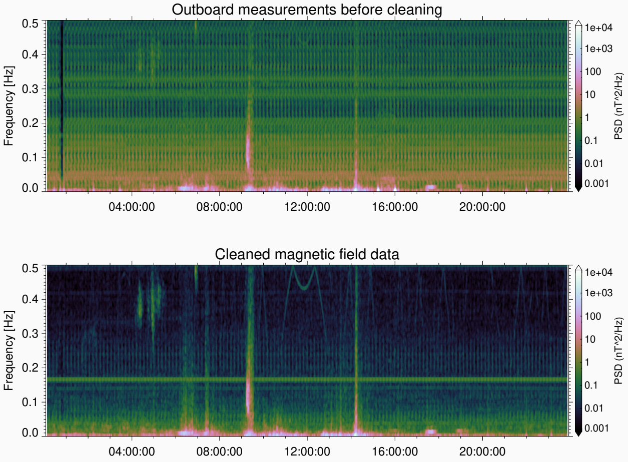

the spectral power of the disturbances is reduced in average by at least a factor of eight:

$$\mathrm{mean}\Big(\sum_{xyz} P_{\text{original}} \Big/ \sum_{xyz} P_{\text{cleaned}}\Big) = 8$$

Summary

- variance analysis is a powerful tool for cleaning magnetometer data
- multiple disturbances (time scales, directions) tend to decouple in the Variance Principal System

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- three from four available sensors on GK-2A were used to clean the data
- the determined cleaning parameters were uploaded to the spacecraft