In orbit alignment of the SWARM ASM and VFM magnetometers

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Introduction

The vector mode of ASM magnetometer will make it possible to carry on comparisons with the nominal VFM magnetometers on each satellite. For this to be possible, one must align both intruments with respect to each other. Here we describe the method that can used for doing this alignment. We present results based on simulations and assess the possibility of detecting boom perturbations.

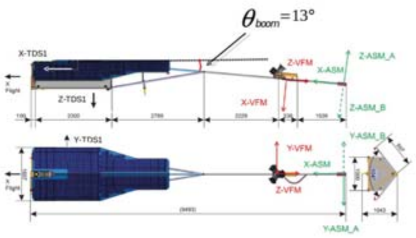
The ASM magnetometer

The Absolute Scalar Magnetometer (ASM) developed by CEA-LETI is an ^{4}He optically pumped magnetometer, which shall provide absolute scalar measurements of the magnetic field with high accuracy and stability. On an experimental basis, the ASM will also be able to operate as a vector field magnetometer.

The alignment problem

This process consists in finding the most accurate way to geometrically relate the VFM and ASM frames, when the same natural field is simultaneously measured in both frames. This geometrical link is described by the Euler Angles.

Defining rotation among frames

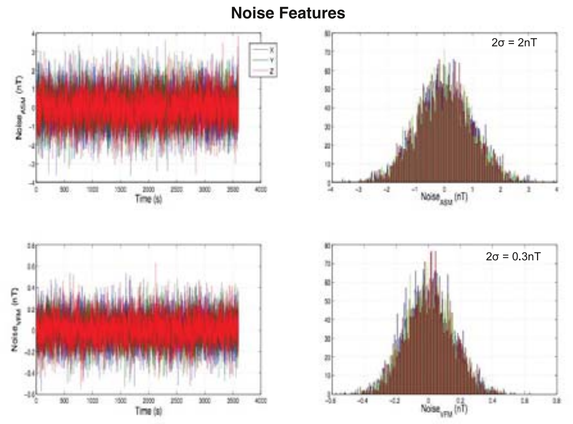


Magnetic Field	Description	Axes
$\vec{B}_{TDS1}$	-Data provided by CHAMP -Satellite reference frame	X_TDS1 Y_TDS1 Z_TDS1
$\vec{B}_{VFM}$	-Axes permutation -13° boom rotation	X_VFM Y_VFM Z_VFM
$\vec{B}_{ASM}$	-Axes permutation -Euler angles rotation	X_ASM Y_ASM Z_ASM
$\vec{B}_{ref_{VFM}}$	Magnetic field in the VFM reference but with the axes permutation of ASM	Not shown

$$\vec{B}_{VFM} = \begin{pmatrix} cos(\theta_{boom}) & 0 & -sin(\theta_{boom}) \\ 0 & 1 & 0 \\ sin(\theta_{boom}) & 0 & cos(\theta_{boom}) \end{pmatrix} \cdot \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{pmatrix} \cdot \vec{B}_{TDS1} + \vec{b}_{VFM}$$ ⇦ Noise VFM

$$\vec{B}_{ASM} = R^{-1}(\alpha,\beta,\gamma) \begin{pmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{pmatrix} \cdot \vec{B}_{VFM} + \vec{b}$$ ⇦ Noise ASM

Noise Features



$$R^{-1} = \begin{pmatrix} cos(\gamma) & sin(\gamma) & 0 \\ -sin(\gamma) & cos(\gamma) & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos(\beta) & 0 & -sin(\beta) \\ 0 & 1 & 0 \\ sin(\beta) & 0 & cos(\beta) \end{pmatrix} \begin{pmatrix} cos(\alpha) & sin(\alpha) & 0 \\ -sin(\alpha) & cos(\alpha) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Simplified ⇨ $$R^{-1} \approx \begin{pmatrix} 1 & \alpha+\gamma & -\beta \\ -(\alpha+\gamma) & 1 & \gamma\cdot\beta \\ \beta & \alpha\cdot\beta & 1 \end{pmatrix}$$

$$\vec{B}_{ref_{VFM}} = \begin{pmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{pmatrix} \cdot \vec{B}_{VFM}$$

For our testing purposes, we choose the following values, for the Euler angles due to the misalignment between the VFM and ASM

$$\begin{pmatrix} \alpha_0 = 5.5° \\ \beta_0 = 4.3° \\ \gamma_0 = 3.75° \end{pmatrix}$$

Recovering the Euler angles

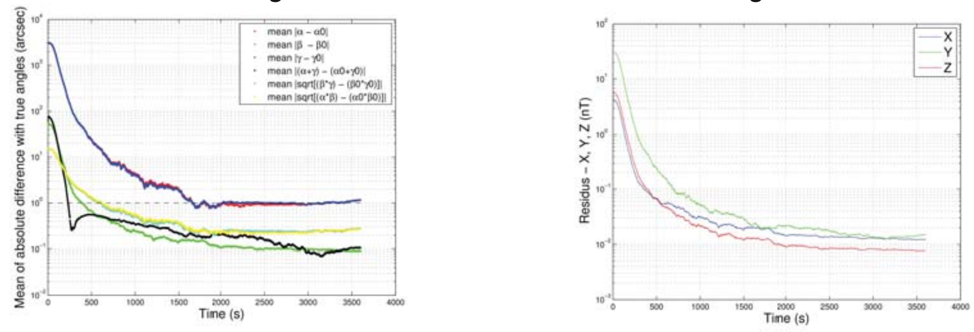
Non-linear function of the Euler angles

$$\chi^2 = \sum_{i=1}^{N} \left\| \vec{B}_{ref_{VFM_i}} - R(\alpha_i,\beta_i,\gamma_i)\vec{B}_{ASM_i} \right\|^2$$

Regularized least squares approach

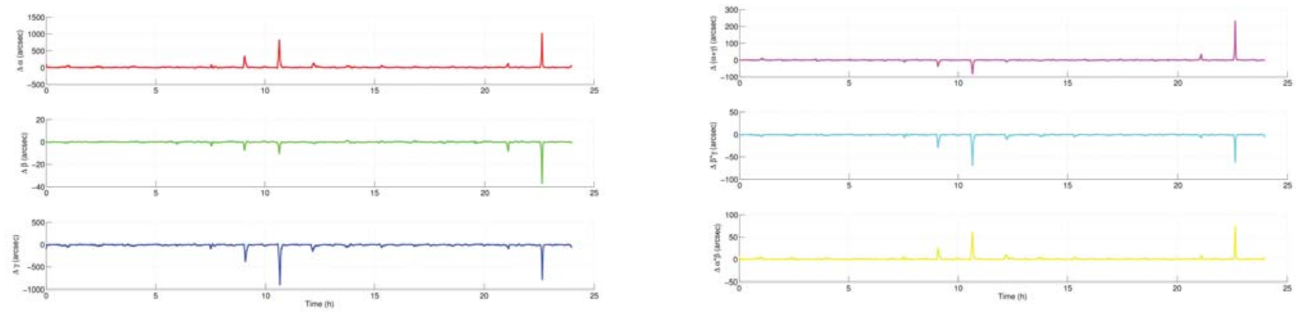
Results

Assessing the time needed to recover the Euler angles in orbit

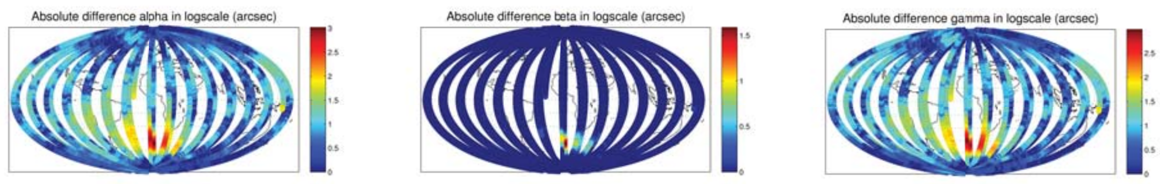


In about 12 minutes we get an accuracy on the relevant angles better than 1 arcsec and on all three components of magnetic field better than 0,1nT

Influence of satellite location along the orbits

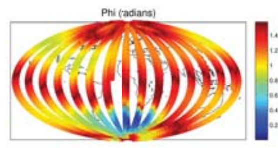


The difference between the recovered and expected angles is small, but there are points where this difference is higher, reaching values up to 200 arcsec in the alpha and gamma angles.

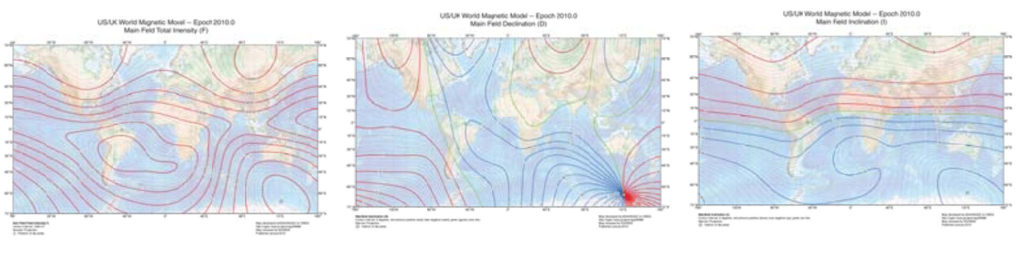


The higher values for the deviation are localized in the South Atlantic region

Study of the anomaly



$$\Phi = \arcsin\left(\frac{\left\|\frac{dB}{dt} \times B\right\|}{\left\|\frac{dB}{dt}\right\| \cdot \|B\|}\right)$$



The anomaly is localized in a region where there is an invariance of the declination and inclination attached to a low field strength, so that variations $\frac{dB}{dt}$ seens by the magnetometers are almost aligned with B (Φ close to 0), preventing an accurate recovery of Euler angles.

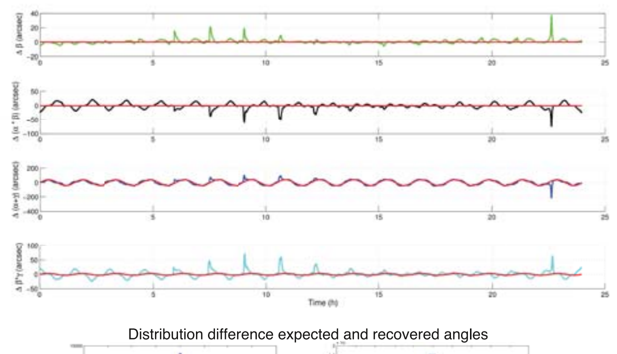
Can boom distortions be detected?

Boom Flexion Y axe direction

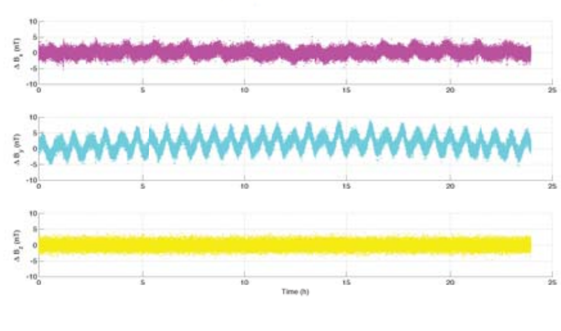
Euler angles with the following time dependence ➡ $\gamma(t) = \gamma_0 + g_1 \sin(\frac{2\pi t}{T})$ where $\gamma_0 = 3.75°$, $T = 1,5h$, $g_1 = 40arcsec$

$$\vec{B}_{ASM} = R^{-1}(\alpha_0,\beta_0,\gamma(t)) \begin{pmatrix} 0 & 0 & -1 \\ 0 & -1 & 0 \\ -1 & 0 & 0 \end{pmatrix} \cdot \vec{B}_{VFM} + \vec{b}$$

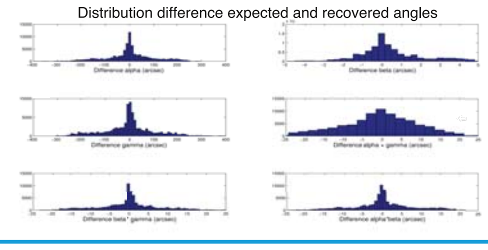
Expected (red lines) and recovered oscilation of the principal angles

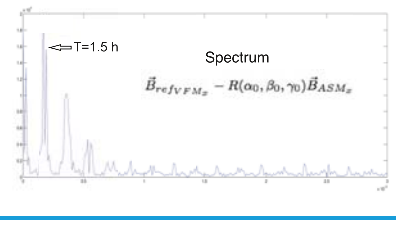


$\vec{B}_{ref_{VFM_i}} - R(\alpha_0,\beta_0,\gamma_0)\vec{B}_{ASM_i}$



Distribution difference expected and recovered angles





Spectrum

$\vec{B}_{ref_{VFM_x}} - R(\alpha_0,\beta_0,\gamma_0)\vec{B}_{ASM_x}$

Conclusions

The alignment process is effective because the difference between the recovered and expected Euler angles is not too large.
The highest variations are of the order of 1000 arcsec and these are located in the south atlantic region where we found that the invariance of the declination and inclination attached to a low field strength affects the alignment process
In addition, boom distortions can be detected.

References

-Friis-Cristensen,E., H.Luhr and G. Hulot (2006). Swarm: A constellation to study the Earth's magnetic field. Earth Planets Space, 58, 351-358

-Gravrand,O., A. Khokhlov, J.L. Le Mouel and J.M.Leger (2001). On the calibration of a vectorial He4 pumped magnetometer. Earth Planets Space, 53, 949-958