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On the advantages of flying absolute vector magnetometers on board satellites, lessons learned from the Swarm mission

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Abstract

ESA's Swarm satellites (Alpha, Bravo and Charlie) carry a new generation of ^{4}He absolute magnetometers (ASM), designed by CEA-Leti and developed in partnership with CNES. These instruments are the first-ever space-born magnetometers to use a common sensor to simultaneously deliver 1Hz independent absolute scalar and vector readings of the magnetic field. They have provided the very high accuracy scalar field data nominally required by the mission (for both science and calibration purposes, since each satellite also carries a low noise high frequency fluxgate magnetometer designed by DTU), but also very useful experimental absolute vector data. In this poster, we report on various studies carried out using these experimental data since the launch of Swarm in November 2013, illustrating the advantages of flying ASM instruments on space-born magnetic missions for nominal data quality checks and geomagnetic field modeling.

References

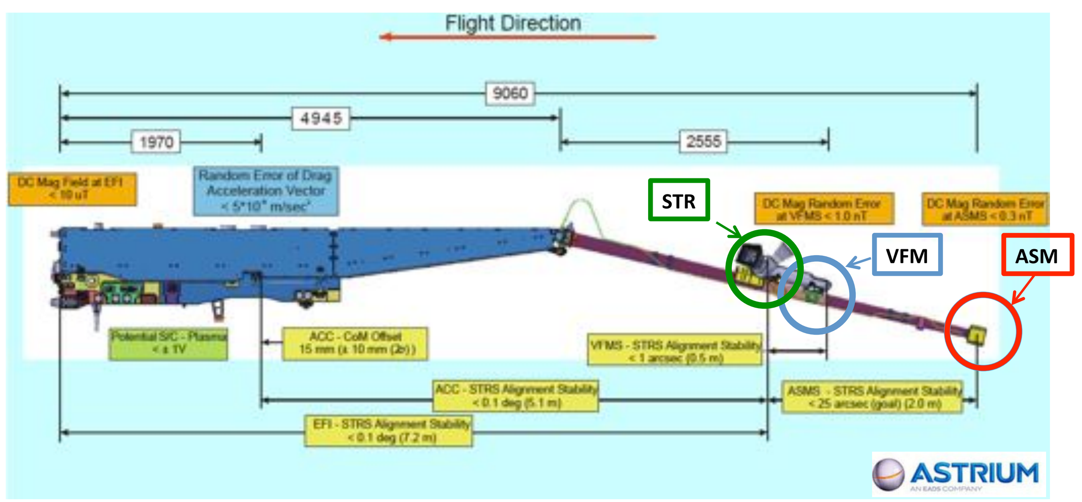
Fratter et al., Swarm Absolute Scalar Magnetometer first in–orbit results, *Acta Astronautica*, submitted, 2015

Hulot et al., Swarm's absolute magnetometer experimental vector mode, an innovative capability for space magnetometry, *Geophys. Res. Lett.*, 42, doi: 10.1002/2014GL062700, 2015.

Léger et al., In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites, *Earth Planets Space,* 67: 57, 2015.

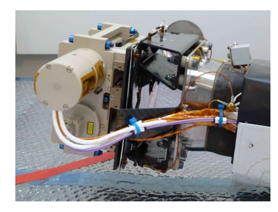
Vigneron et al., A 2015 International Geomagnetic Reference Field (IGRF) Candidate Model Based on *Swarm*'s Experimental Absolute Magnetometer Vector Mode Data, *Earth Planets Space,* in press, 2015

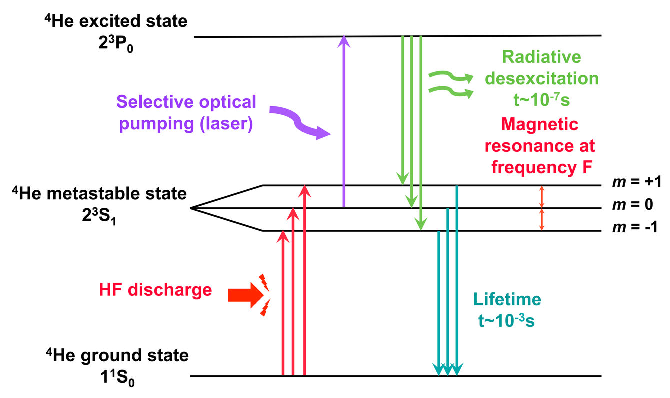
1 SWARM instruments



- Absolute Scalar Magnetometer (ASM) (CEA/LETI, CNES), 1 Hz
- Vector Field Magnetometer (VFM) and Star Tracker (STR) (DTU Space), 50 Hz, 1 Hz
- Accelerometer (VZLU, CZ), 1 Hz
- Electric Field Inst. (Charge particle imager, UC; Langmuir Probe, Uppsala), 2 Hz
- GPSR (Ruag), 1 Hz

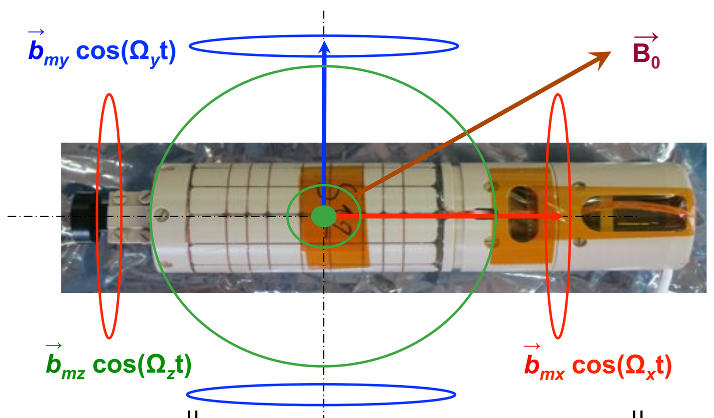
2 The ASM: an optically pumped ^{4}He magnetometer

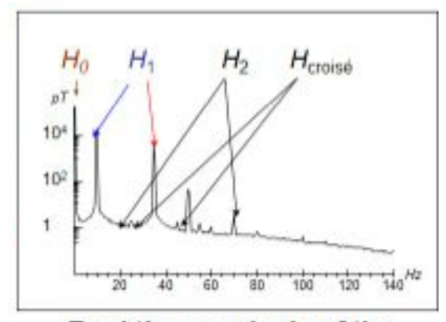




- The ASM is a magnetic field to frequency converter, with B=F/γ
- γ is the ^{4}He gyromagnetic ratio for the 2^3S_1 state, and F is the magnetic resonance frequency between the Zeeman sublevels (proportional to B), measured through magnetic resonance with a signal enhanced by optical pumping
- Scalar data can be acquired up to 250 Hz rate (cut-off at 100 Hz, "Burst mode")

3 Principle of the ASM vector measurement



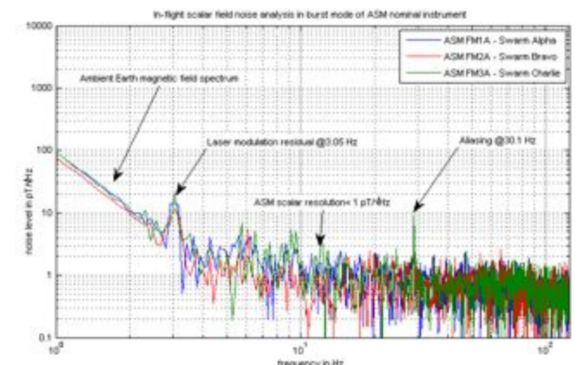


Real time analysis of the scalar output

$$\left\|\vec B_{tot}\right\| = \left\|\vec B_o + \sum_{i=x,y,z}\vec b_{mi}\cos\left(\Omega_i t\right)\right\|$$

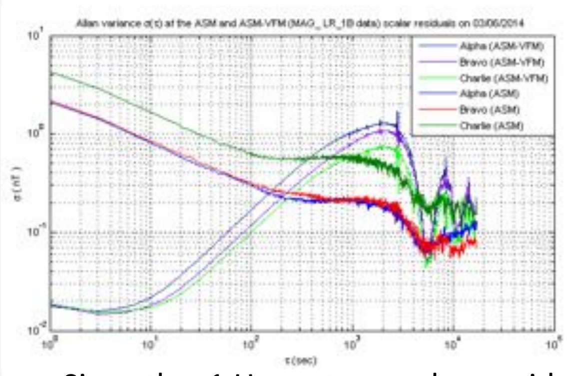
- Three perpendicular coils generate periodic magnetic fields with known amplitudes (b_m~ 50 nT) and three different known (and adjustable) frequencies beyond 1 Hz (typically between 5 Hz and 50 Hz).
- Real time analysis of the scalar field measured by the (scalar) sensor at high frequency (1 kHz internal sampling rate) makes it possible to measure the scalar field at 1 Hz (with near nominal performance) together with all field components along the three coil axis (cut-off at 0.2 Hz, "Vector mode").
- However, vector component performances are intrinsically degraded by a factor (b_m/B_0) compared to the performances achieved for the scalar measurement.

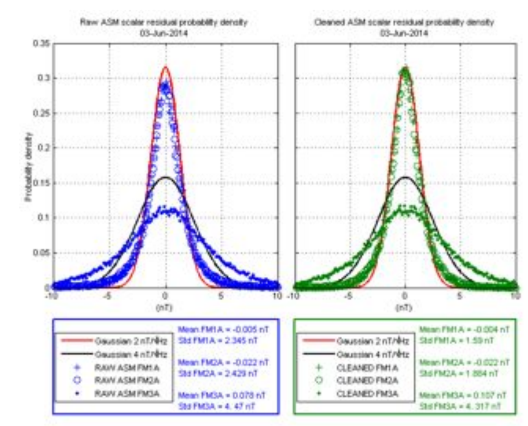
4 ASM scalar performances



- In-flight analysis of 5 s Burst mode data (**Figure above**) confirms the expected resolution close to 1 pT/√Hz
- Precision at 1 Hz (for a 0.4 Hz bandwidth): better than 1 pT
- Accuracy at 1 Hz : (checked on ground, after instrument correction) σmax of 65 pT
- For details, see Léger et al. (2015) and Fratter et al. (2015)

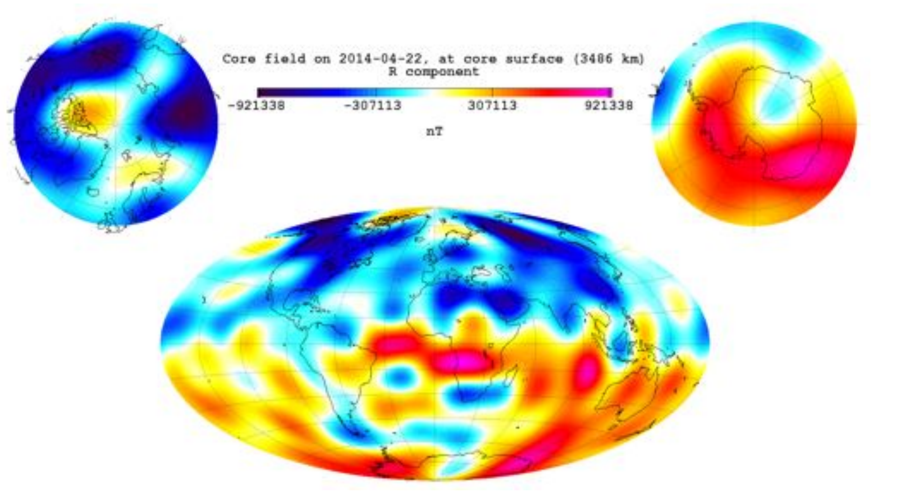
5 ASM vector performances



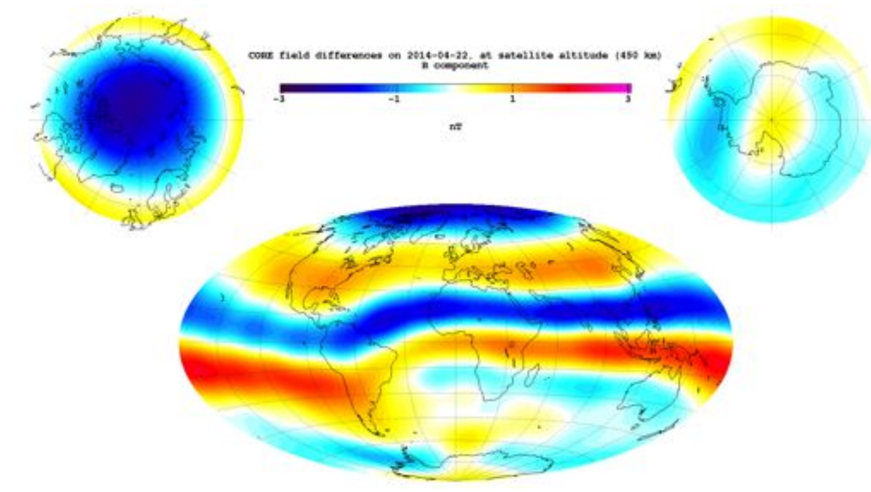


- Since the 1 Hz vector mode provides vector components and a scalar measurement, all synchronous at the same physical location, self-calibration is possible, and scalar residuals (difference between the modulus of the vector data and the scalar data) can be used to monitor the quality of the calibrated vector data.
- An Allan variance analysis of this residuals when calibration is carried out on a daily basis (as has been done for all results discussed here) confirms the lack of low frequency biases (**Figure above, left**). This contrasts with the same analysis carried out on the residuals computed from the early nominal L1b data of the mission (VFM data calibrated using the ASM scalar data), which reveals a "VFM-ASM" disturbance field affecting this data (still investigated by a dedicated Task Force, and now essentially understood).
- For the Alpha and Bravo satellites, noise of the 1 Hz vector data is otherwise at the 2.3 and 2.4 nT level (1 σ) when all data are considered, and at the close-to-expected values of 1.6 and 1.9 nT when removing outliers due to identified issues (**Figure above, right**). As expected, this is higher than the L1b noise level but still of considerable value, thanks to the intrinsic lack of low frequency bias.
- For Charlie, performances are not as good, for reasons yet unknown.
- For more details, see Léger et al. (2015).

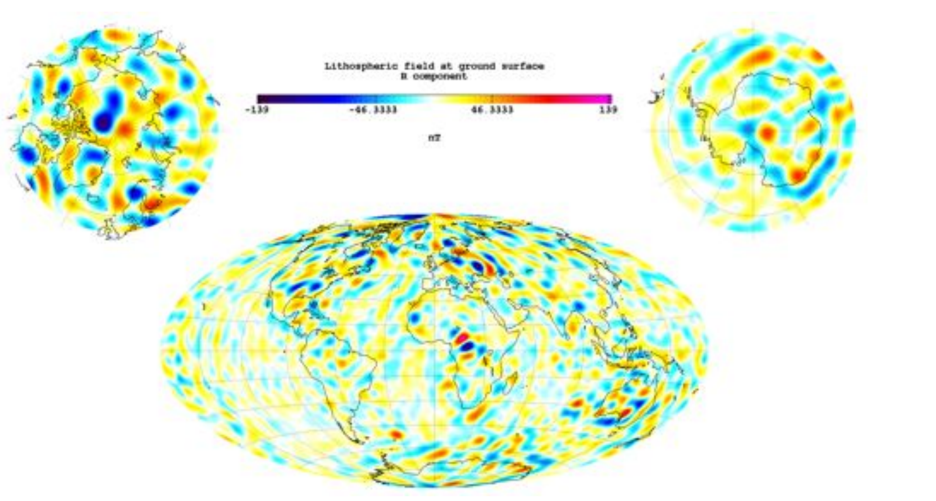
6 Geomagnetic field modelling using ASM vector data



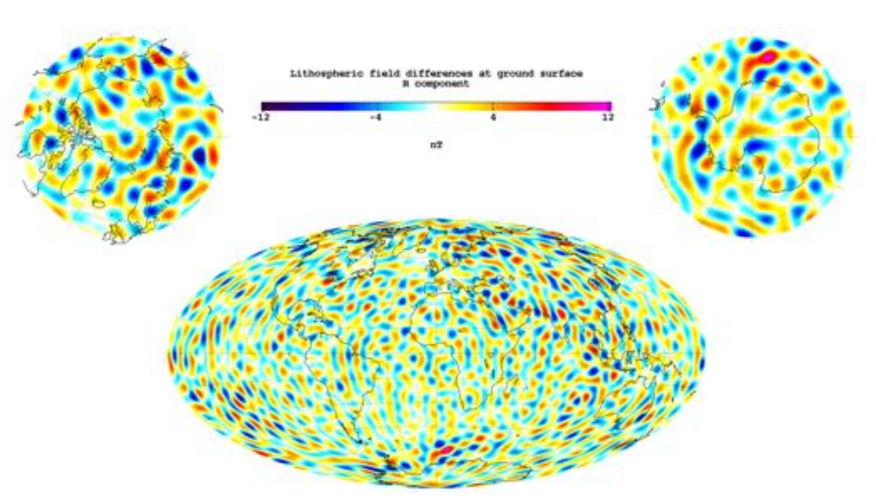
Br at the core surface (n=1-13), ASM-V model (using ASM vector data)



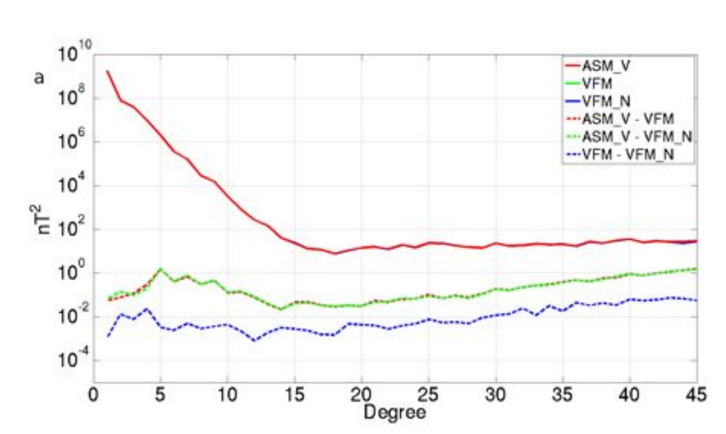
ΔBr difference at satellite altitude (n=1-13) between ASM-V (ASM vector data) and VFM (L1b VFM data) models



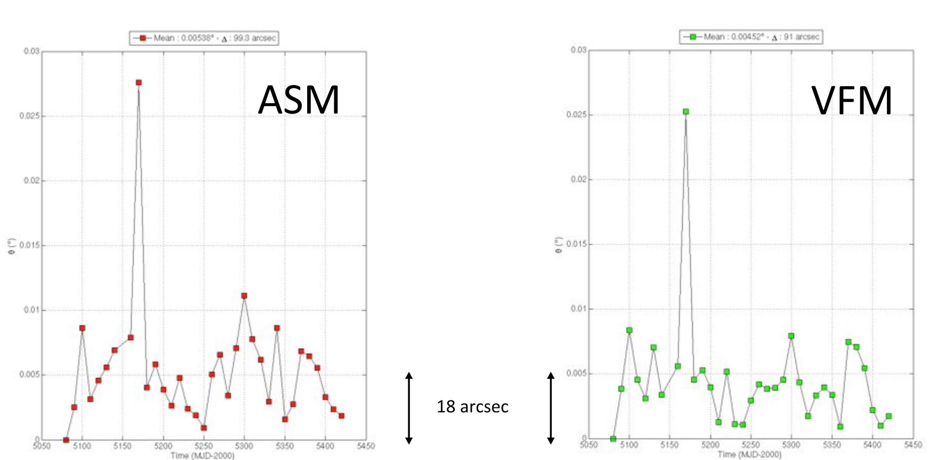
Br at the Earth's surface (n=15-45), ASM-V model (using ASM vector data)



ΔBr difference at Earth's surface (n=15-45) between ASM-V (ASM vector data) and VFM (L1b VFM data) models



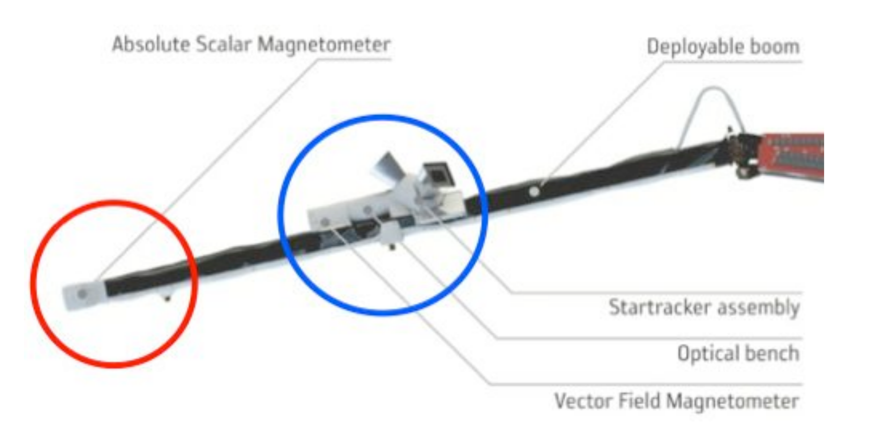
Spectral comparison at Earth's surface of the ASM-V, VFM and VFM-N models (the latter using renormalized L1b VFM data)

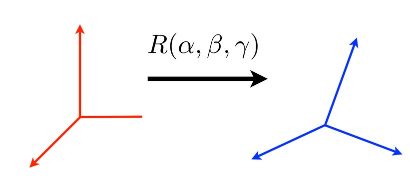


Apparent angular fluctuations between ASM or VFM frames and the STR frame for Alpha (co-estimated with models ASM-V and VFM, respectively)

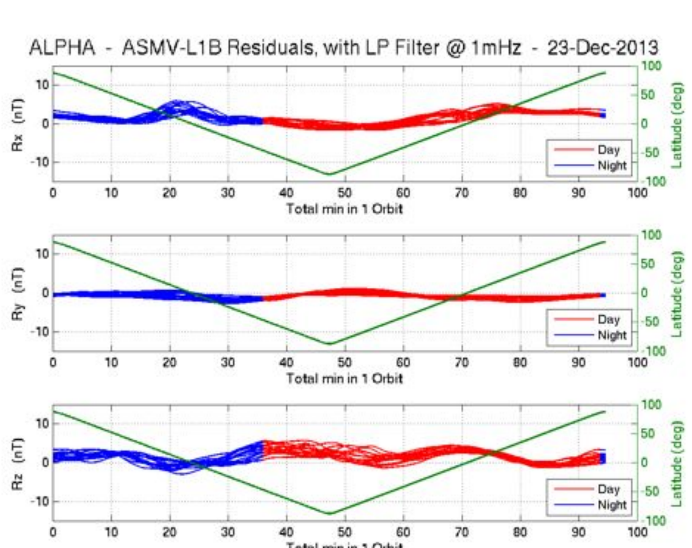
- ASM vector data could be used in combination with STR data (for attitude restitution) to produce a geomagnetic field model of extremely satisfying value, despite the non-ideal mechanical link between the ASM and STR instruments (recall box 1).
- The quality of this model "ASM-V", based on less than one year of night-time data from the Alpha and Bravo satellites, is very close to that of a model "VFM" built in the same way from L1b VFM data (same method, same satellites, same data selection, just using readings from the VFM instrument, rather than from the ASM instrument) as shown by **the four maps above**.
- These results also show that for such modelling purposes, the mechanical link between the ASM and STR instruments proved almost as good as the one between the VFM and STR instruments, as estimated from the co-estimated apparent angular fluctuations shown above (**bottom right plots**).
- There nevertheless are some systematic differences between the two models, consistent with possible orbital boom oscillations and deformations (20 arcsec oscillations can produce peak signals up to 8 nT). Indeed, differences in the models are mainly produced by directional disagreements between the ASM and VFM data (as shown by comparison with the VFM-N model computed from renormalized VFM data to ensure perfect agreement between the modulus of these data and that of the ASM-V data, see **bottom left plot**). Note, however, that directional disagreement between the ASM and VFM data might also partly reflect the "VFM-ASM" disturbance field affecting the VFM data used here (recall box 5).
- For more details, see Hulot et al. (2015) and Vigneron et al. (2015).

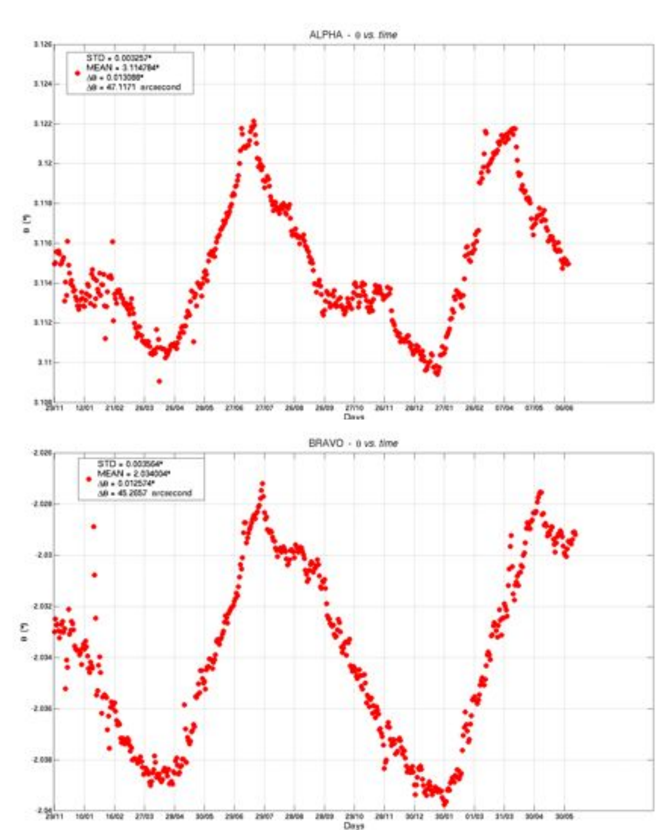
7 Comparison of ASM vector data with nominal L1b VFM vector data





$$\chi^2 = \sum_{i=1}^{N}\left\|\vec B_{VFM_i} - R(\alpha,\beta,\gamma)\left(\frac{\left\|\vec B_{VFM_i}\right\|}{\left\|\vec B_{ASM_i}\right\|}\vec B_{ASM_i}\right)\right\|^2$$





- ASM vector data can also be directly compared to nominal L1b VFM data.
- To achieve this, one first needs to align ASM vector data to L1b VFM data, by seeking the best rotation between the ASM and VFM frame of references, that is, by seeking the rotation that makes the ASM vector data best coincide with L1b VFM data in the VFM frame of reference (**top Figure above**).
- This was done on a daily basis for the Alpha and Bravo satellites. The corresponding best daily rotation angle can be plotted to infer the apparent daily deformation between the two reference frames. This angle is shown for Alpha and Bravo in the **two bottom right panels above**, revealing a clear periodic pattern, associated with changes in the local time witnessed by each satellite (hence solar exposure).
- The corresponding amplitudes (of order 45 arcsec) are significant, but changes over ten days are on the order of 5 arcsec, somewhat less than the changes observed every ten days in the apparent angular fluctuations between the ASM or VFM frames with respect to the STR frame of reference (recall box 6). This explains why these apparent fluctuations are almost the same for the ASM and VFM instruments. This also is consistent with the fact that field modelling is possible with the ASM vector data in the same way as with the VFM data.
- Having aligned the data, one can also compute the ASM minus L1b VFM vector residuals in the VFM frame of reference, filtered at 1 mHz to highlight orbital signals (**bottom left figure**).
- Such signals (together with the local-time dependence seen in the best daily rotation, recall above) are currently being used to investigate the sensitivity of the VFM/STR/ASM instrumental suite to solar exposure and particularly the "VFM-ASM" disturbance field responsible for the VFM scalar residual anomaly (recall box 5).