The absolute magnetometers on board Swarm, lessons learned from more than two years in space.

EART-49

G. Hulot[1], J.M. Léger[2], P. Vigneron[1], M. Ferand[1], N. Olsen[3], T. Jager[2], F. Bertrand[2], I. Fratter[4], P. Coïsson[1], O. Sirol[1], X. Lalanne[1]
[1]IPG Paris, Université Sorbonne Paris Cité – Université Paris Diderot – CNRS, France; [2]CEA, LETI, MINATEC Campus, Grenoble, France; [3]DTU Space, National Space Institute, TUD, Lyngby, Denmark; [4]Centre National d'Etudes Spatiales, Toulouse, France.

Abstract

ESA's Swarm satellites (Alpha, Bravo and Charlie) carry ^{4}He absolute magnetometers (ASM), designed by CEA-Léti 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. They have also been run for short periods of time in a so-called burst mode to deliver absolute scalar data at 250 Hz. In this poster, we report on various studies carried out using these experimental data since the launch of Swarm in November 2013. In particular, we illustrate the advantages of flying ASM instruments on space-born magnetic missions for data quality checks, geomagnetic field modeling and science objectives.

References

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Léger et al., In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites, *Earth Planets Space*, 67: 57, doi: 10.1186/s40623-015-0231-1, 2015.

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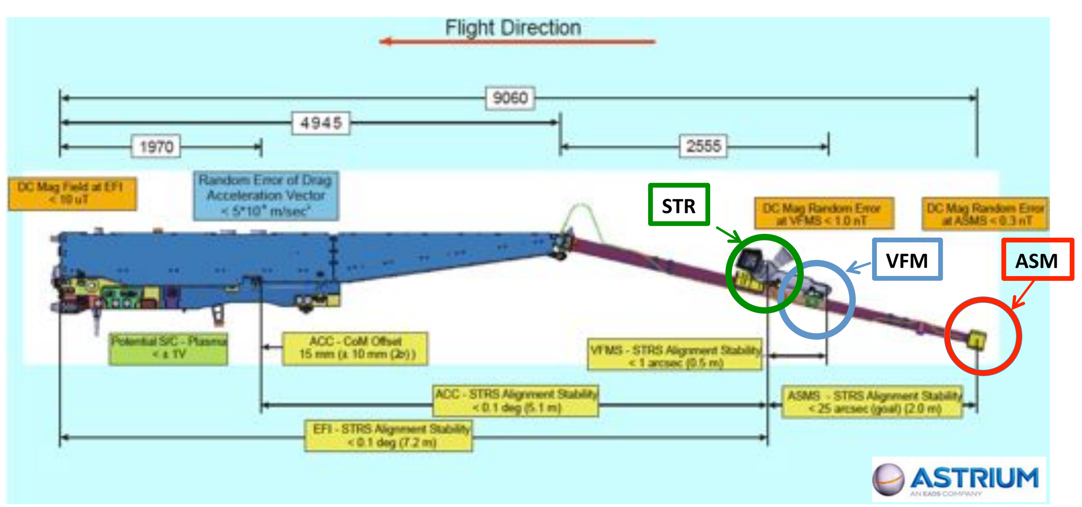
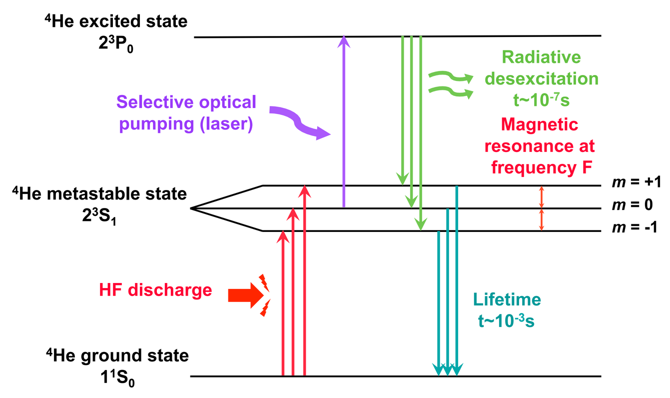
1 SWARM instruments



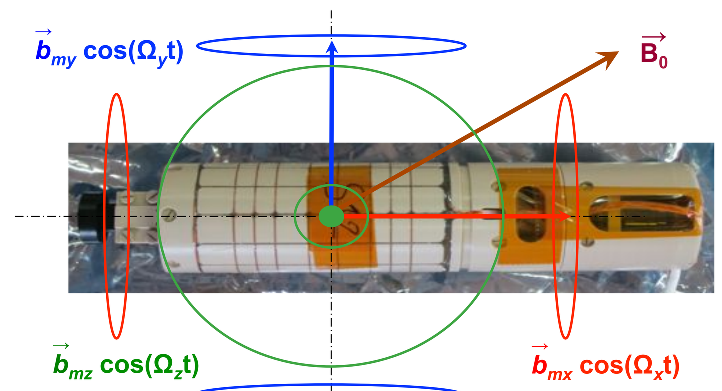
- Absolute Scalar Magnetometer (ASM) (CEA/LETI, CNES), 1 Hz
- Vector Field Magnetometer (VFM) and Star Tracker (STR) (DTU Space), 50 Hz, 1 Hz
- Accelerometer (VZLU, CZ), 1 Hz
- Electric Field Inst. (Charge particle imager, UC; Langmuir Probe, Uppsala), 2 Hz
- GPSR (Ruag), 1 Hz

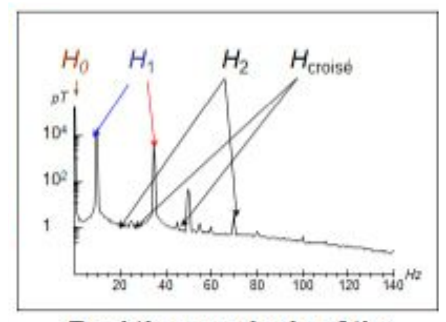
2 The ASM: an optically pumped ^{4}He magnetometer



- 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



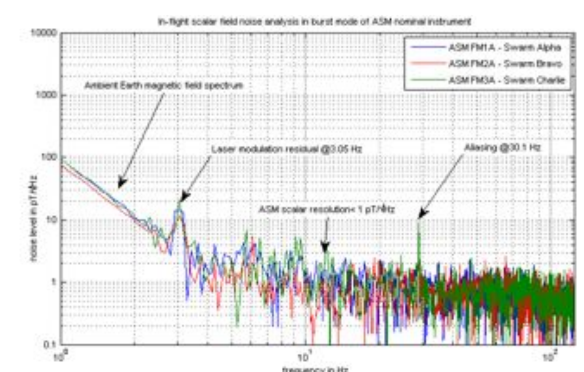


Real time analysis of the scalar output

$$\left\|\vec{B}_{tot}\right\| = \left\|\vec{B}_o + \sum_{i=x,y,z} \vec{b}_{mi}\cos(\Omega_i t)\right\|$$

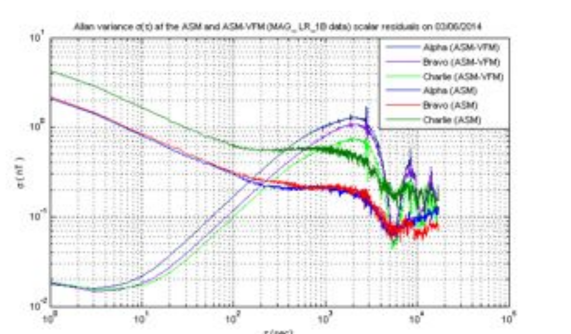
- Three perpendicular coils generate periodic magnetic fields with known amplitudes (b_m~ 50 nT) and three different known (and adjustable) frequencies beyond 1 Hz (currently at about 8 Hz, 11 Hz and 13 Hz).
- Real time analysis of the scalar field measured by the (scalar) sensor at high frequency (1 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.

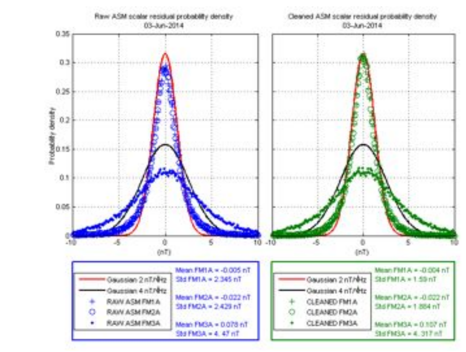
4 ASM scalar performances



- 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)

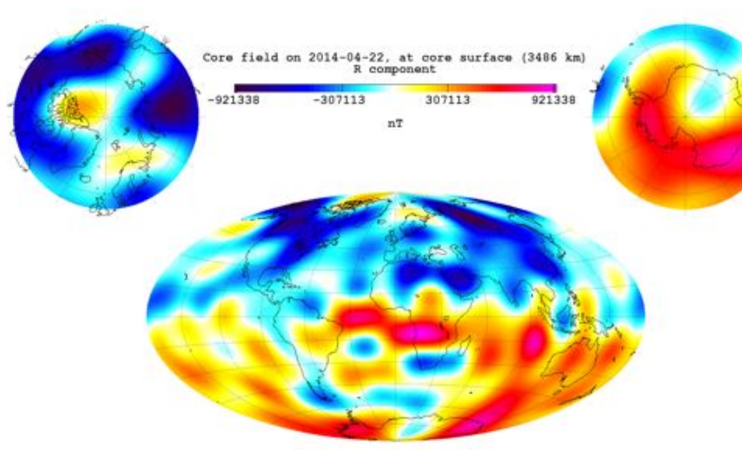
5 ASM vector performances



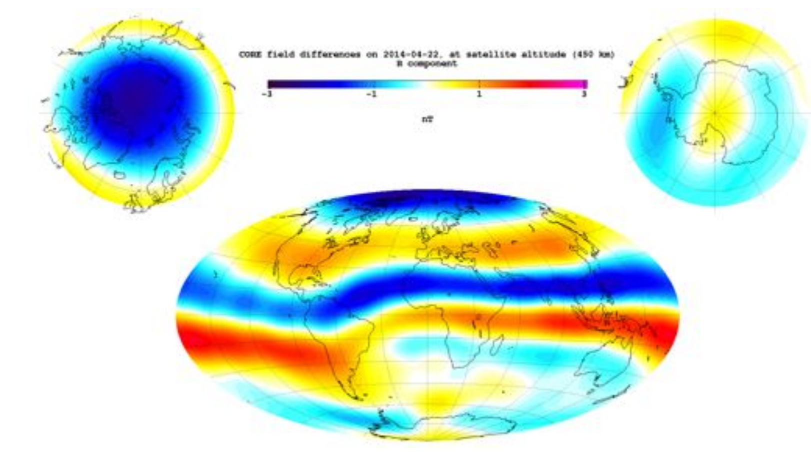


- Since the 1 Hz vector mode provides vector components and a scalar measurement, all synchronous at the same physical location, self-calibration is possible, and scalar residuals (difference between the modulus of the vector data and the scalar data) can be used to monitor the quality of the calibrated 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 (the so-called Sun related disturbance investigated by a dedicated Task Force, and now corrected for, see Box 7).
- 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. Unfortunately, also, no more ASM is operating on Charlie since a failure due to a heavy ion impact on November 5, 2014.
- For more details, see Léger et al. (2015) and Fratter et al. (2016).

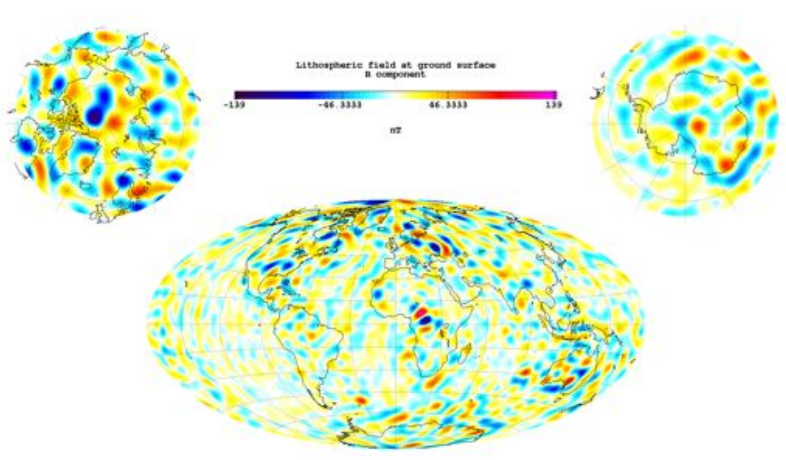
6 Geomagnetic field modelling using ASM vector data



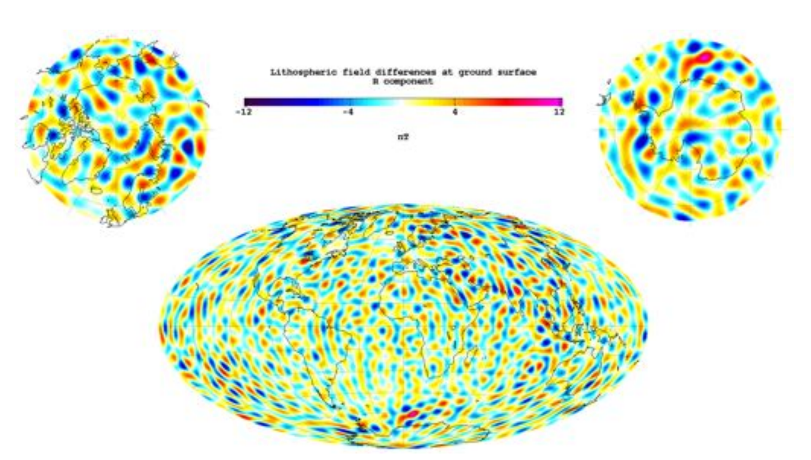
Br at the core surface (n=1-13), ASM-V model (using ASM vector data)



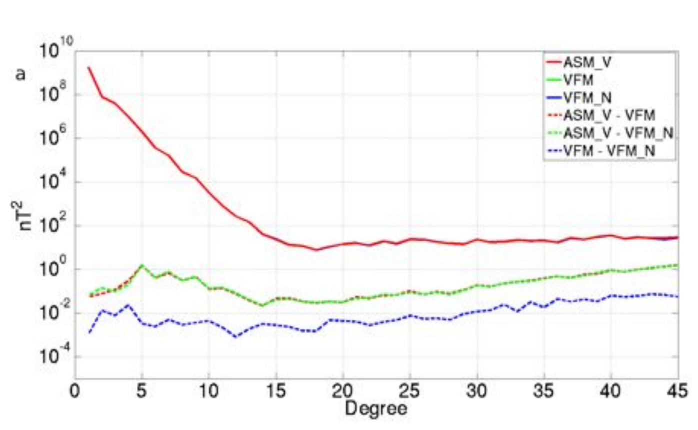
ΔBr difference at satellite altitude (n=1-13) between ASM-V (ASM vector data) and VFM (L1b VFM data) models



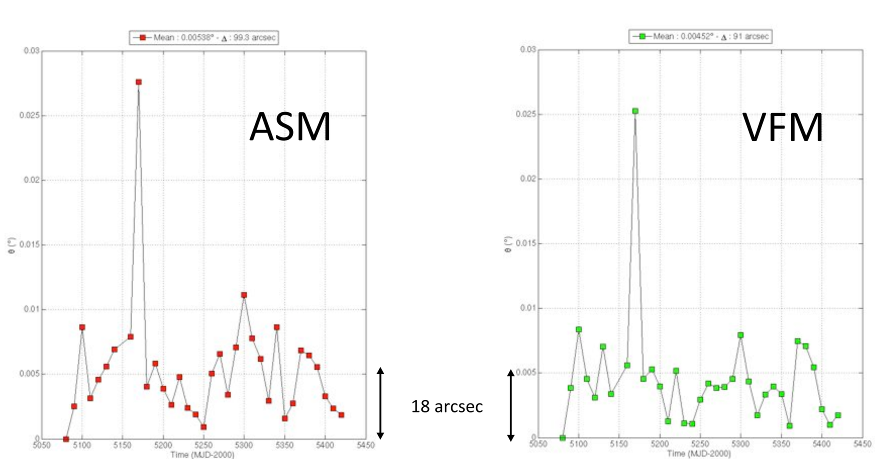
Br at the Earth's surface (n=15-45), ASM-V model (using ASM vector data)



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



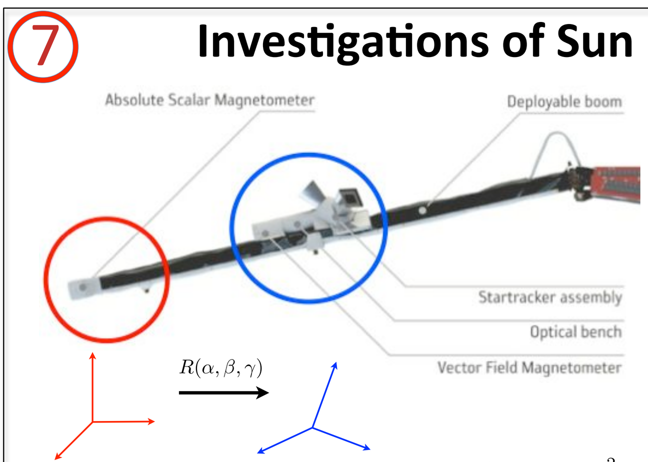
Spectral comparison at Earth's surface of the ASM-V, VFM and VFM-N models (the latter using renormalized L1b VFM data)



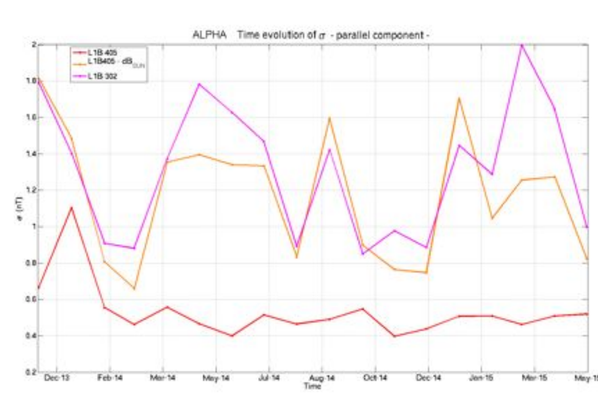
Apparent angular fluctuations between ASM or VFM frames and the STR frame for Alpha (co-estimated with models ASM-V and VFM, respectively)

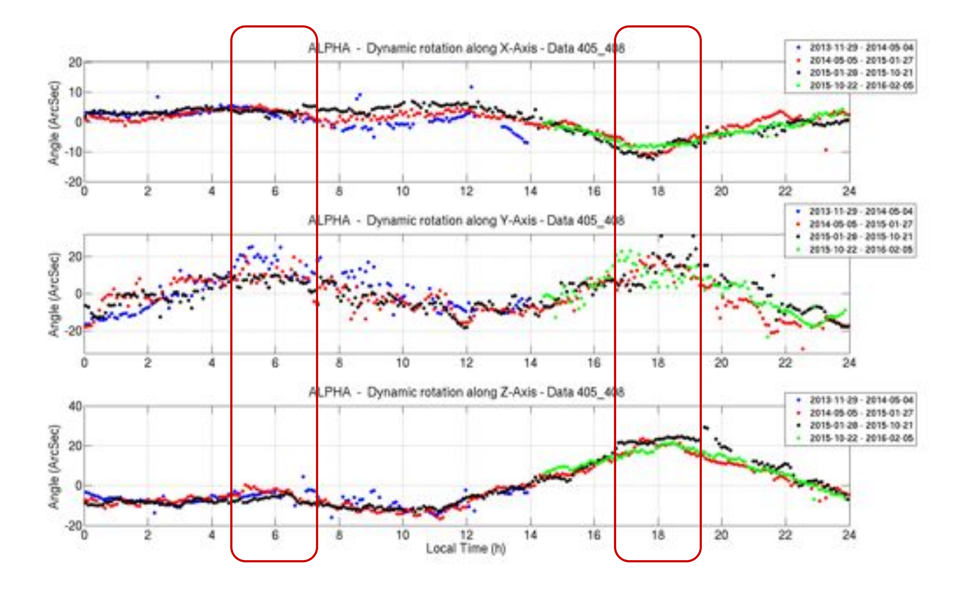
- ASM vector data could be used in combination with STR data (for attitude restitution) to produce a geomagnetic field model of extremely satisfying value, despite the non-ideal mechanical link between the ASM and STR instruments (recall box 1).
- The quality of this model "ASM-V", based on less than 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 the original readings from the VFM instrument before any Sun-related "VFM-ASM" disturbance field correction, 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 Sun-related "VFM-ASM" disturbance field affecting the VFM data used here (recall box 5, see also box 7).
- For more details, see Hulot et al. (2015) and Vigneron et al. (2015).

7 Investigations of Sun related satellite disturbance field and boom distortion

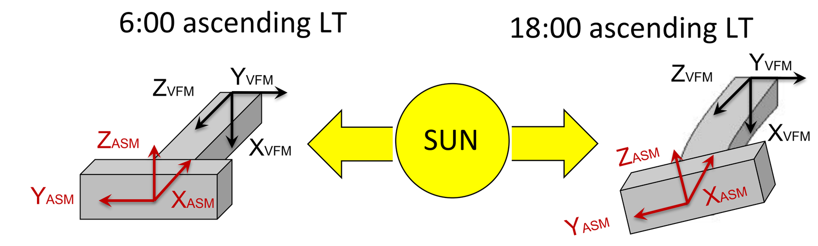


$$\chi^2 = \sum_{i=1}^{N}\left\|\vec{B}_{VFM_i} - R(\alpha,\beta,\gamma)\left(\frac{\|\vec{B}_{VFM_i}\|}{\|\vec{B}_{ASM_i}\|}\vec{B}_{ASM_i}\right)\right\|^2$$



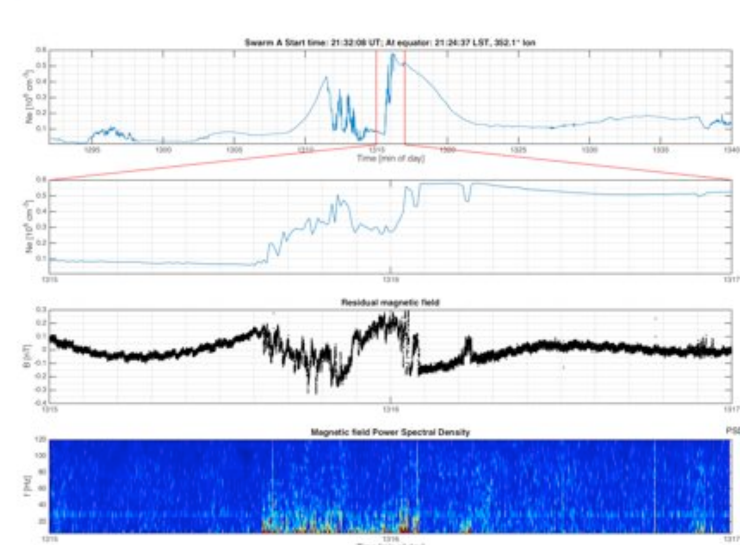


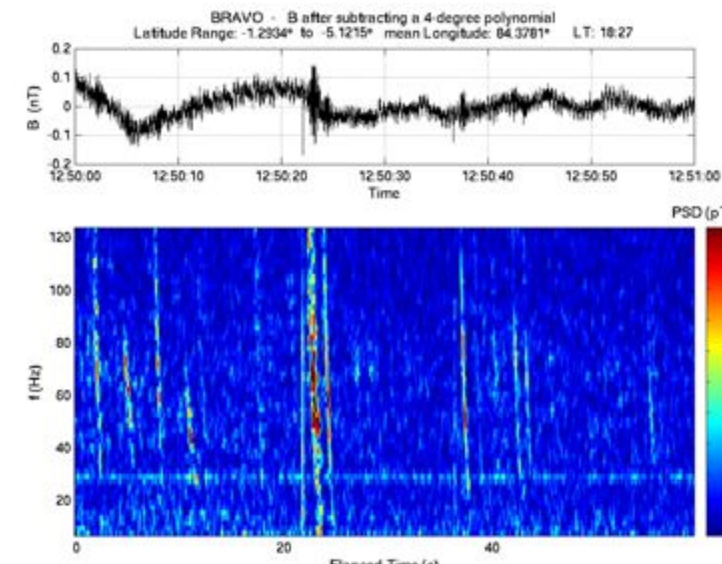
6:00 ascending LT 18:00 ascending LT



- ASM vector data could also be directly compared to L1b VFM data. To achieve this, ASM vector data were aligned to L1b VFM data by seeking the rotation that makes the ASM vector direction best coincide with L1b VFM direction in the VFM frame of reference (minimizing χ^2, **left figure above**).
- This was done on a daily basis before and after accounting for the Sun-related disturbance field and revealed a clear variance reduction in the disagreement between the ASM-V data and the level 1b VFM data after correction on both the field aligned (parallel, **central figure above**) and field perpendicular (**right figure above**) components, the latter providing an independent validation of the disturbance field model now used to correct nominal L1b VFM data.
- The corresponding daily rotation angles (about the X, Y and Z angles in the VFM frame of reference) could also be plotted to infer the daily deformation between the two reference frames after correction for the Sun-related disturbance field (**middle right panel**).
- This revealed clear patterns as a function of the local time witnessed by the satellites (hence solar exposure), with three characteristic features: 1) higher noise along the Y direction (up-down oscillations) traced back to ASM internal deformations, 2) a seasonal periodicity in the same Y direction consistent with a downward deformation of the boom when permanently exposed to the Sun (6h00 and 18h00 LT, as opposed to alternating day-night orbits at noon and midnight LT), 3) clear 18:00 LT peak rotations along the X and Z directions, consistent with a torsion of the (known to be right-left asymmetric) ASM mounting when exposed to the Sun from the left-hand side (with respect to flight direction). Similar patterns were found on all three satellites.

8 Science investigations using ASM burst mode data





- The ASM burst mode was run during seven sessions on all three satellites (between a few hours and up to two days), during the commissioning phase. This allowed performance analysis of the instruments (recall Box 4), but also revealed the ability of the instrument to detect high-frequency field fluctuations during plasma bubble events, as well as low-frequency "whistler" type of events. Detailed investigations are under way.
- **Left figure**: Plasma bubble signals detected by Alpha on 19/01/2014, 21:24 LT near the equator (long. 352°), during 120s.
- **Right figure**: "Whistler" type of signals detected by Bravo on 08/02/14, 18:27 LT near the equator (long. 84°), during 60s. These signals are detected by all three satellites and seem to be related to lightning activity in the troposphere.