



The absolute vector magnetometers on board Swarm, lessons learned from two years in space





References

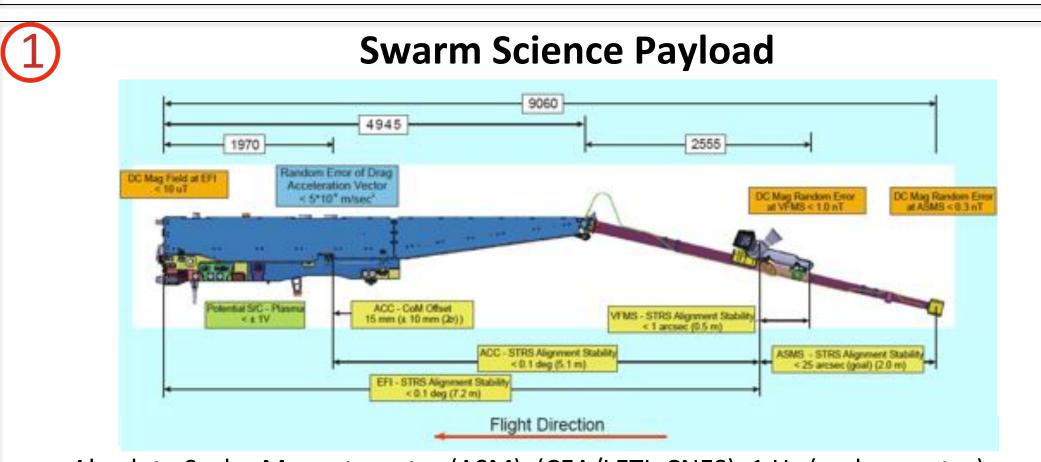
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G. Hulot¹, J.M. Léger², P. Vigneron¹, L. Brocco¹, N. Olsen³, V. Lesur¹, T. Jager², F. Bertrand², I. Fratter⁴, O. Sirol¹, X. Lalanne¹

¹IPG Paris, Sorbonne Paris Cité, Université Paris Diderot – CNRS, France; ²CEA-Leti, MINATEC Campus, Grenoble, France; ³DTU Space, National Space Institute, Technical University of Denmark, Denmark; ⁴CNES, Toulouse, France.

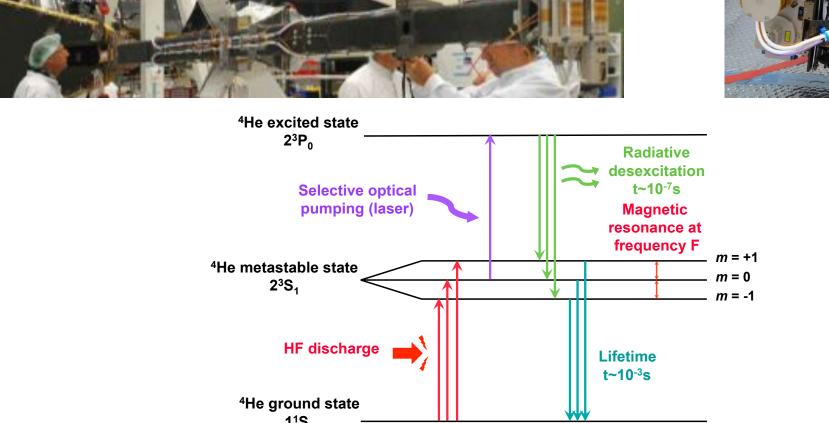
Abstract

ESA's Swarm satellites carry ⁴He 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. In this poster, we report on the status of the instruments, as well as on the various tests and investigations carried out using these experimental data since launch in November 2013. In particular, we illustrate the advantages of flying ASM instruments on space-born magnetic missions for nominal data quality checks, geomagnetic field modeling and science objectives.



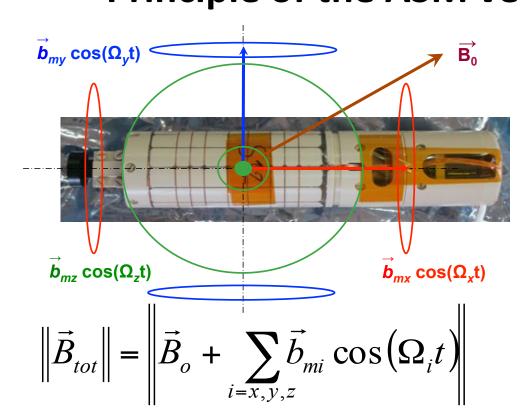
- Absolute Scalar Magnetometer (ASM) (CEA/LETI, CNES), 1 Hz (scalar+vector) or 250 Hz (scalar)
- Vector Field Magnetometer (VFM) and Star Tracker (STR) (DTU Space), 50 Hz, 1 Hz
- Accelerometer (VZLU, CZ), 1 Hz
- Electric Field Inst. (Charge particle imager, UC; Langmuir Probe, Uppsala), 2 Hz
- GPSR (Ruag), 1 Hz

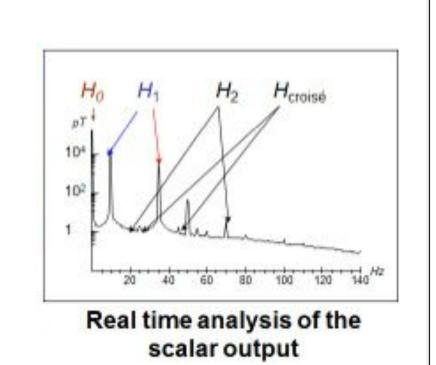
The ASM: an optically pumped ⁴He magnetometer



- The ASM is a magnetic field to frequency converter, with $B=F/\gamma$
- γ is the ⁴He 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")

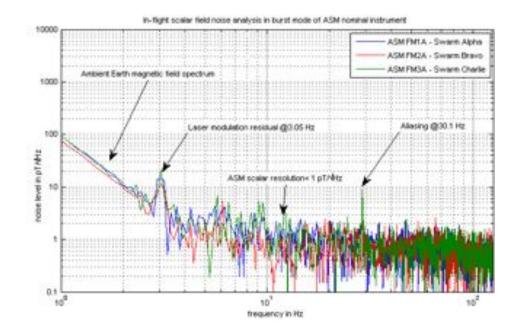
Principle of the ASM vector measurement



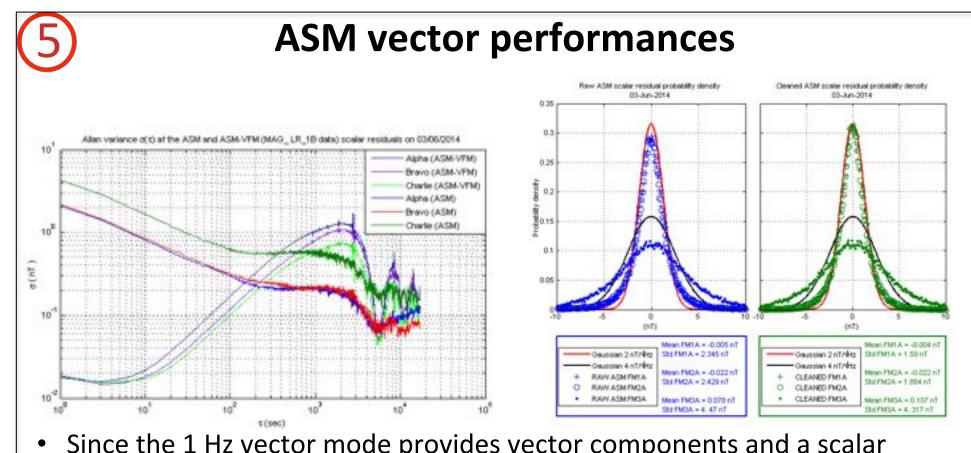


- Three perpendicular coils generate periodic magnetic fields with known amplitudes (b_m~ 50 nT) and three different known (and adjustable) frequencies beyond 1 Hz (typically between 5 Hz and 50 Hz).
- Real time analysis of the scalar field measured by the (scalar) sensor at high frequency (1 kHz internal 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

ASM scalar performances



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



- 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 these 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 (0301 and 0302 VFM data, calibrated using the ASM scalar data), which reveals a "VFM-ASM" disturbance field affecting this data (investigated by a Task Force, and now mainly understood, 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 are 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. (2015)

Sun-related satellite disturbance determination

Fratter et al., Swarm Absolute Scalar Magnetometers first in-orbit results, Acta Astronautica, revised, 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, 67:95, 2015

(6) Geomagnetic field modelling using ASM vector data Br at the core surface (n=1-13), ASM-V model Spectral comparison at Earth's surface of the ASM-V. VFM Δ Br difference at satellite altitude (n=1-13) between (using ASM vector data) ASM-V (ASM vector data) and VFM (L1b VFM data) models and VFM-N models (the latter using renormalized L1b VFM data)

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

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 very satisfying value, despite the non-ideal mechanical link between the ASM and STR instruments (recall box 1).

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

(using ASM vector data)

above) and next comparing the ASM-V data to the L1b data used for the alignment. This was done on a daily basis and

revealed a clear variance reduction in the disagreement between the ASM-V data and the level 1b VFM data after

figure above) components, the latter providing an independent validation of the disturbance field model.

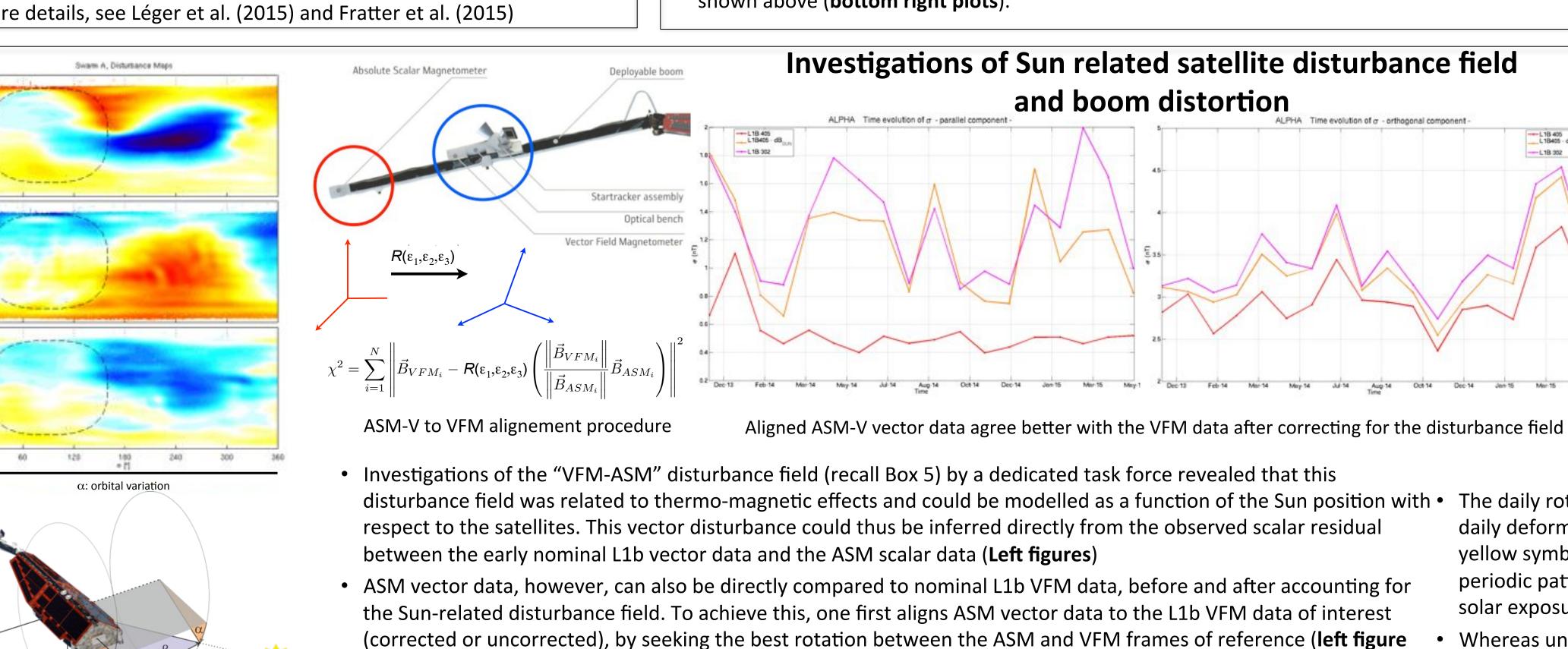
correction. This was the case on both the field aligned (parallel, central figure above) and field perpendicular (right

- 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 top right 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, and see box 7).
- For more details, see Hulot et al. (2015) and Vigneron et al. (2015).

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The daily rotation angle between the ASM-V and VFM frames can also be plotted to infer the apparent daily deformation between the two reference frames. This angle, computed either before (blue and yellow symbols) of after (red symbols) correction, is shown for Alpha (Figure above), revealing a clear periodic pattern, associated with changes in the local time witnessed by the satellite (hence, again, solar exposure).

Whereas uncorrected L1b data lead to different apparent deformation at 0:00 and 12:00 LT, corrected data make this deformation identical in both cases, as one would expect if the apparent deformation is a true one (Sun exposure is the same for the boom at both LTs), thus again validating the disturbance field model and providing what is a likely true estimate of the mechanical distortion (of amplitude maximum 40 arcsec for LT 18:00) between the ASM and VFM instruments (boom and brackets).