Geomagnetic field modelling based on ASM-V experimental data

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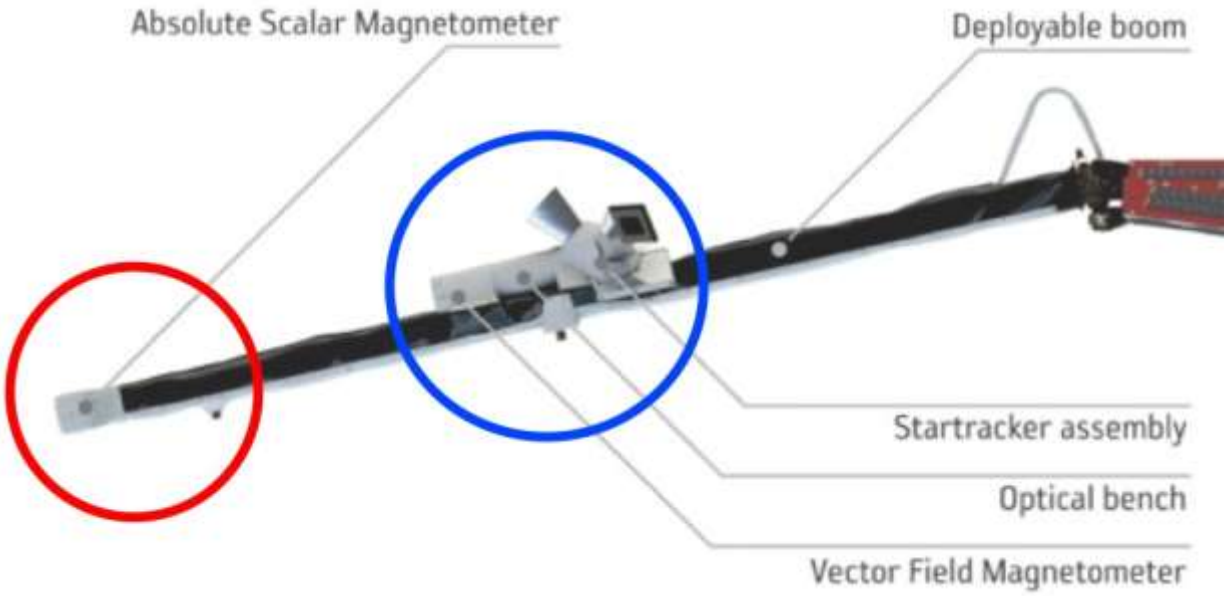
ASM-V data



The ASM is first and foremost an **absolute scalar magnetometer** (based on atomic spectroscopy of ^{4}He, and relying on the Zeeman effect)

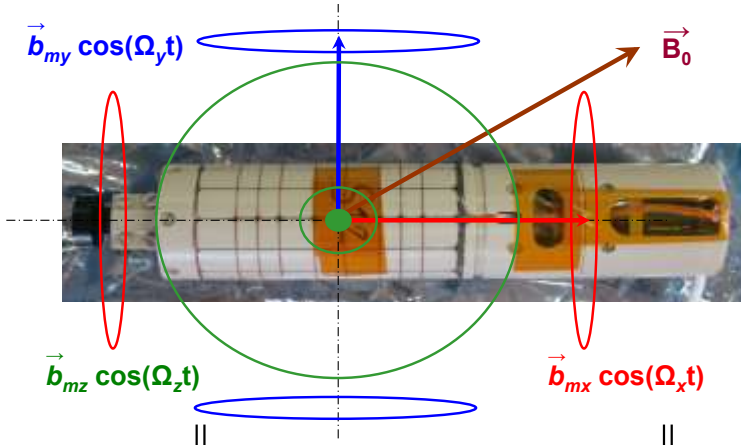
Its **nominal role** in the Swarm mission is twofold:

- **Produce accurate absolute scalar measurements of the Earth's magnetic Field** (1 Hz L1b scalar data)
- **Provide an absolute reference for calibrating L1b vector data** provided by a fluxgate vector field magnetometer (VFM, 1 Hz and 50 Hz L1b vector data)

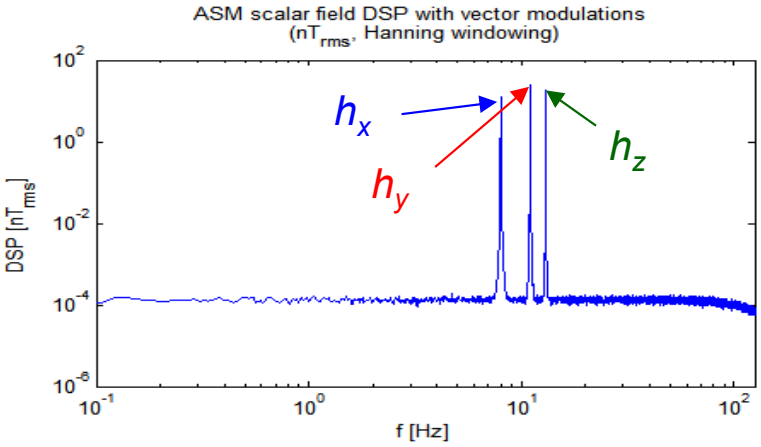
But **it can also simultaneously produce self-calibrated vector data**: **ASM-V** data.

These data are **independent from the nominal L1b data** produced by the **VFM** instrument.

ASM vector mode principle



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

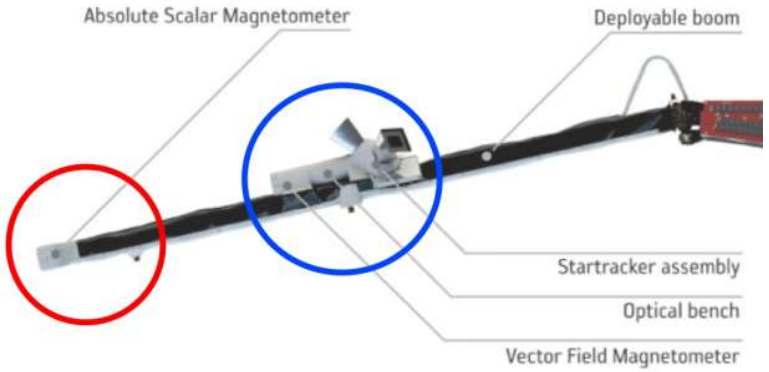


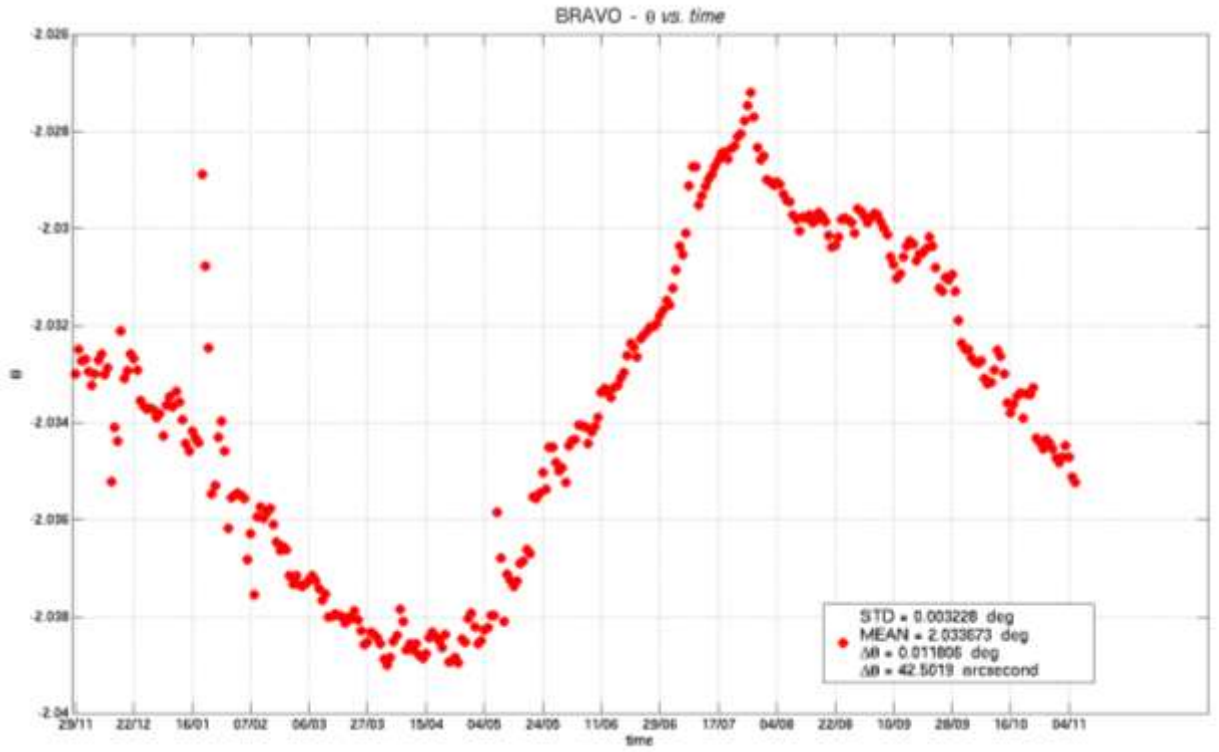
The internal sampling of the scalar sensors at **1kHz**, **allows** the instruments to be used in conjunctions with three sets of coils to also derive vector components at 1 Hz (**1 Hz "vector mode"**)

In this vector mode, three perpendicular coils generate periodic magnetic fields with known amplitudes (~ 50 nT) and three different known (and adjustable) frequencies beyond 1 Hz (7.92 Hz, 10.98 Hz, 12.97 Hz).

Real time analysis (with appropriate sampling rate) of the scalar field measured by the (scalar) sensor then makes it **possible to measure the scalar field at 1 Hz (with nominal performance) together with all field components along the three coil axis**.

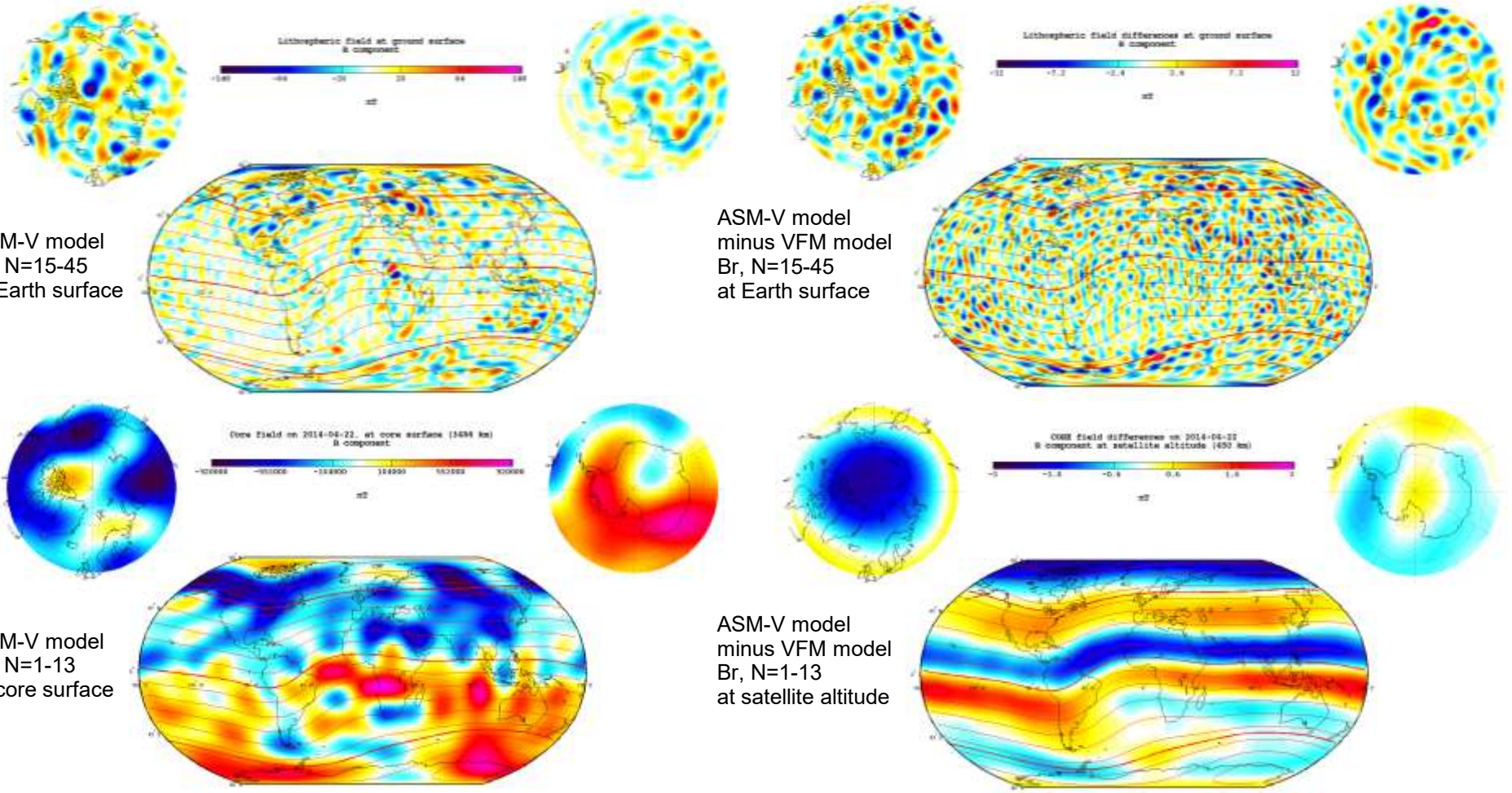
Stability of the boom between the ASM and VFM/STR assembly was found to be very good





- Seasonal variations were observed in daily alignments, with amplitude of 40 arcsec, but with **less than 4 arsec deformations within 10 consecutive days**.
- **This led to the possibility of testing ASM-V data** (used together with STR data) **for global field modelling**.

A very good global field model could be constructed early on using ASM-V and STR data



ASM-V model
Br, N=15-45
at Earth surface

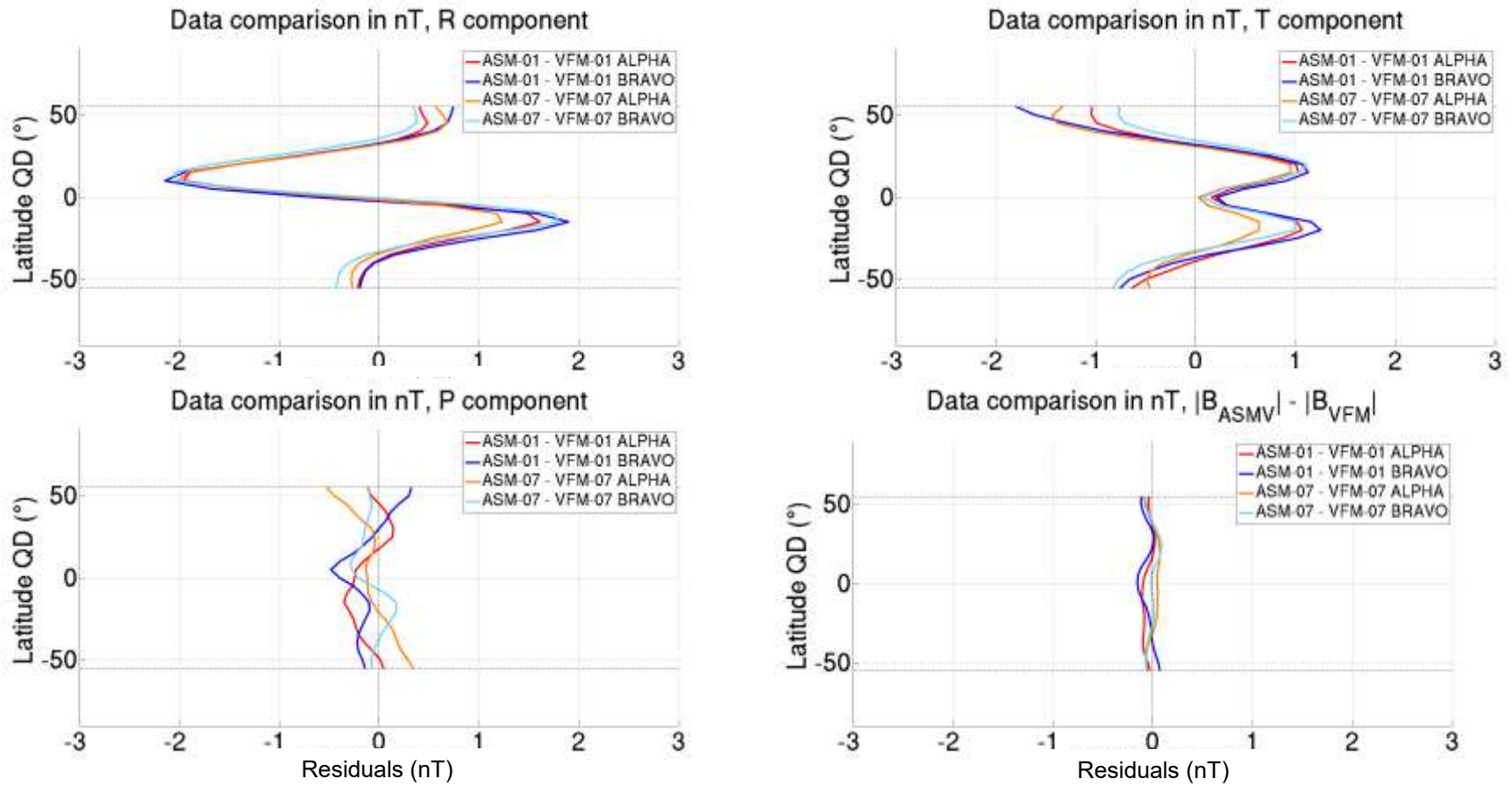
ASM-V model
minus VFM model
Br, N=15-45
at Earth surface

ASM-V model
Br, N=1-13
at core surface

ASM-V model
minus VFM model
Br, N=1-13
at satellite altitude

- **Early model** of Hulot et al. (2015), N=1-45, with SV N=1-13, using 11 months of Swarm Alpha and Bravo data
- **But this revealed some intriguing large scale systematic differences** when compared to an analogous model computed from L1b VFM data.

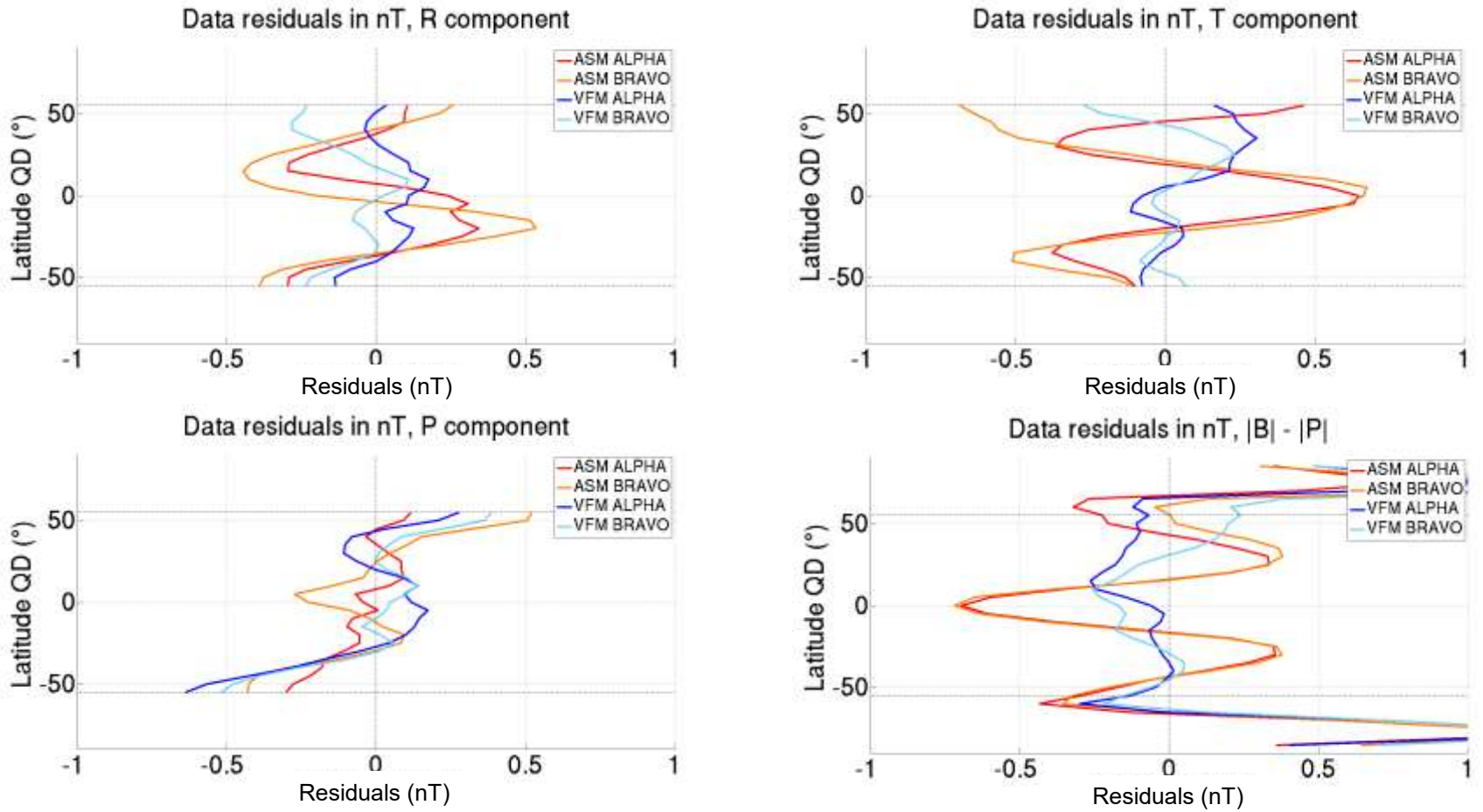
These differences arose because of disagreements between ASM-V and VFM data



Average QD latitudinal profiles of the differences between the ASM-V and VFM data in NEC frame

- **Note that the differences are mainly in the B_r and B_θ coordinates -> possible up and down boom oscillations along the orbit ?**
- **But they also are a function of QD latitude (and NOT of orbital latitude)**

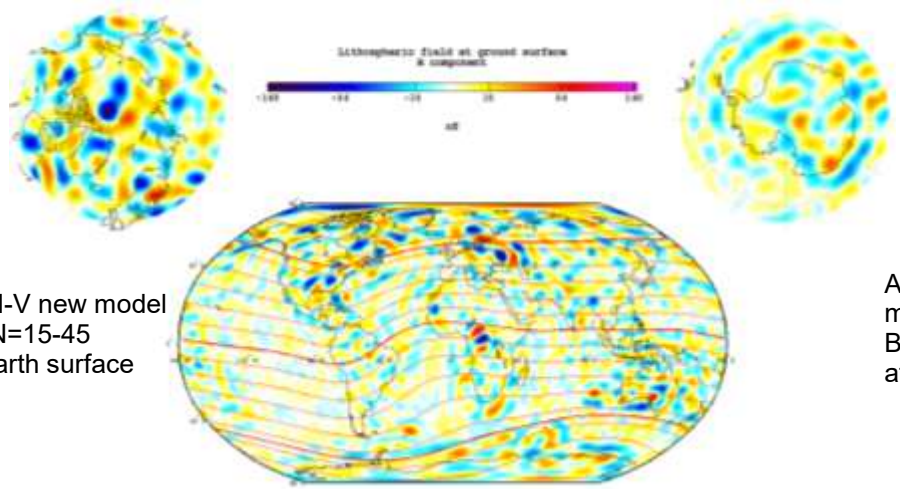
Data residuals with respect to their matching model pointed at an issue with the ASM-V data



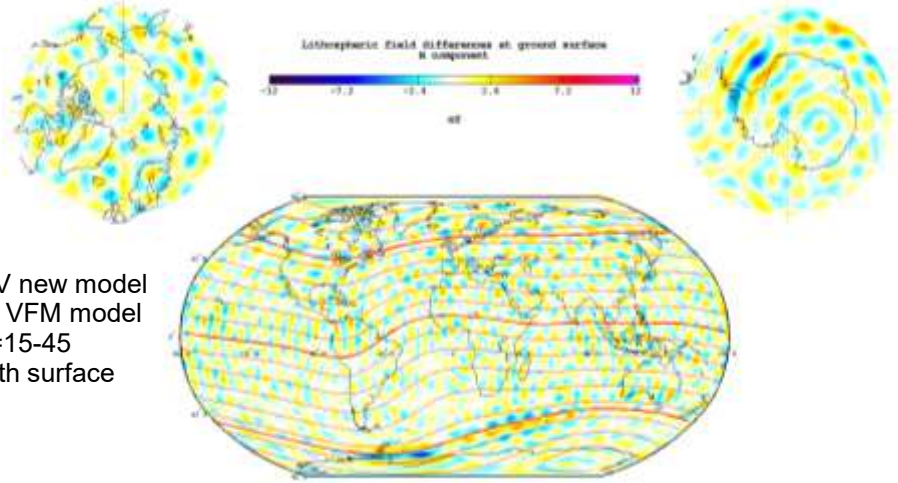
Average QD latitudinal profiles of the differences between the ASM-V and VFM data in NEC frame

- **Data residuals show a much stronger systematic signature when comparing ASM-V data to the ASM-V model**
- **This signature suggested a self-calibrating issue with the ASM**

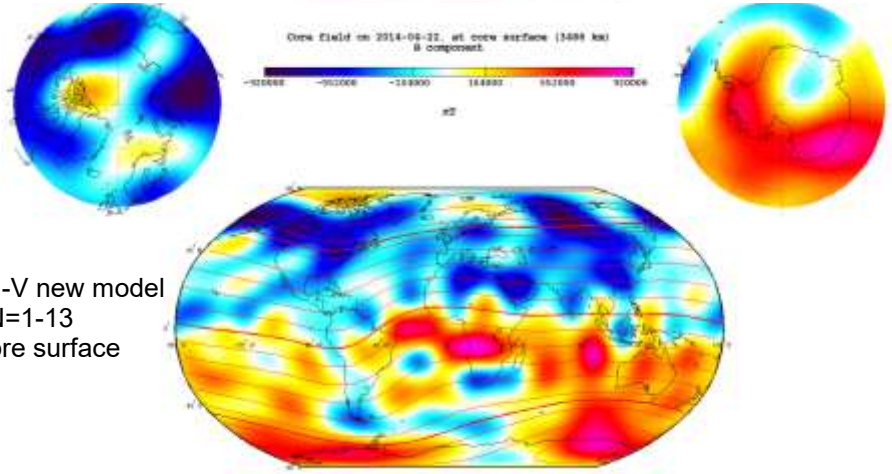
A Better global field model could be constructed by using recalibrated ASM vector mode (and STR) data



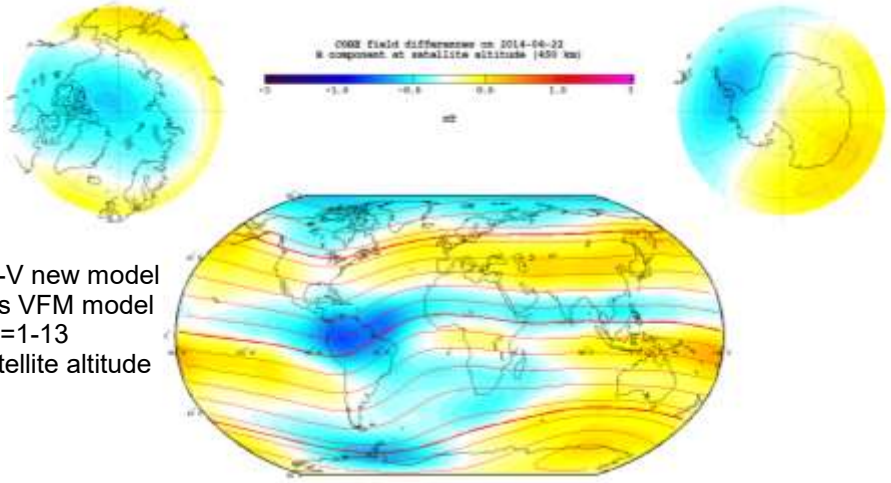
ASM-V new model
Br, N=15-45
at Earth surface



ASM-V new model
minus VFM model
Br, N=15-45
at Earth surface



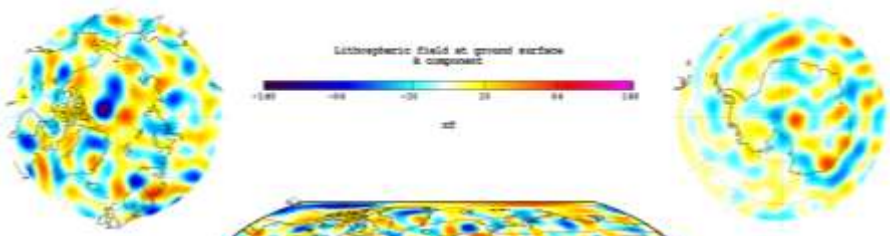
ASM-V new model
Br, N=1-13
at core surface



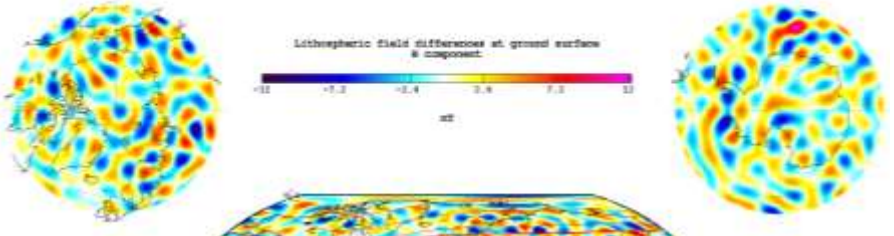
ASM-V new model
minus VFM model
Br, N=1-13
at satellite altitude

- **Latest model**, N=1-45, CHAOS-4 type temporal splines for N=1-13, **using 4 years of Swarm Alpha and Bravo data and an improved self-calibration procedure**
- **Leads to much better agreement** when compared to an analogous model computed from L1b VFM data (version 0503).

Recall the earlier situation with initial calibration (and using less data)



ASM-V model
Br, N=15-45
at Earth surface



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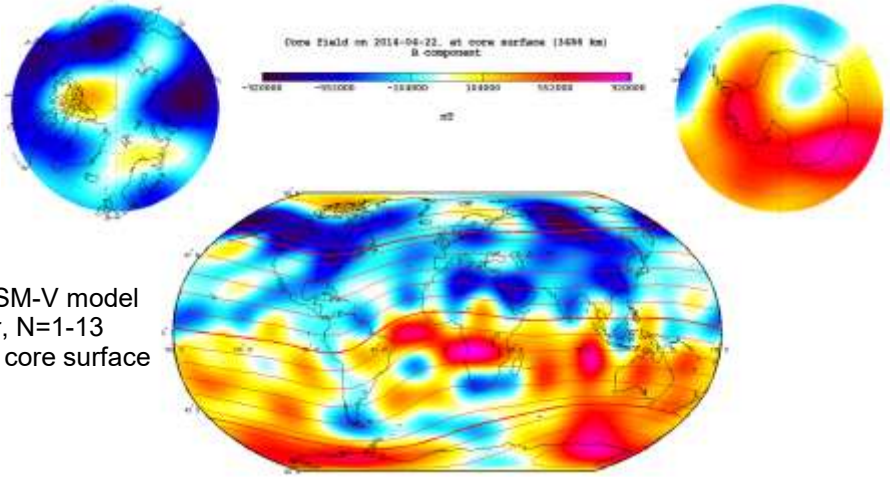

ASM-V model
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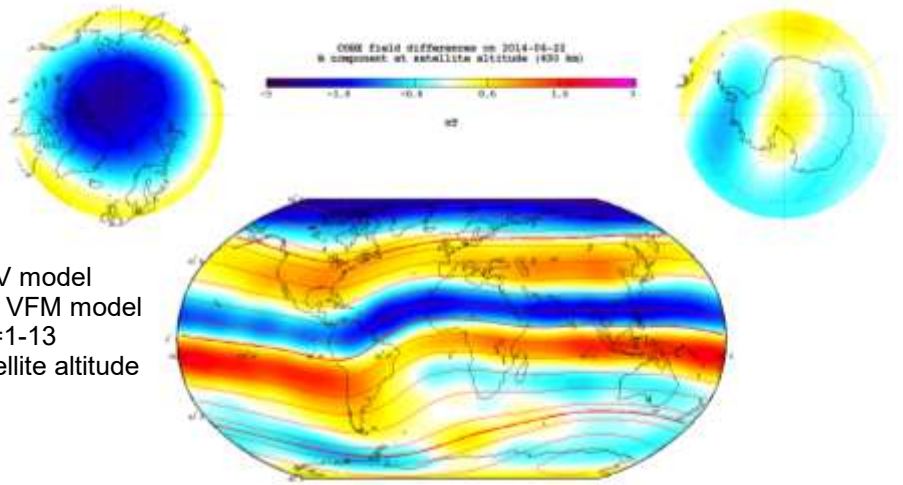
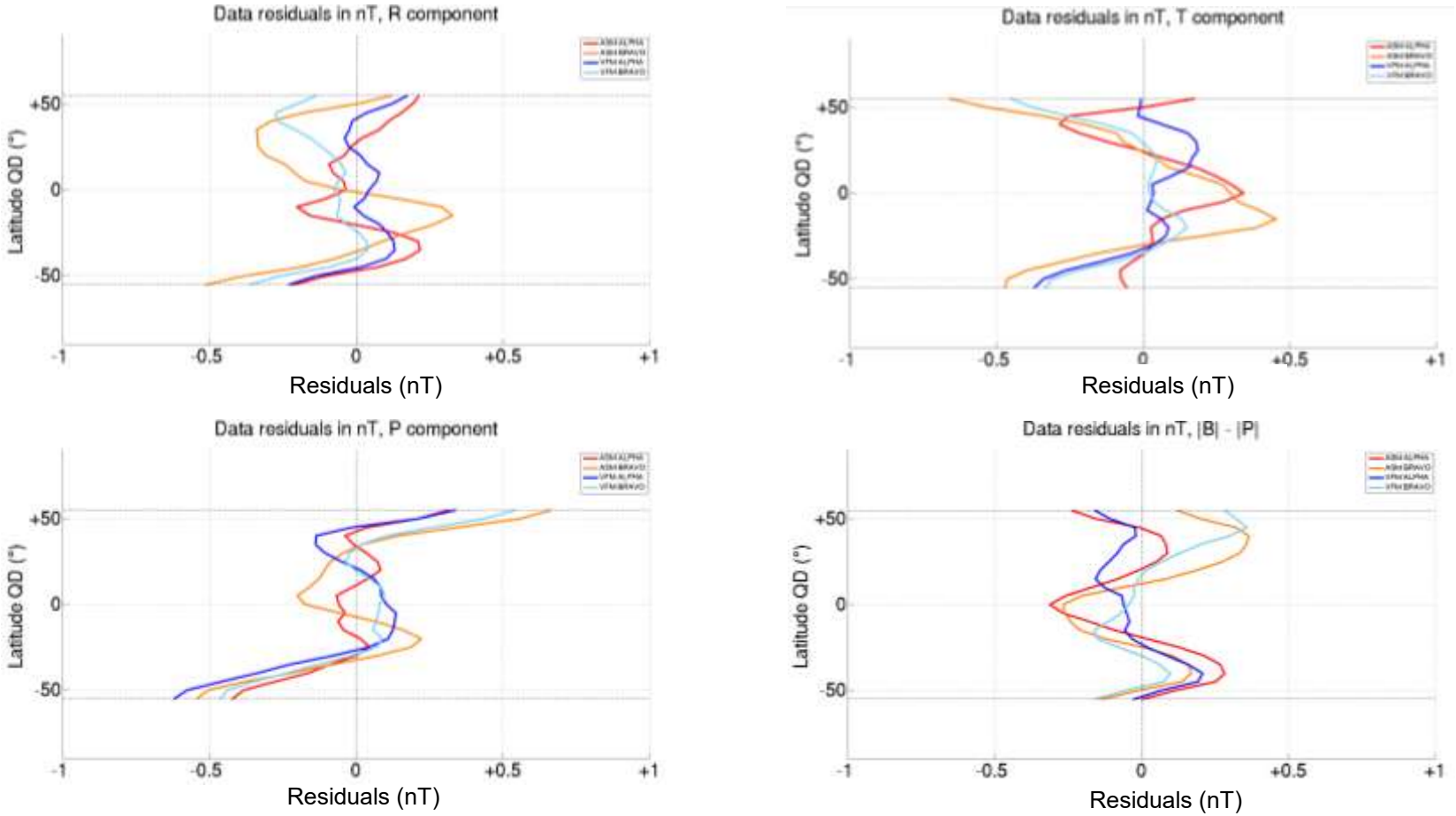


ASM-V model
minus VFM model
Br, N=1-13
at satellite altitude

- **Early model** of Hulot et al. (2015), N=1-45, with SV N=1-13, using 11 months of Swarm Alpha and Bravo data
- **Most of the intriguing large scale systematic differences** have been corrected for and the crustal field is much improved.

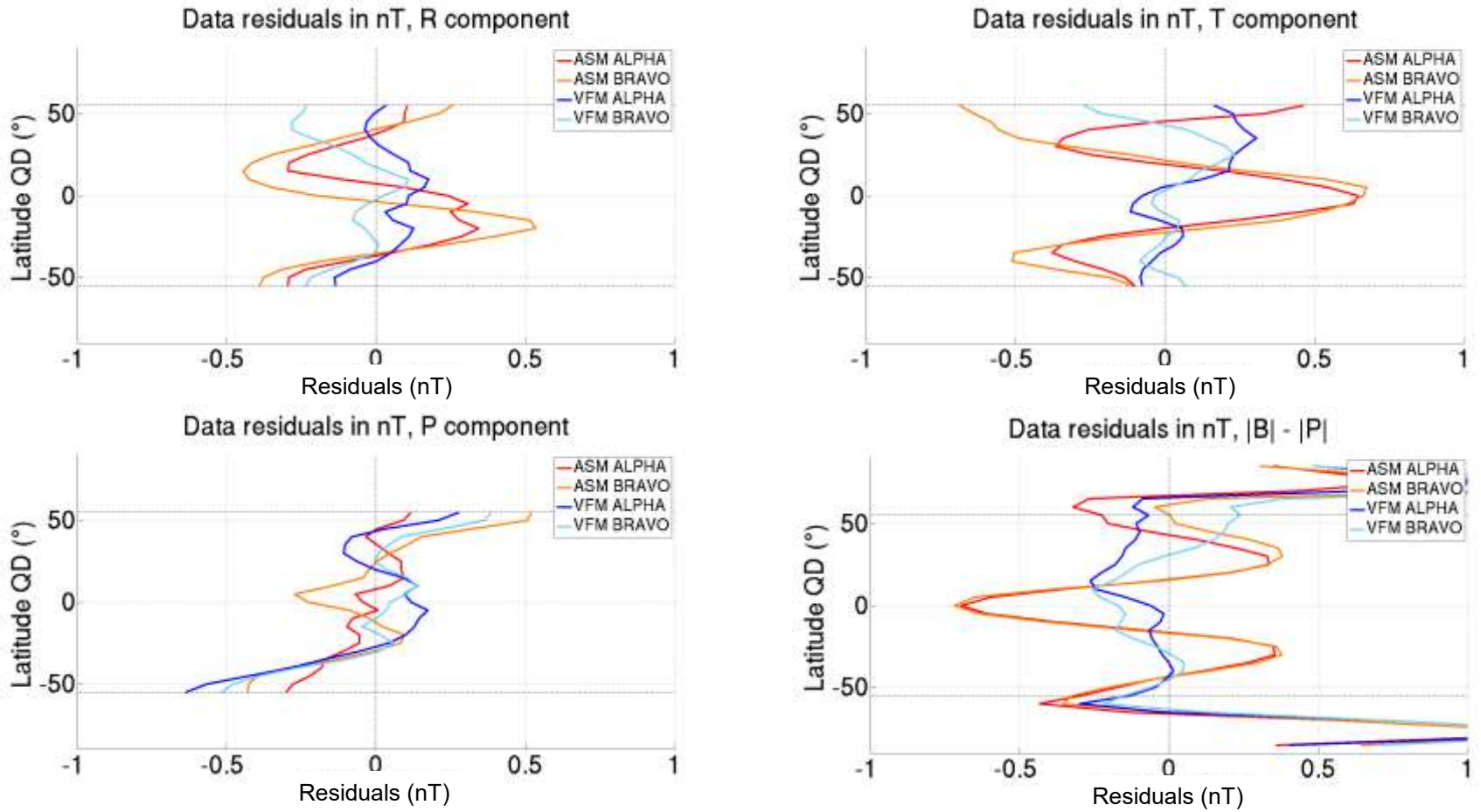
Data ASM-V residuals with respect to the ASM-V model are also improved



Average QD latitudinal profiles of the differences between the ASM-V and VFM data in NEC frame

- **Data residuals show a much weaker systematic signature when comparing ASM-V data to the ASM-V model**
- **Recall also that boom distortion and other effects may still play a role...**

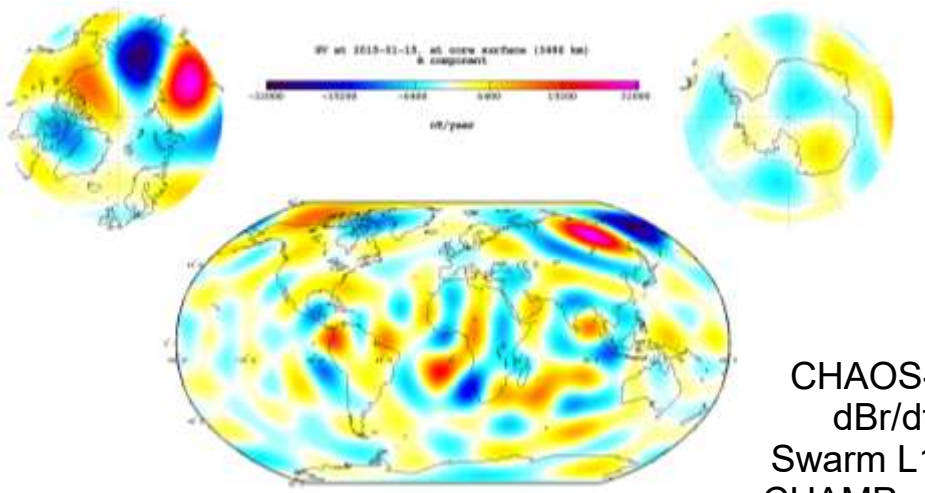
Recall the earlier situation with initial calibration (and using less data)



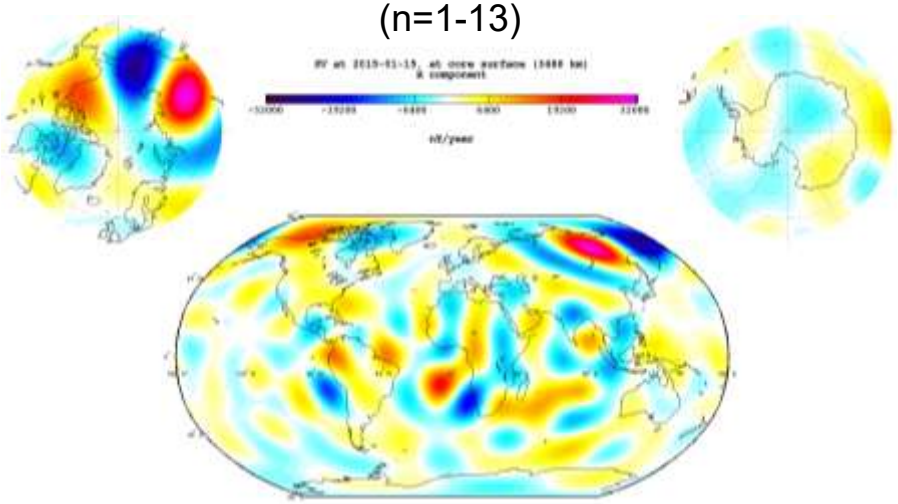
Average QD latitudinal profiles of the differences between the ASM-V and VFM data in NEC frame

- **Data residuals show a much weaker systematic signature when comparing ASM-V data to the ASM-V model**
- **Recall also that boom distortion and other effects may still play a role...**

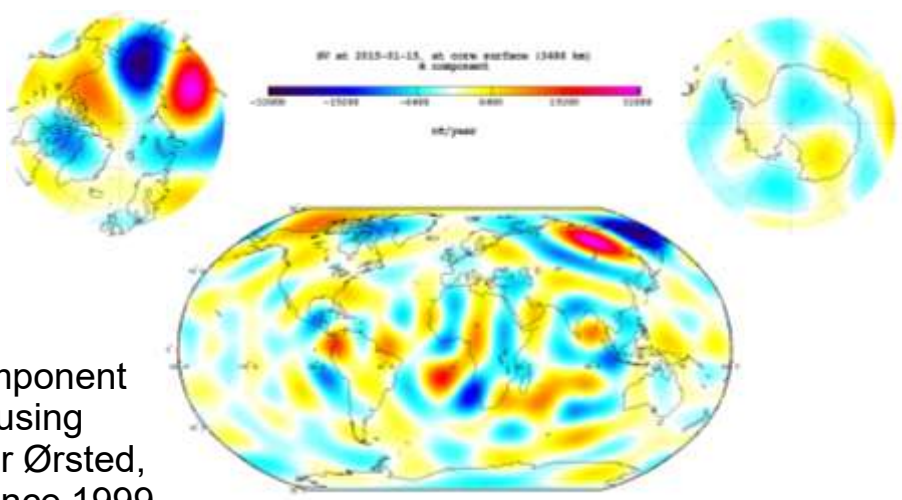
Recovery of Secular Variation is also hugely improved



ASMV field model component dBr/dt at core surface only using ASM-V data (n=1-13)



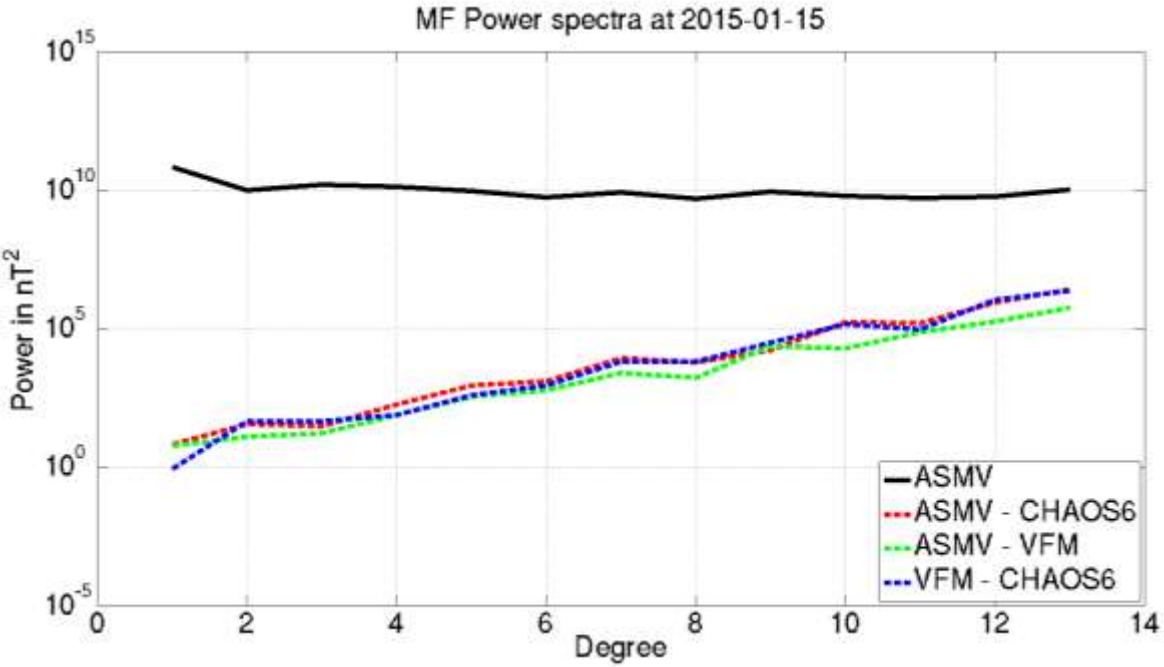
CHAOS-6 field model component dBr/dt at core surface, using Swarm L1b data and earlier Ørsted, CHAMP and SAC-C data since 1999 (n=1-13)



VFM field model component dBr/dt at core surface using Swarm L1b data (n=1-13)

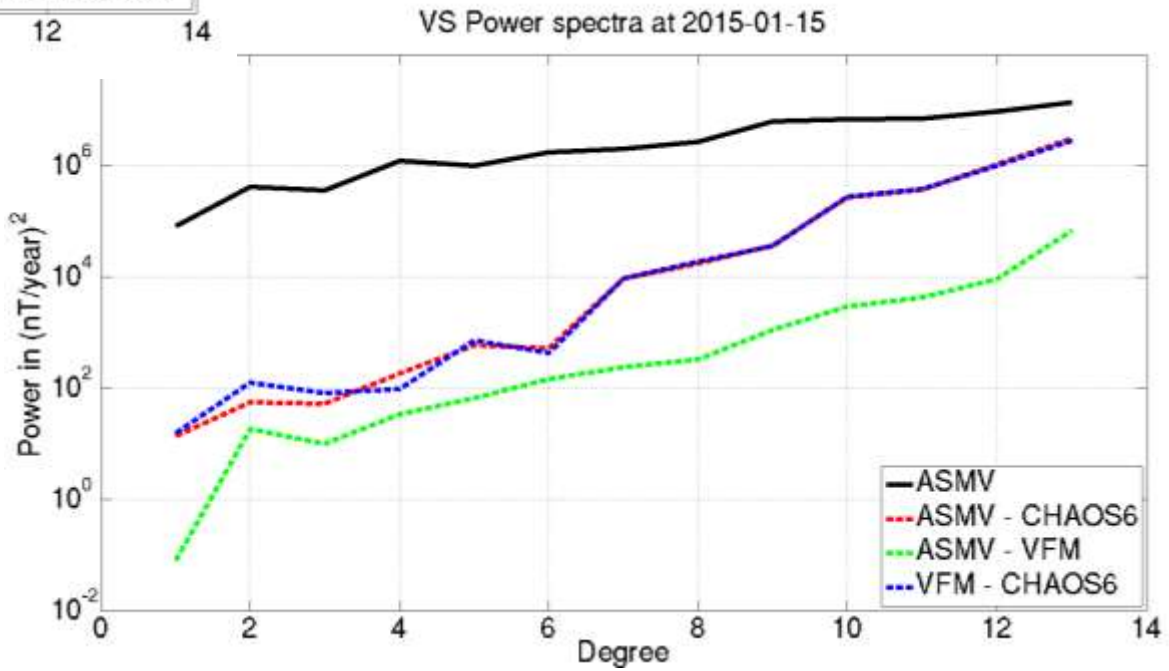
- **Secular Variation (here January 15, 2015)**, now compares very well with the SV computed from L1b VFM data (0503) and with the CHAOS-6 model (which also uses Ørsted, CHAMP and SAC-C data, Finlay et al., 2016).

Differences with respect to CHAOS-6 are now mainly due to differences in modelling strategy



ASM-V model spectrum (black) with spectra of the differences between ASM-V and CHAOS-6 models (red), ASM-V and VFM models (green), and VFM and CHAOS_6 models, all at core surface on 15/01/2015 (n=1-13)

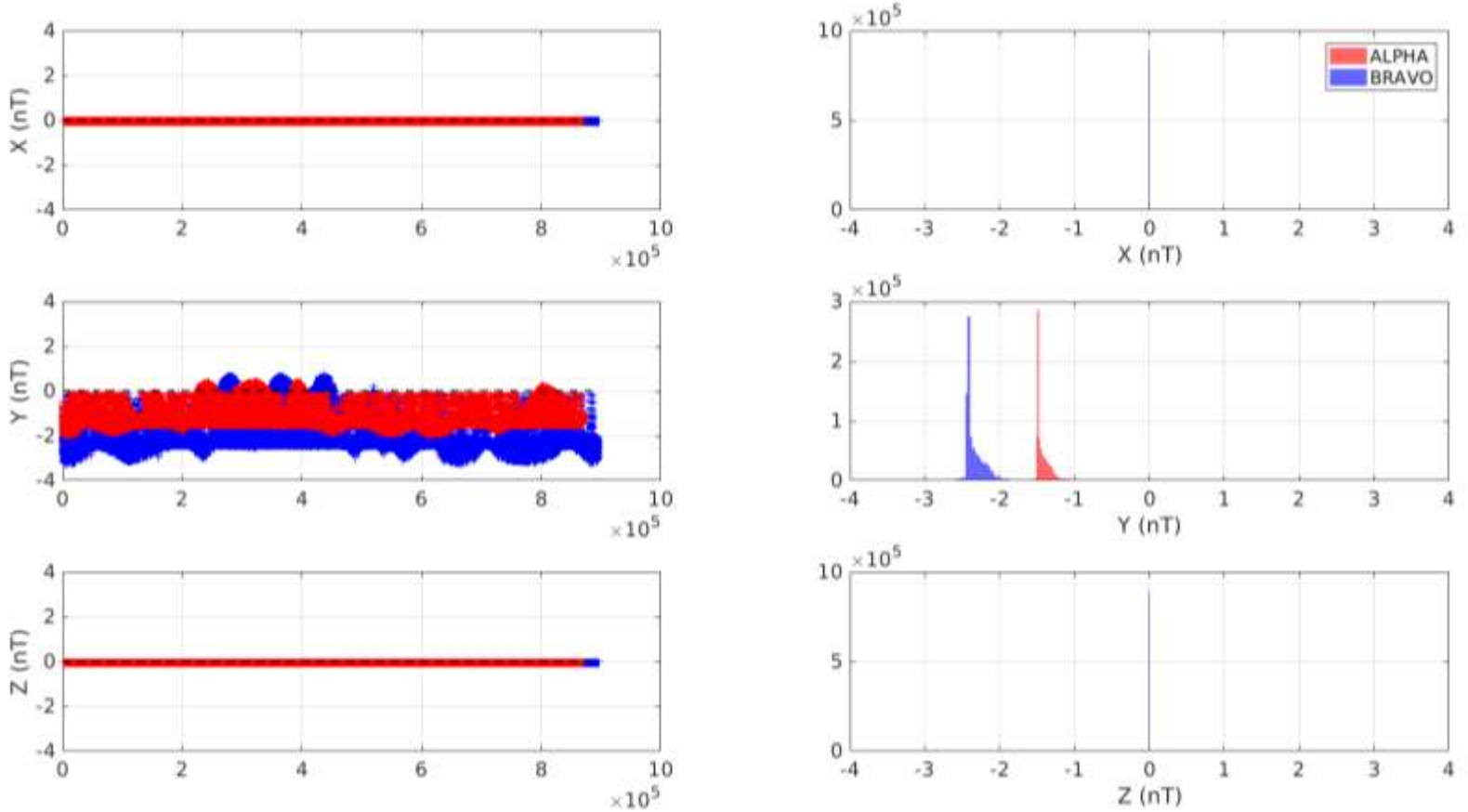
ASM-V field SV model spectrum (black) with spectra of the differences between ASM-V and CHAOS-6 SV models (red), ASM-V and VFM SV models (green), and VFM and CHAOS_6 SV models, all at core surface on 15/01/2015 (n=1-13)



What about the dBSun issue affecting both the ASM and VFM instruments ?

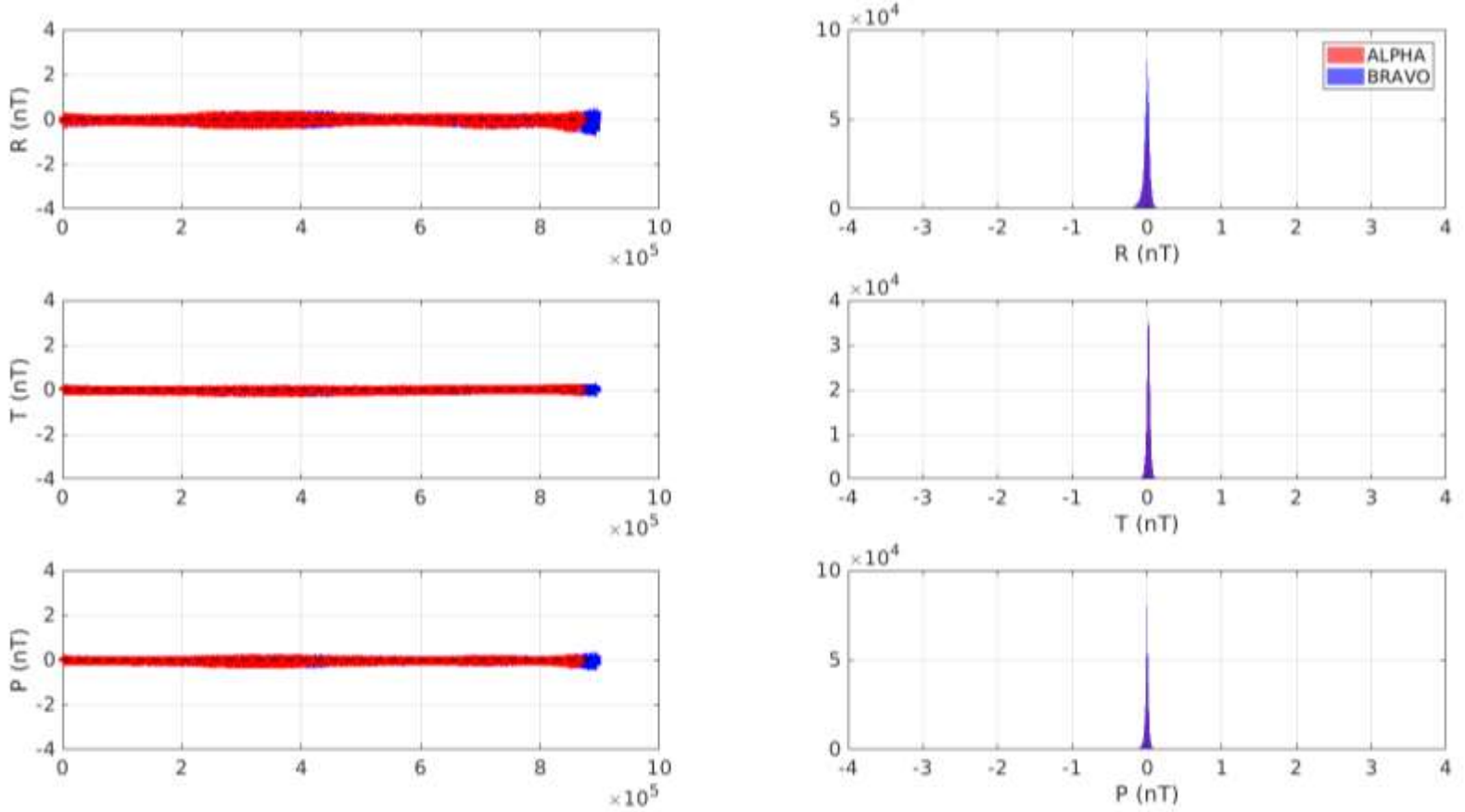
- We know **dBSun perturbations are affecting both the ASM and VFM instruments** (recall previous talks)
- **ASM-V/VFM model comparisons shown so far in this talk were based on the assumption that the effect was only affecting the VFM instruments** (we used L1b VFM data version 0503, which included such a correction to make the VFM L1b data modulus consistent with the scalar readings of the ASM). **But we know this is incorrect...**
- **Is there a way global field modelling could help validating the part of the dBSun that is affecting the ASM instrument ?**
- **We started looking into this and tested the impact of introducing a correction for the dBSun effect on the ASM-V data based on the model proposed by P. Brauer** (using the model parameters inferred from the analysis of manoeuvres, recall talk by Vigneron and Hulot “Towards correcting ASM data for the Sun-related thermoelectric effect”).
- **In what follows we compare the (recalibrated) ASM-V model analysed so far with a model built in the same way but using (recalibrated) ASM-V data corrected for the dBSun effect predicted to affect it.**
- How does the modelling deal with this correction ?

dBSun correction predicted by the model of P. Brauer on the ASM-V data



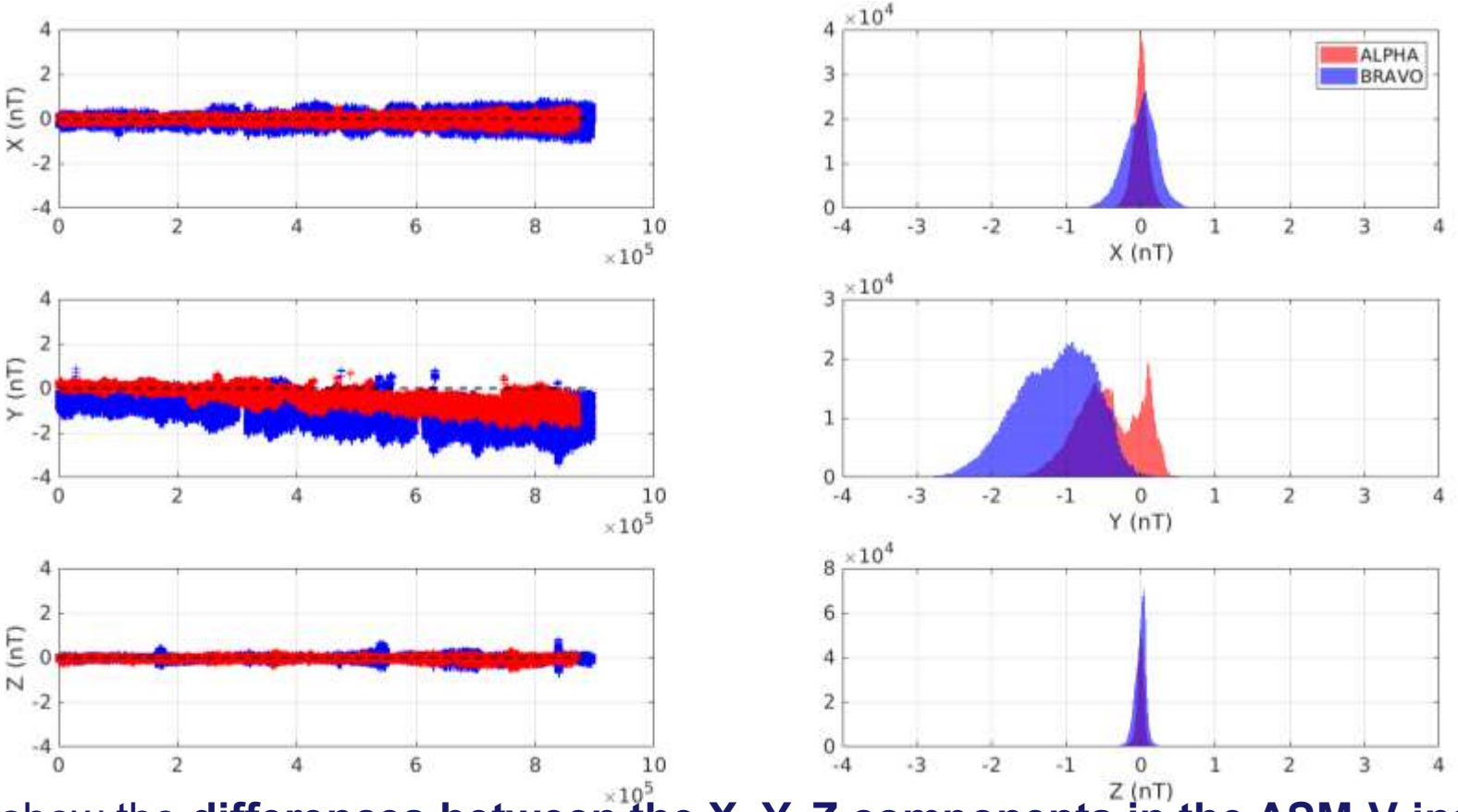
- **Corrections are shown here for the X, Y, Z components in the ASM-V instrument frame of reference, for the four years of data used for the modelling**
- They only affect the **Y-component** of the ASM-V data
- Because **the data** for modelling are **selected on the night side**, the **correction is mainly negative**
- The correction is **stronger on Bravo than on Alpha**

Impact on the core and lithospheric parts of the model is negligible



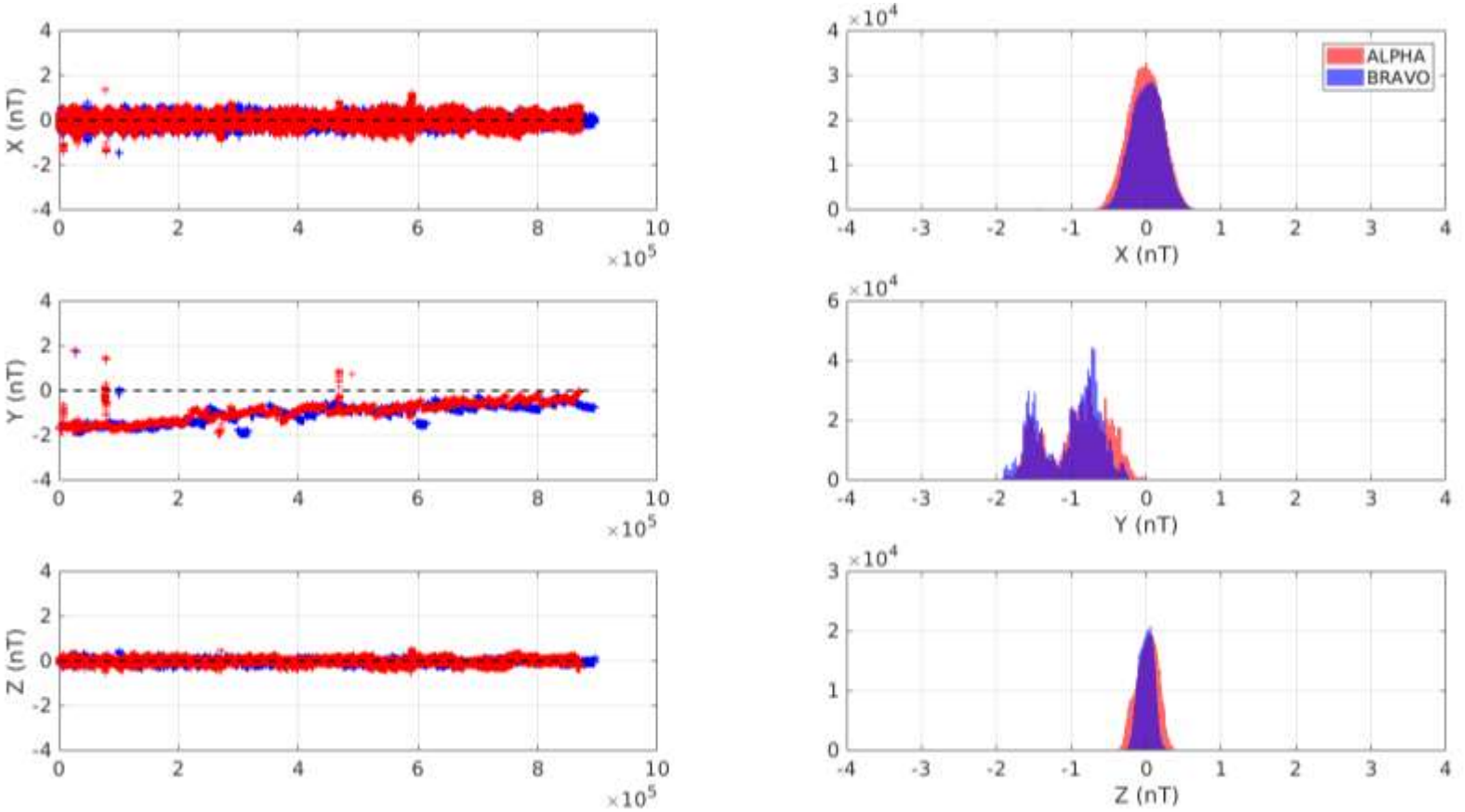
- Here, we show the **differences between the B_r, B_θ, B_ϕ spherical components predicted by the original ASM-V model and those predicted by the corrected ASM-V model** for the four years of data used in the modelling.
- Differences are **very small** (less than a few 0.1 nT)
- **dBSun corrections are NOT affecting the core and lithospheric part of the model**
- Where does the dBSun correction go ?

Part of the dBSun is absorbed in the form of an apparent rotation between the ASM-V and STR frames of references



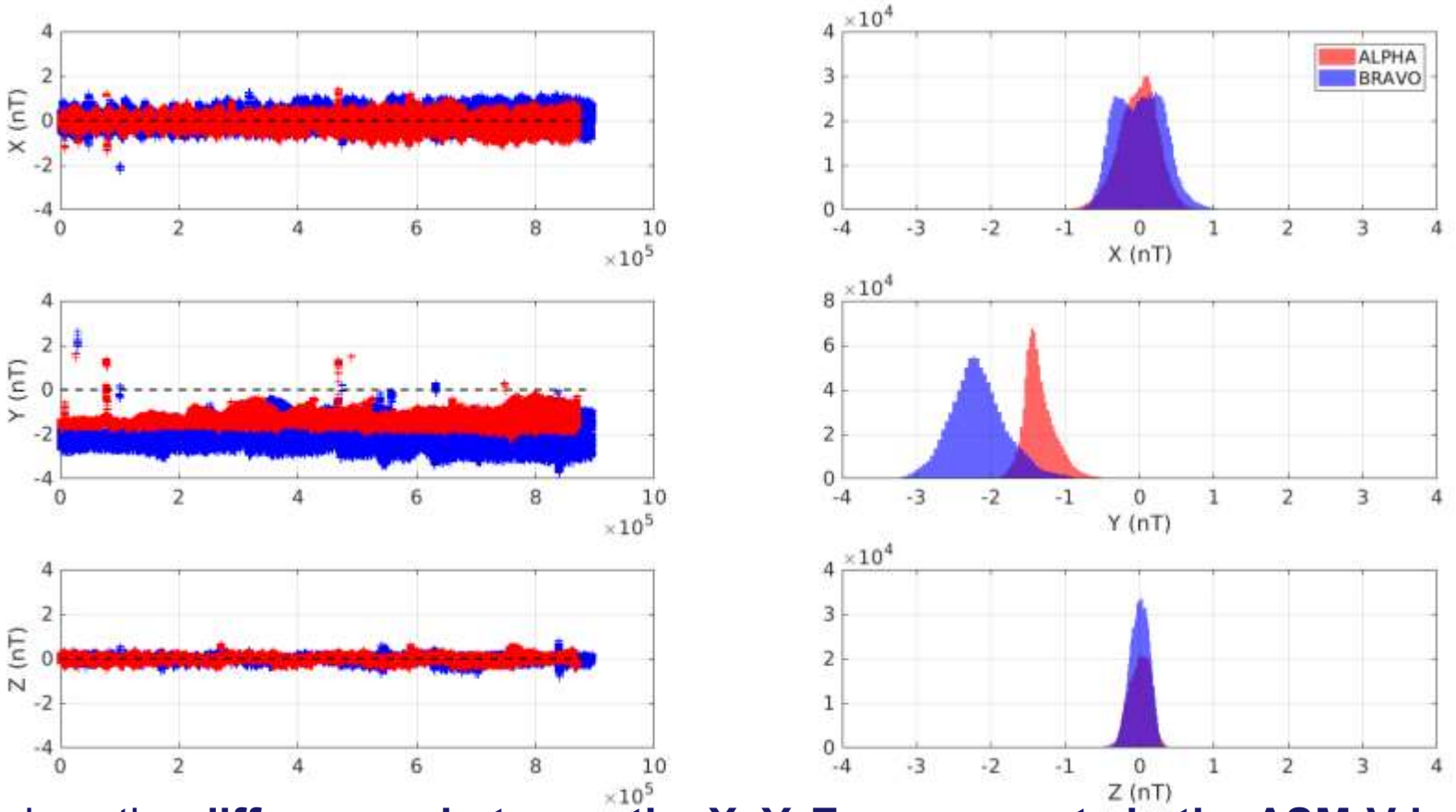
- Here, we show the **differences between the X, Y, Z components in the ASM-V instrument frame of reference predicted by the original ASM-V model and those predicted by the corrected ASM-V model (only core and lithosphere).**
- **Differences are now commensurate with the dBSun correction and have a similar bias.**
- **dBSun corrections are partly mapped in the Euler angles**
- Note however **an intriguing trend in the Y component**

Another part is absorbed in the form of an apparent external field



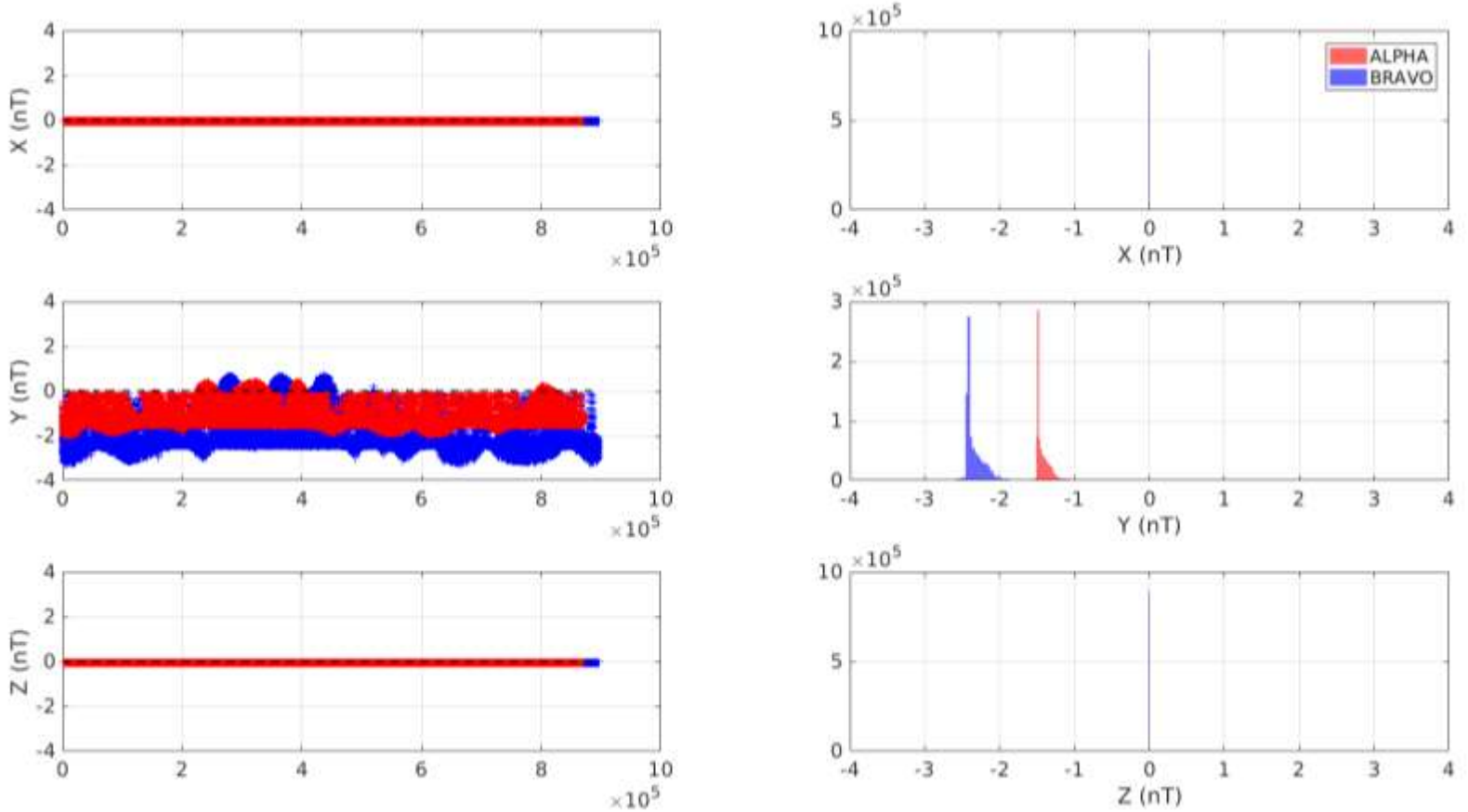
- Here, we show the **differences between the X, Y, Z components in the ASM-V instrument frame of reference predicted by the original ASM-V external field model and those predicted by the corrected ASM-V external field model.**
- **An opposite trend is now seen in the Y component.**
- **dBSun corrections are also partly mapped in the external field**

The combined apparent rotation and external field account for the systematics of the dBSun correction



- Here, we show the **differences between the X, Y, Z components in the ASM-V instrument frame of reference predicted by the original ASM-V field model and those predicted by the corrected ASM-V field model (core+lithosphere+external).**
- **The combined apparent rotation and external field account for the systematic negative bias of the dBSun correction on the Y component.**
- Note, however, the **wider distributions,** which suggest that **the rest of the dBSun correction must be rejected in the model residuals.**

dBSun correction predicted by the model of P. Brauer on the ASM-V data



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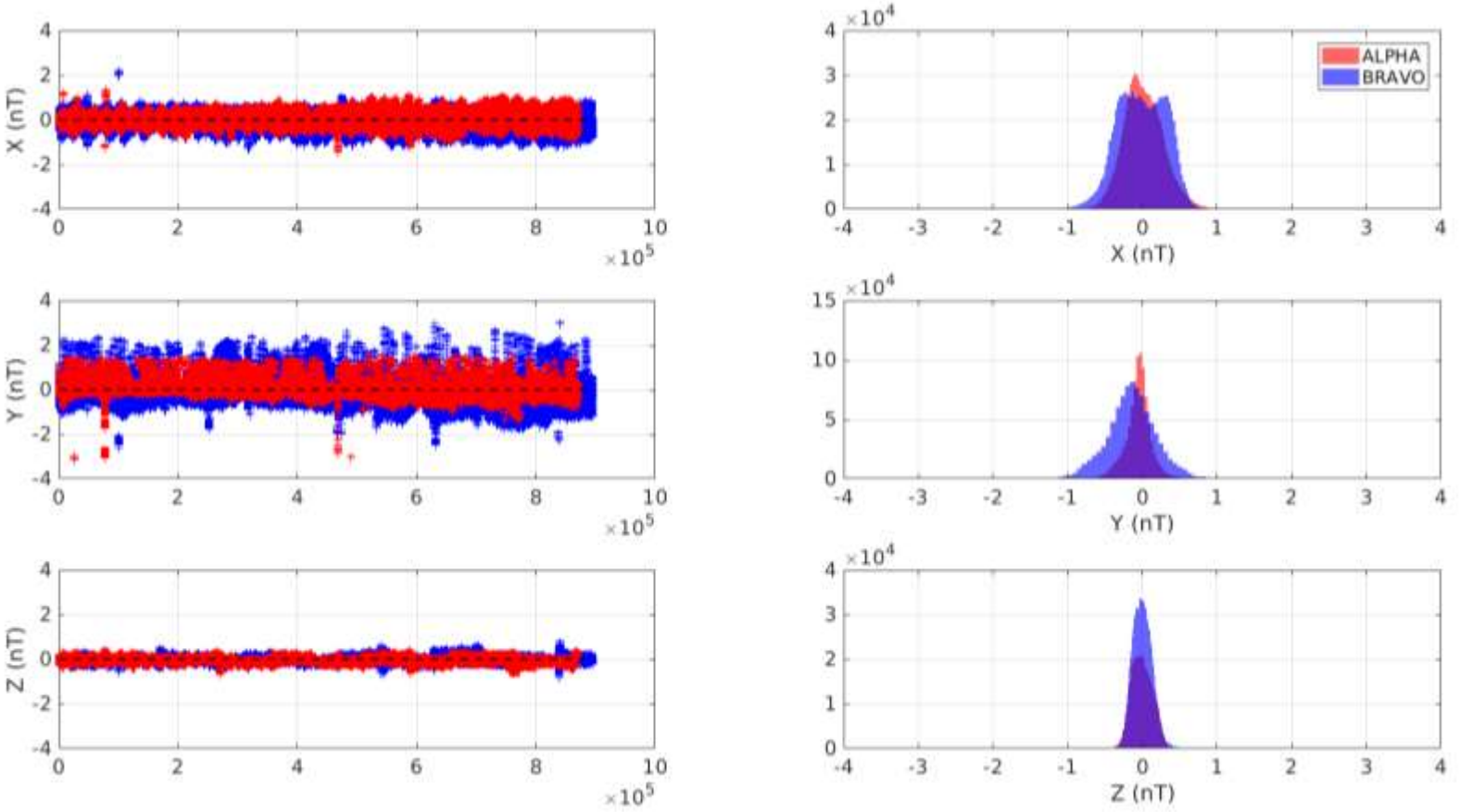
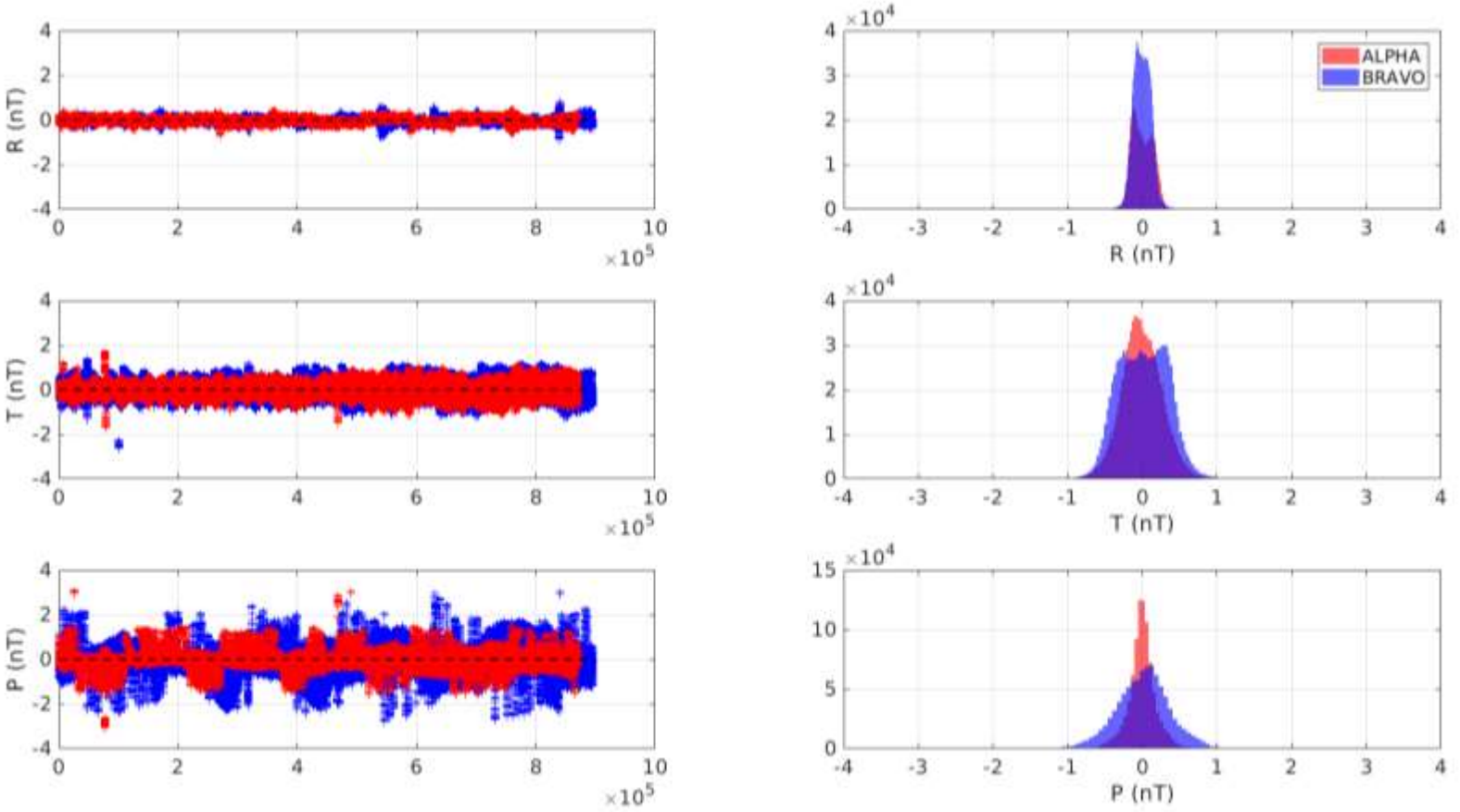
- They only affect the **Y-component** of the ASM-V data
- Because **the data** for modelling are **selected on the night side**, the **correction is mainly negative**
- The correction is **stronger on Bravo than on Alpha**

The rest of the dBSun correction is indeed rejected in the residuals



- Here, we show the **differences between the X, Y, Z residuals in the ASM-V instrument frame of reference (with respect to the full core+lithosphere+external fields).**
- Typical order of magnitude is 1nT on X and Y, much less on Z.

The rest of the dBSun correction is indeed rejected in the residuals



- Here, we show the **differences between the B_r, B_θ, B_ϕ spherical component residuals (with respect to the full core+lithosphere+external fields).**
- Typical order of magnitude is 1nT on B_θ and B_ϕ, much less on B_r.
- **Note the pattern on the B_ϕ residuals, reflecting opposite effects when the satellites are up or down-going on the (selected) day side of their orbit.**

Conclusion and way forward

- **Geomagnetic field models built from recalibrated ASM-V data** (over four years, November 2013 to November 2017) now **compare very well (including the secular variation) with models built in the same way from nominal L1b VFM data, and with other more elaborate models** (e.g., CHAOS-6) also taking advantage of the Charlie and gradient data and relying on additional data (Champ, Oersted, etc..), **despite the higher noise levels of the ASM-V data and the more unfavourable location of the ASM with respect to the STR**

-> **very encouraging results for the NanoMagSat project** (see talk on Thursday)

- **Investigations of the impact of the dBSun correction on the Y component of the ASM-V data suggest** that the corresponding **perturbation does not affect the modelled core and lithospheric fields**, but is **mapped into an Euler angle correction combined with an apparent external field perturbation, with a significant fraction rejected in the residuals**

-> **good news for core and lithospheric field modelling ? Possibly...**

-> **bad news for external field investigations ?** (especially if ASM dBSun corrections are wrongly applied to L1b VFM data)

- **Checking the validity of the ASM dBSun corrections with the help of geomagnetic field modelling using ASM-V data** might be possible but **would require a smart way of measuring the improvement brought by the correction**: not possible to rely on core and lithospheric field comparisons, but looking into systematic in the residuals (on the day side, not used for modelling ? Bias/Variance reduction ?) could possibly help

-> more work is needed...