Lessons learnt from (near) ten years of dual-mode operation of the Swarm (CNES-CFI) CEA-Leti ASM instruments

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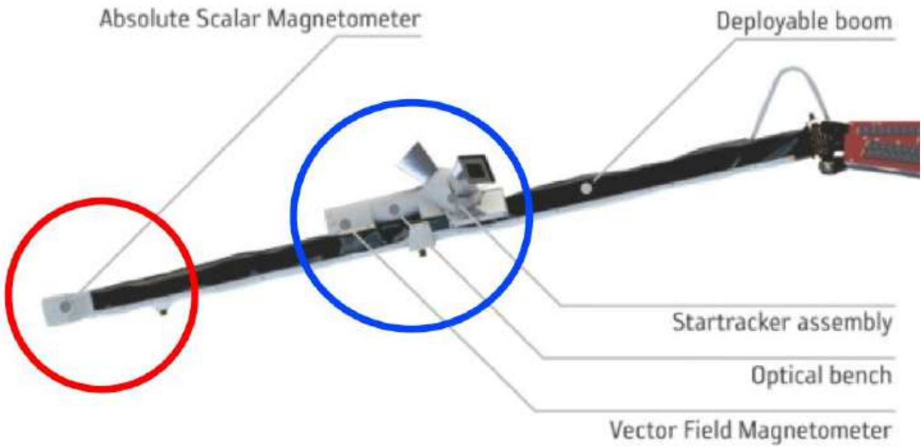
Swarm ASM operating modes



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

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

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

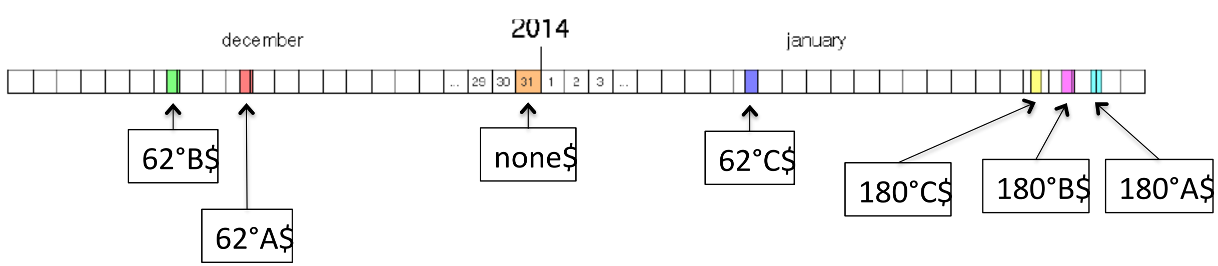
But **it can also simultaneously produce (see poster by T. Jager et al.):**

- When in **burst mode: 250 Hz scalar data**
- When in **vector mode: 1 Hz self-calibrated ASM-V vector** data (independent from the nominal L1b data produced by the VFM instrument)

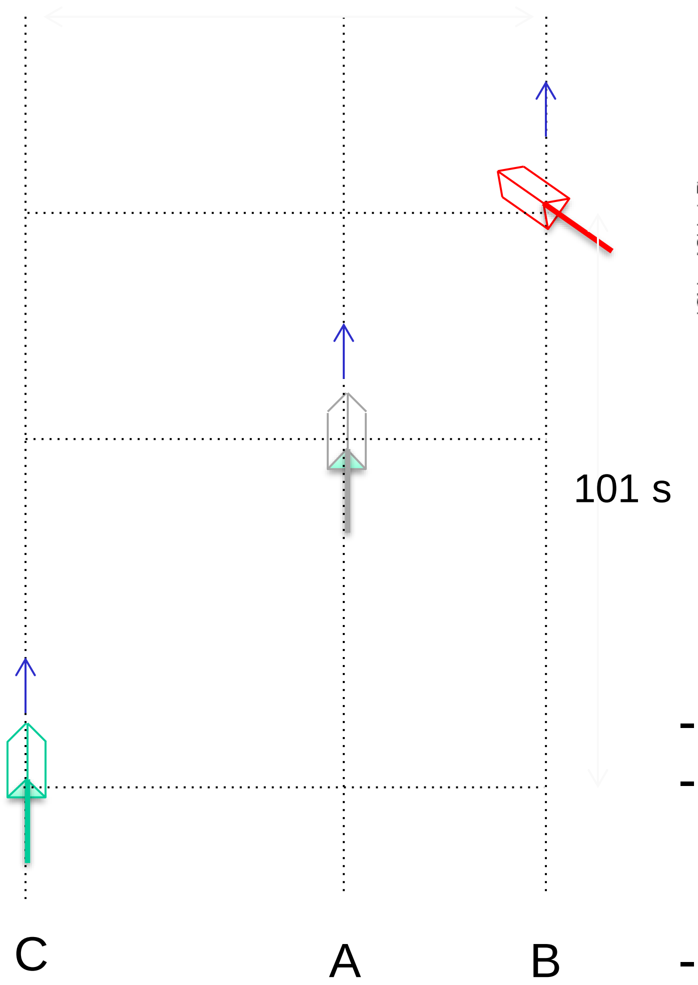
Only one mode can be operated at a time and the **burst mode is now run (since 2019) one week per month on Alpha and Bravo** (usually not at the same time, but occasionally so)

Early identification of a "dBSun" issue on the ASM, thanks to manoeuvres

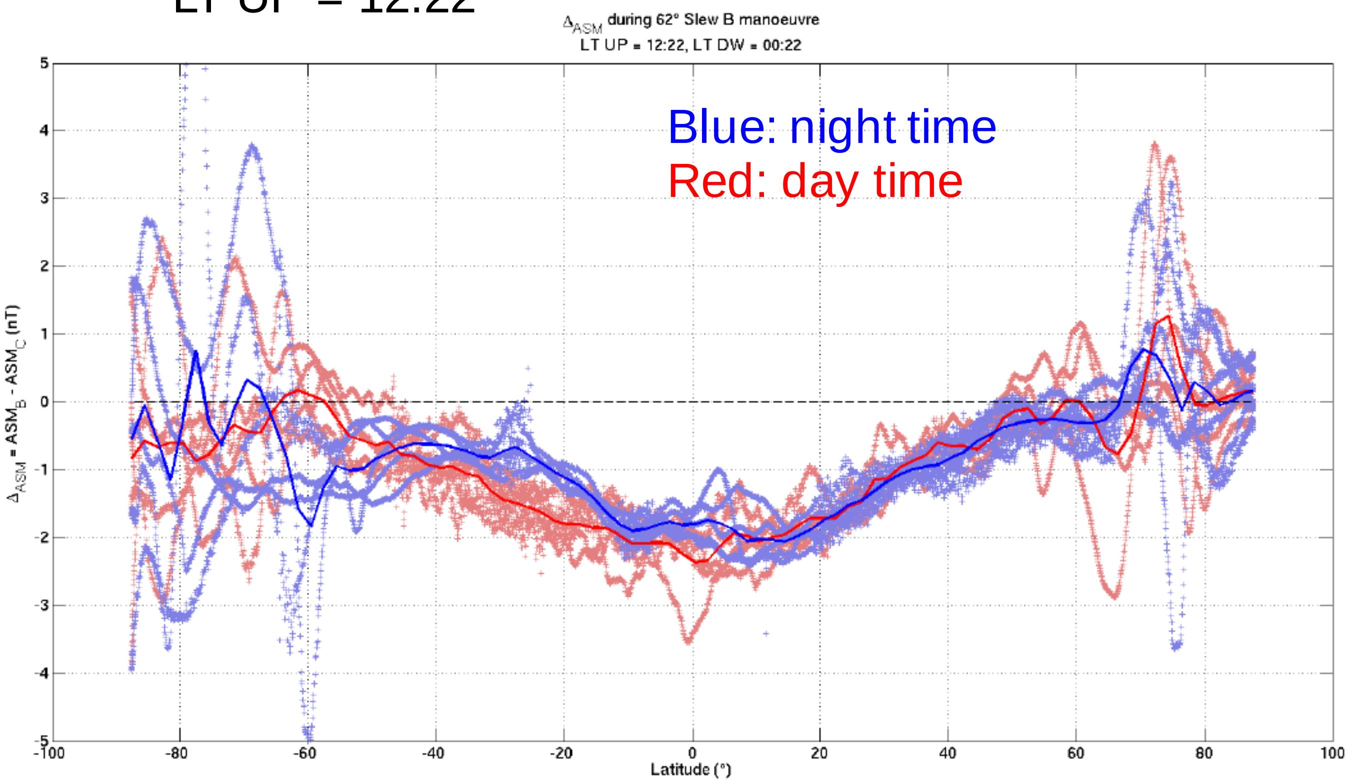
manoeuvres	Begin (UTC)		End (UTC)		0408 DATA AVAILABILITY			LT UP
					A	B	C	
62° A	19/12/13	14:00:00	20/12/13	02:00:00	100%	100%	100%	12:09
62° B	16/12/13	14:00:00	17/12/13	02:00:00	0%	100%	100%	12:22
62° C	09/01/14	11:58:00	09/01/14	23:58:00	100%	100%	100%	10:16
180° A	23/01/14	17:55:00	24/01/14	05:55:00	100%	100%	50%	09:05
180° B	22/01/14	14:20:00	23/01/14	02:20:00	20%	100%	100%	09:10
180° C	21/01/14	06:00:00	21/01/14	18:00:00	100%	100%	100%	09:15
+/- 90° AC	13/05/14	00:49:00	14/05/14	09:51:00	100%	NA	100%	23:15
None	31/12/13	00:00:00	31/12/13	23:59:59	100%	100%	100%	11:05



Example: 62° Slew Bravo Manoeuvre



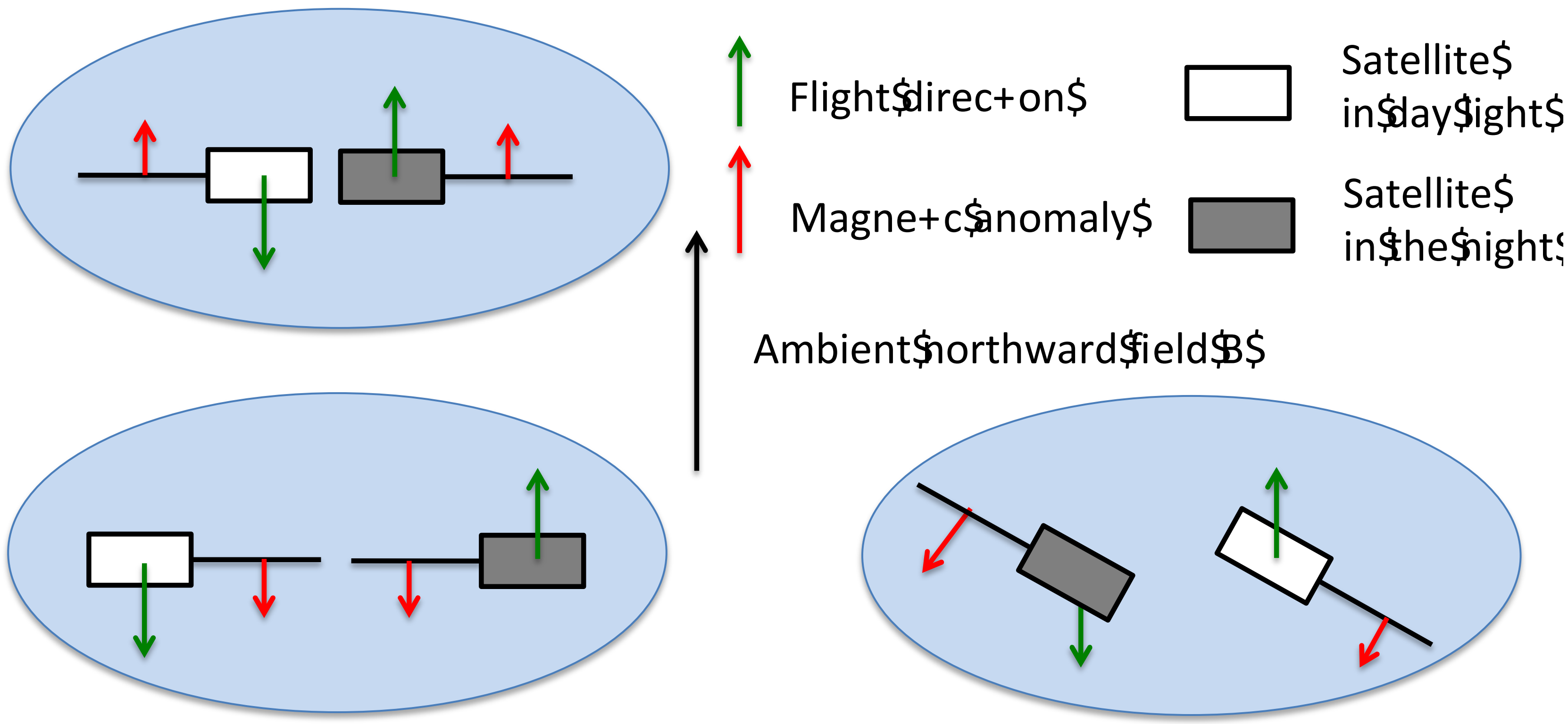
LT UP = 12:22



- The discrepancy is **maximum at the equator**
- NO similar discrepancies are found between Charlie and Alpha -> **not related to local ionospheric currents** between Alpha and Bravo
- Amplitudes and signs are **similar during day when moving northwards and at night when moving southwards**

Anomaly direction and sign rules inferred

The fact that disagreements between satellites are only seen for +/- 90° and 62° slew manoeuvres, are maximum at the equator and change sign in specific ways, suggested that **a slight anomalous field is being produced in the horizontal transverse direction** (Y component in the ASM frame of reference), as summarized here, **with a sign depending on whether the satellite is in the day light or not**.



Disagreements predicted during slew manoeuvres

- We assume that the perturbation is negligible on satellite flying nominal (or 180° slew) -> assumption that could later be relaxed

- If the slew manoeuver is on SAT-U, while SAT-V is nominal, the expected signature on the scalar disagreement is :

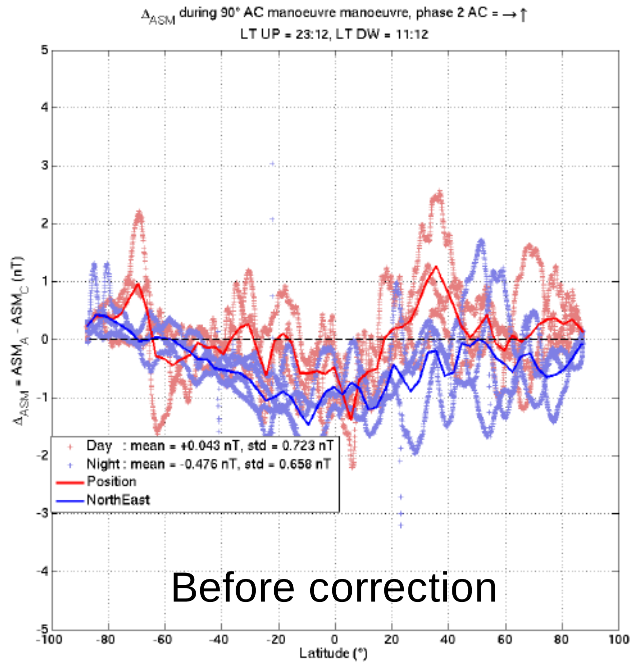
$$S_{UV} = \frac{\Delta B \cdot B}{\|B\|} = \frac{dBSunY_U \cdot Y_U}{F}$$

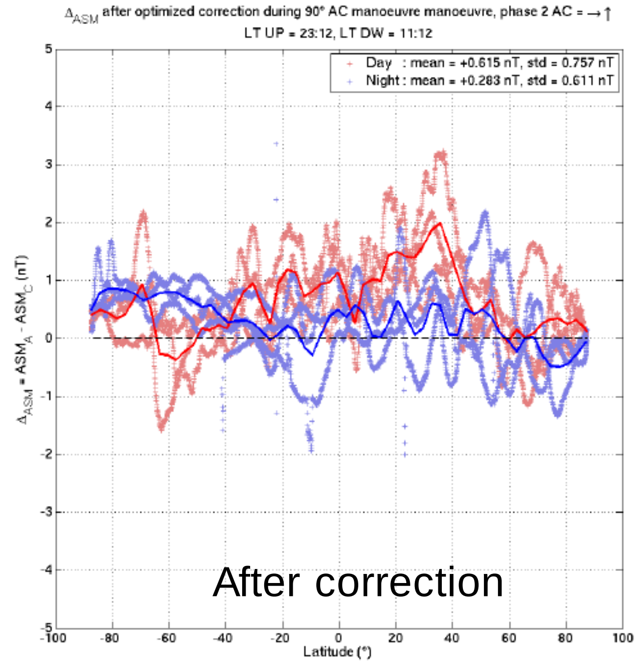
- Which we compare to the observed disagreement $\Delta_{UV,\,ASM}$

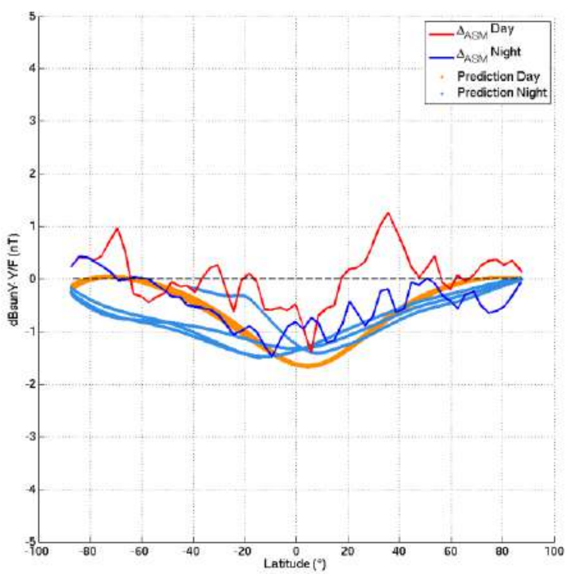
$$R_{UV} = S_{UV} - \Delta_{UV,ASM}$$

Testing the models with the 90° Alpha/Charlie manoeuvres

Phase	C	A
1	↑	↑
2	↑	→
3	←	→
4	←	↓
5	↓	↓
6	↓	←
7	→	←
8	→	↑
9	↑	↑







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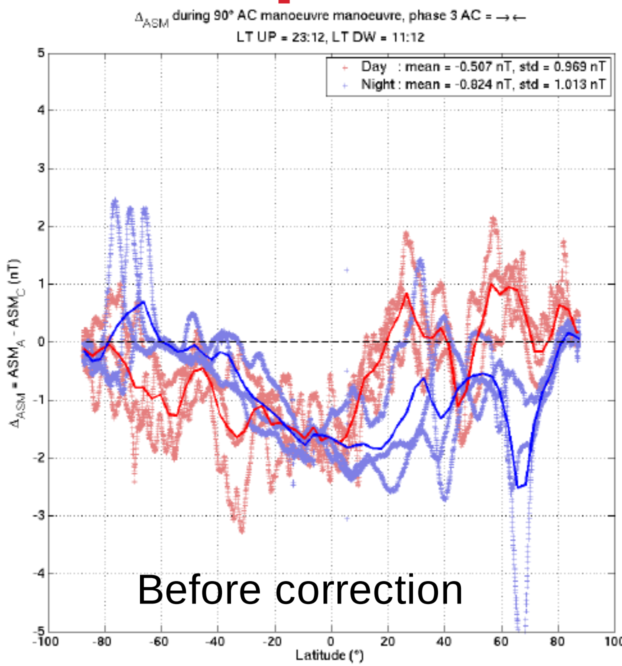
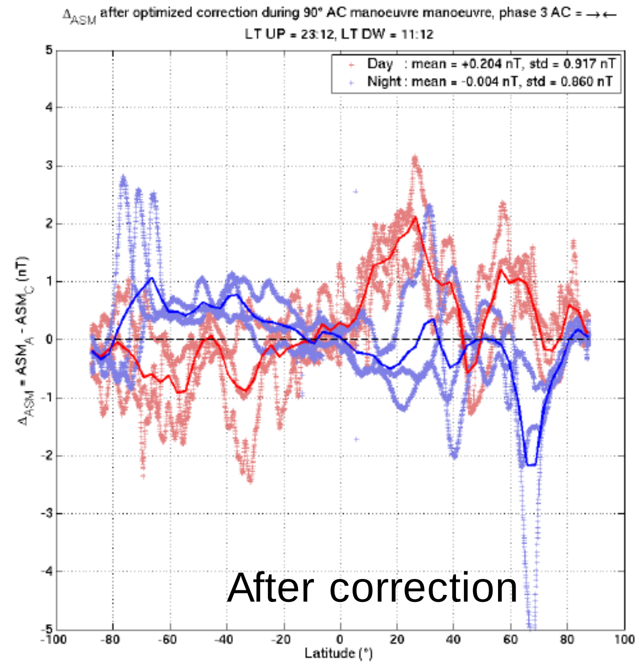
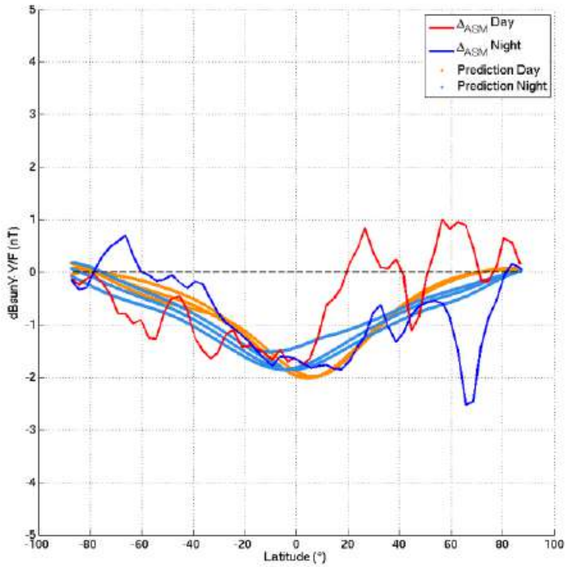
9	↑	↑







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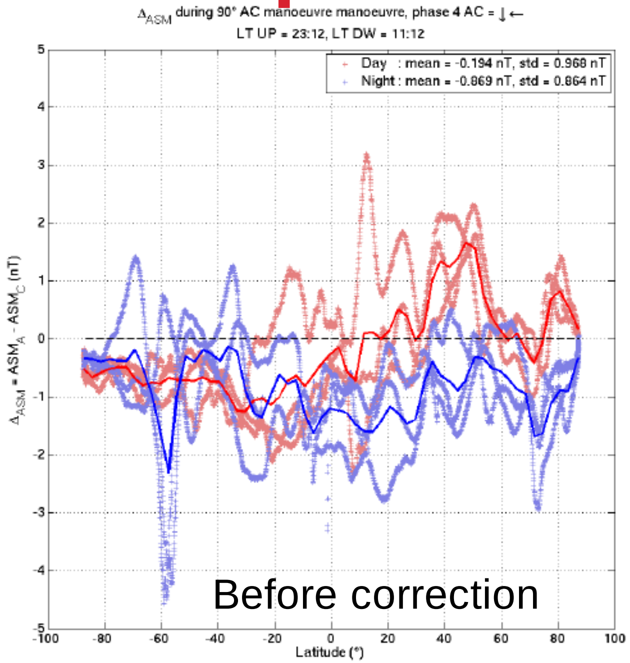

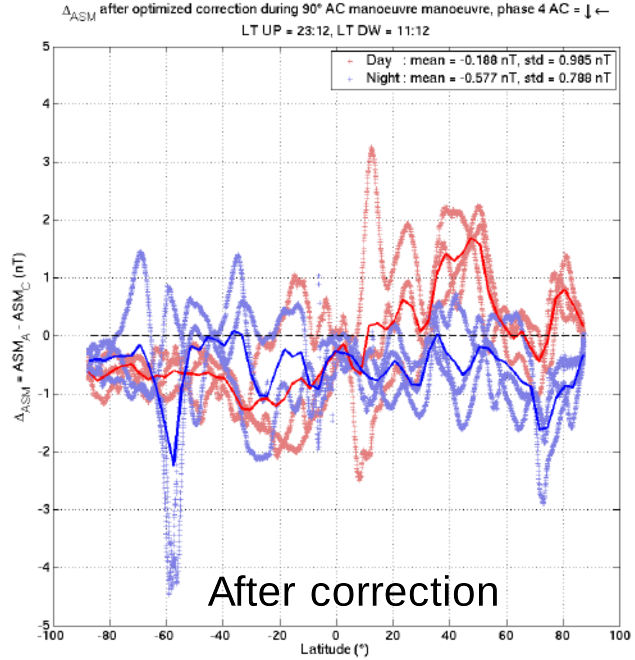

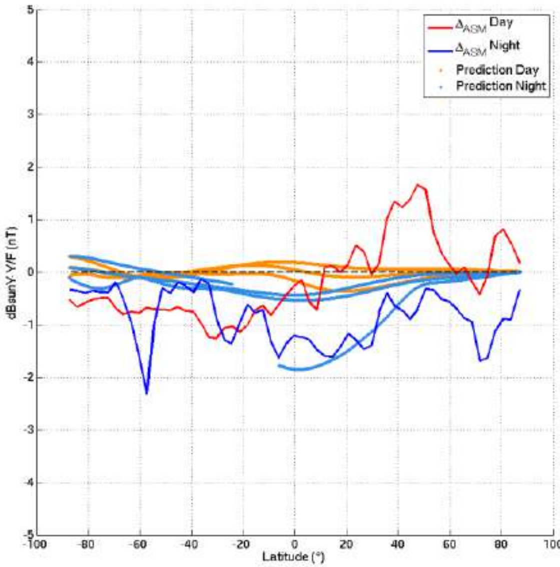

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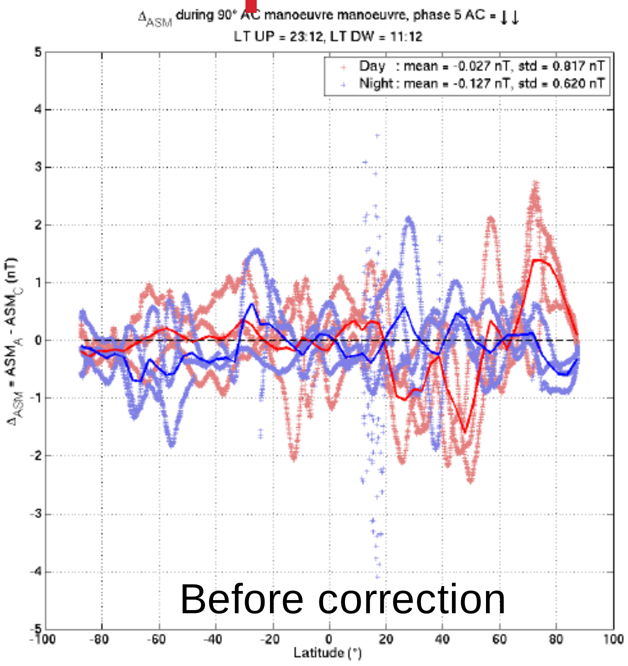

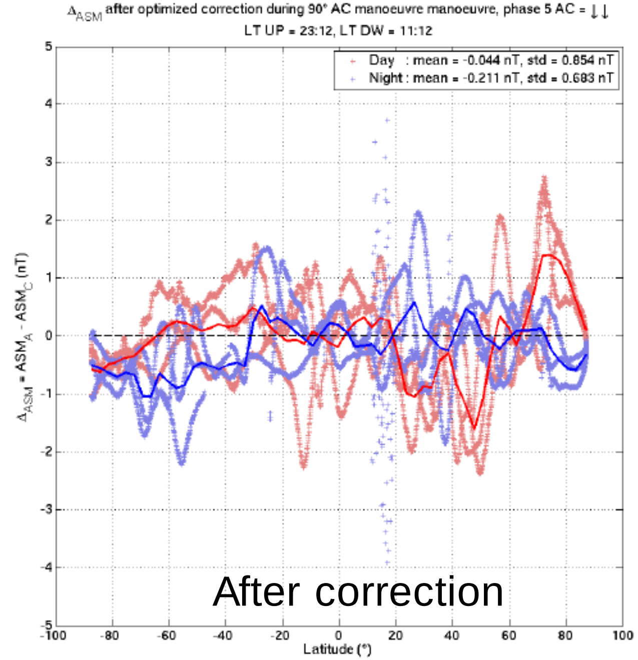

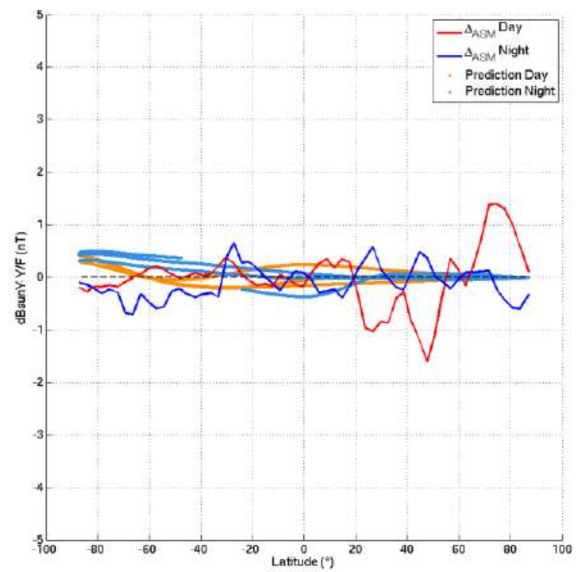

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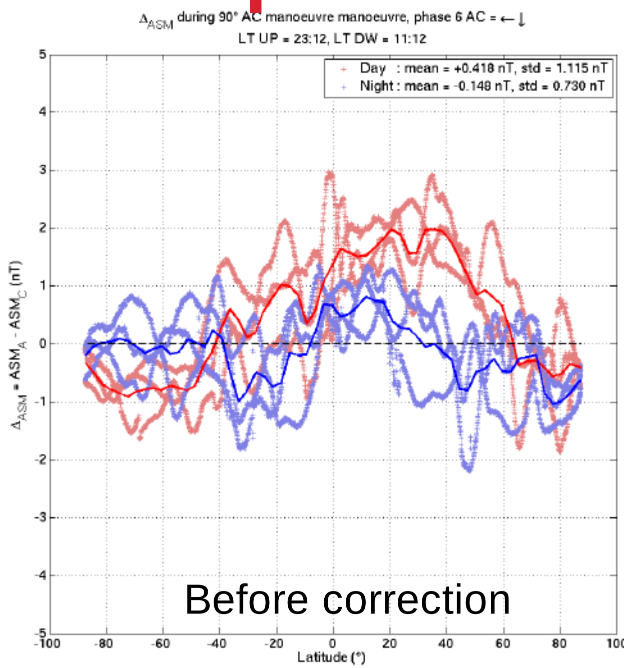

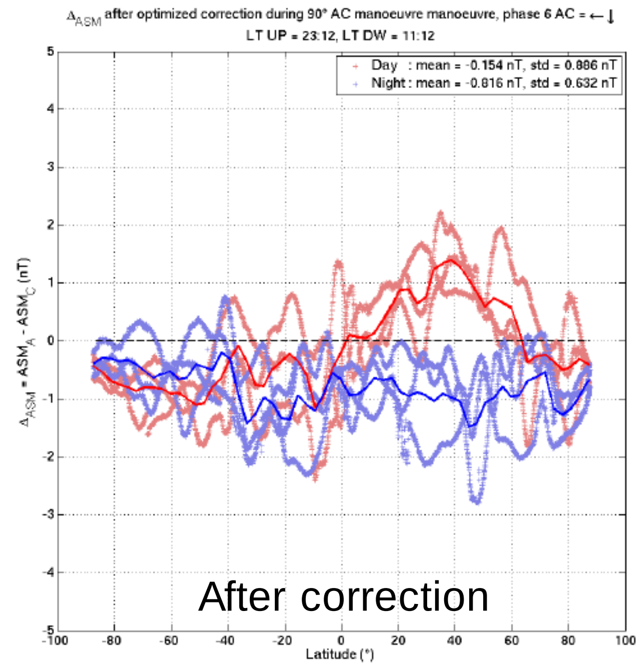

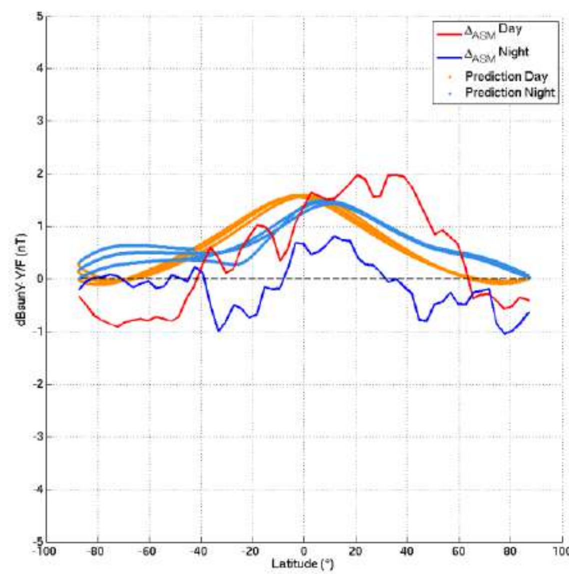

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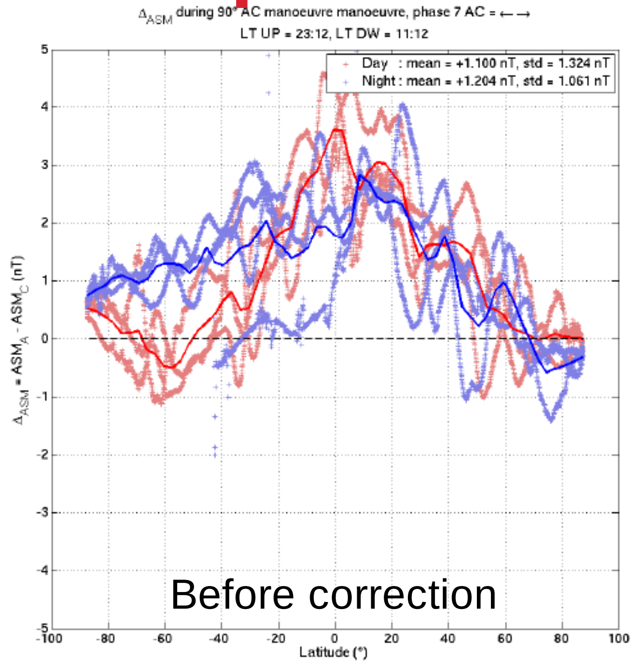

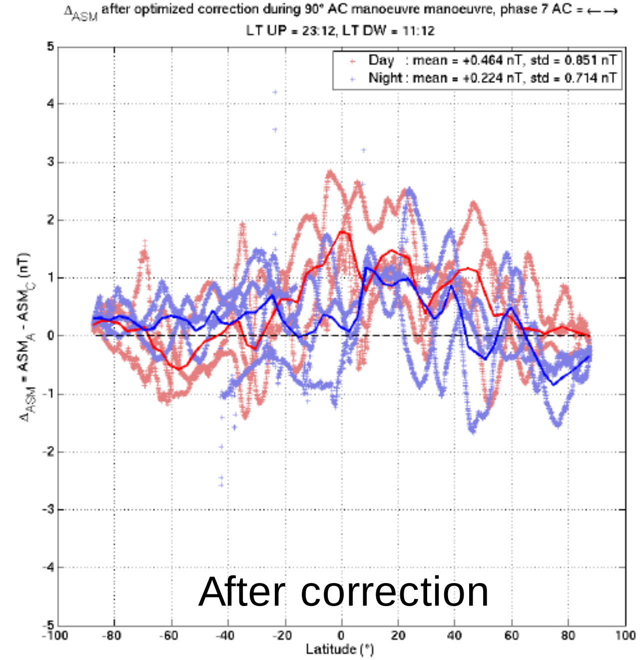

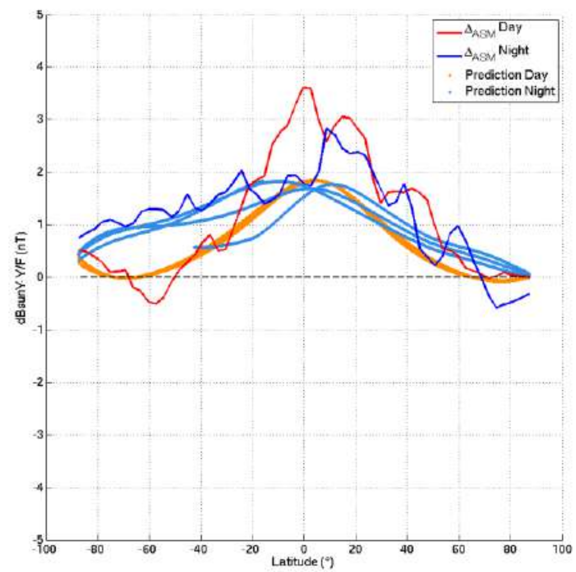

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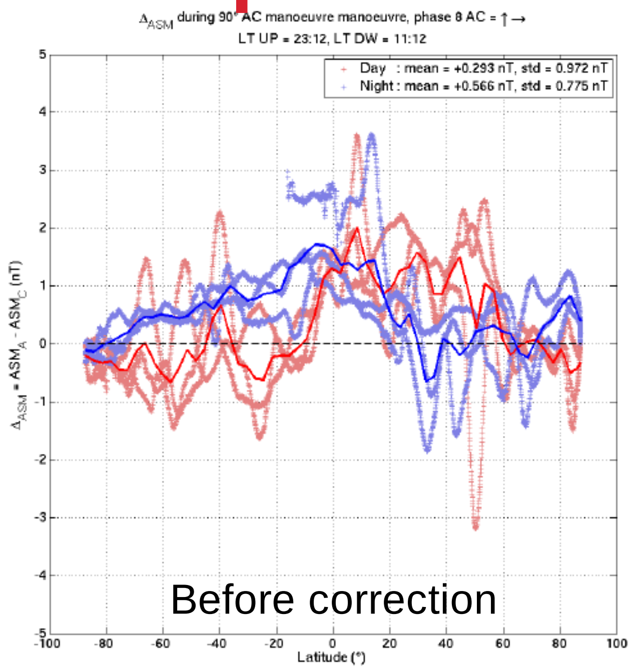

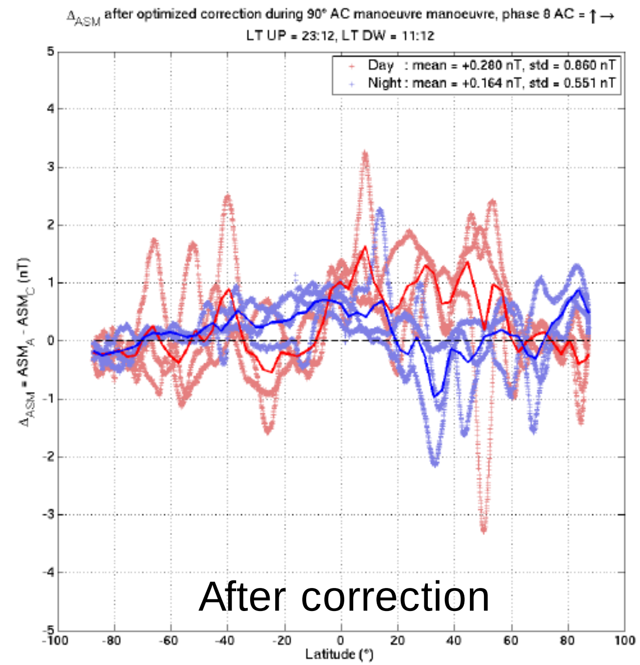

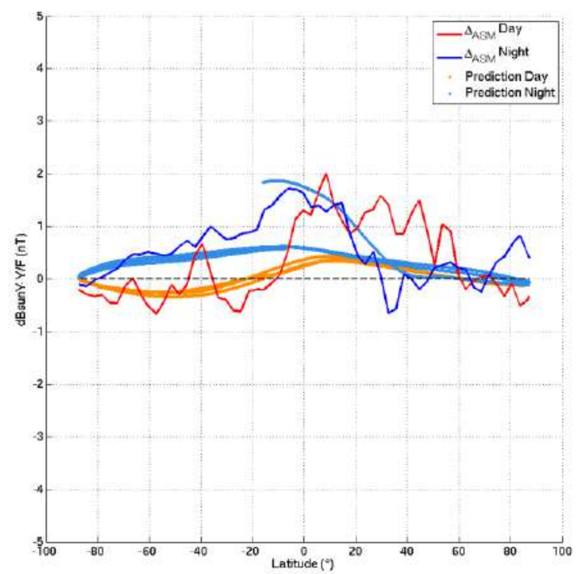

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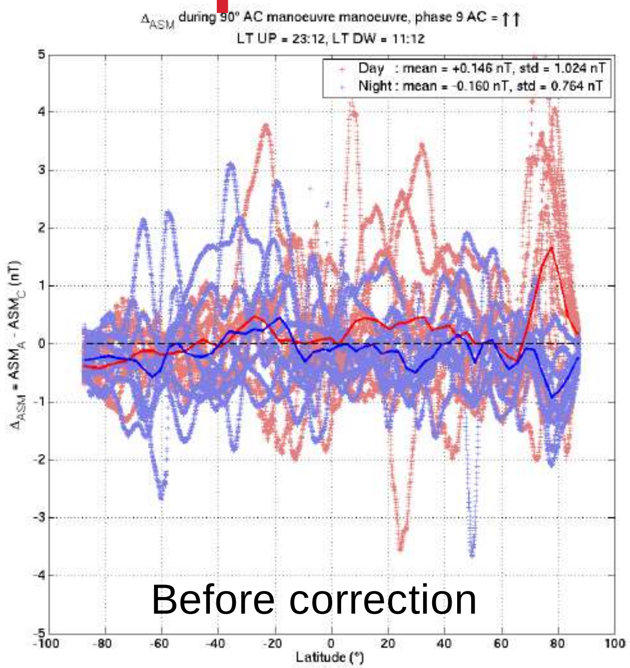
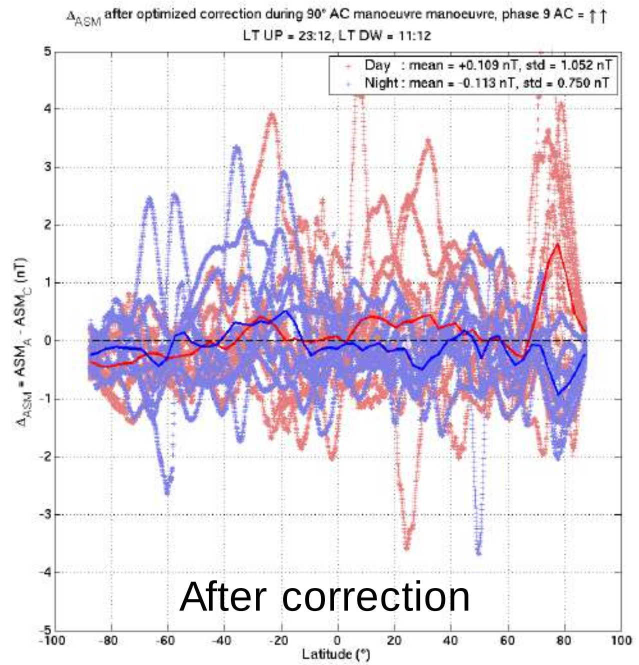
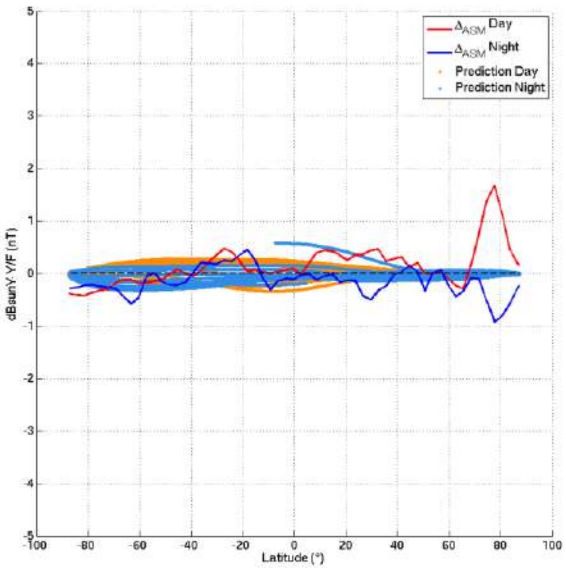


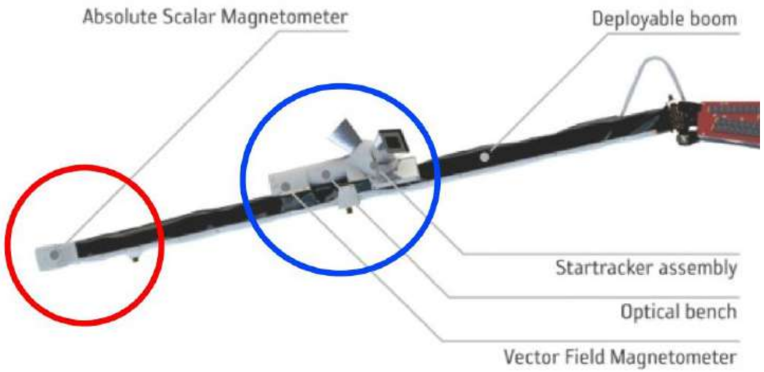


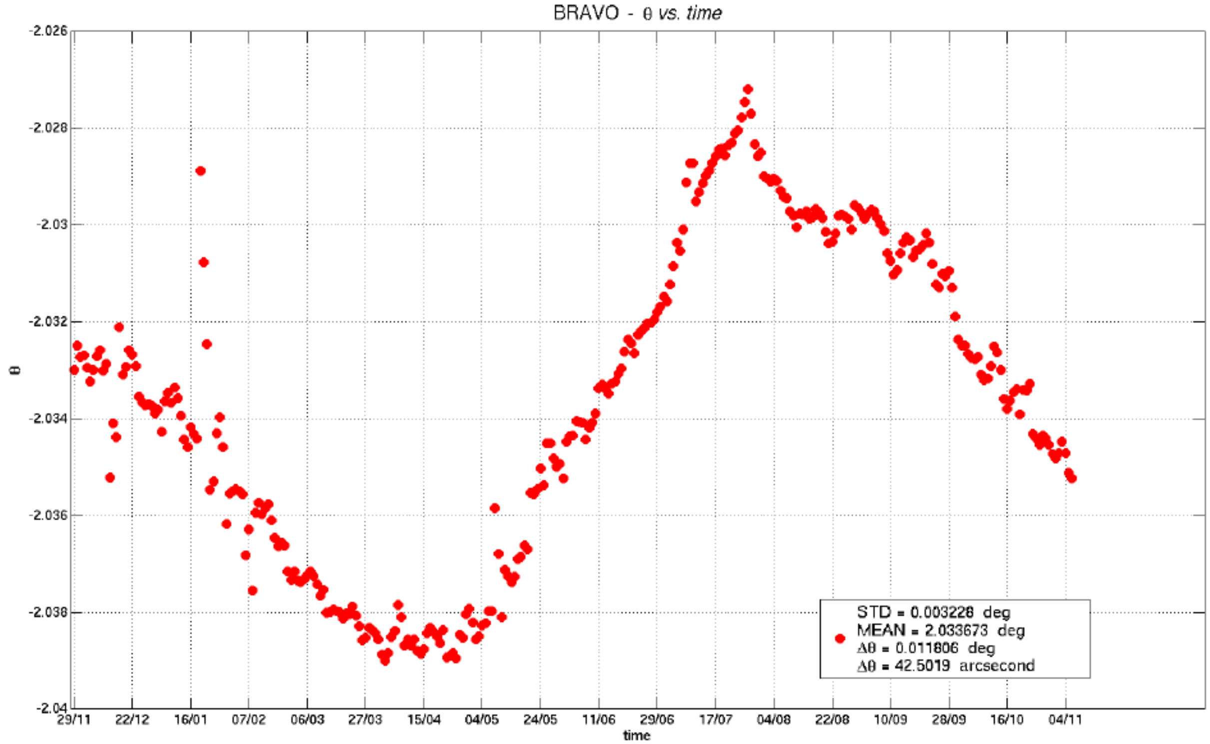


“dBSun” issues are now taken into account

- **A similar “dBSun” issue had also been identified even earlier on the VFM instrument** (Lesur et al., Earth, Planets and Space, 67(1) DOI: 10.1186/s40623-015-0239-6, 2015)
- **This VFM dBSun was first corrected for, by first ignoring the ASM “dBSun” issue** (up to 05XX version of the official ESA Swarm MAGx_LR and MAGx_HR 1B products)
- **Joint efforts by DTU (L. Tøffner-Clausen, P. Brauer) and IPGP have since led to a joint correction of both dBSun effects on the VFM and ASM, leading to a much improved version 06XX** of the official ESA Swarm MAGx_LR and MAGx_HR 1B products
- **Efforts to even further improve this correction data are still ongoing (see Posters by L. Toffner-Clausen and P. Brauer),**

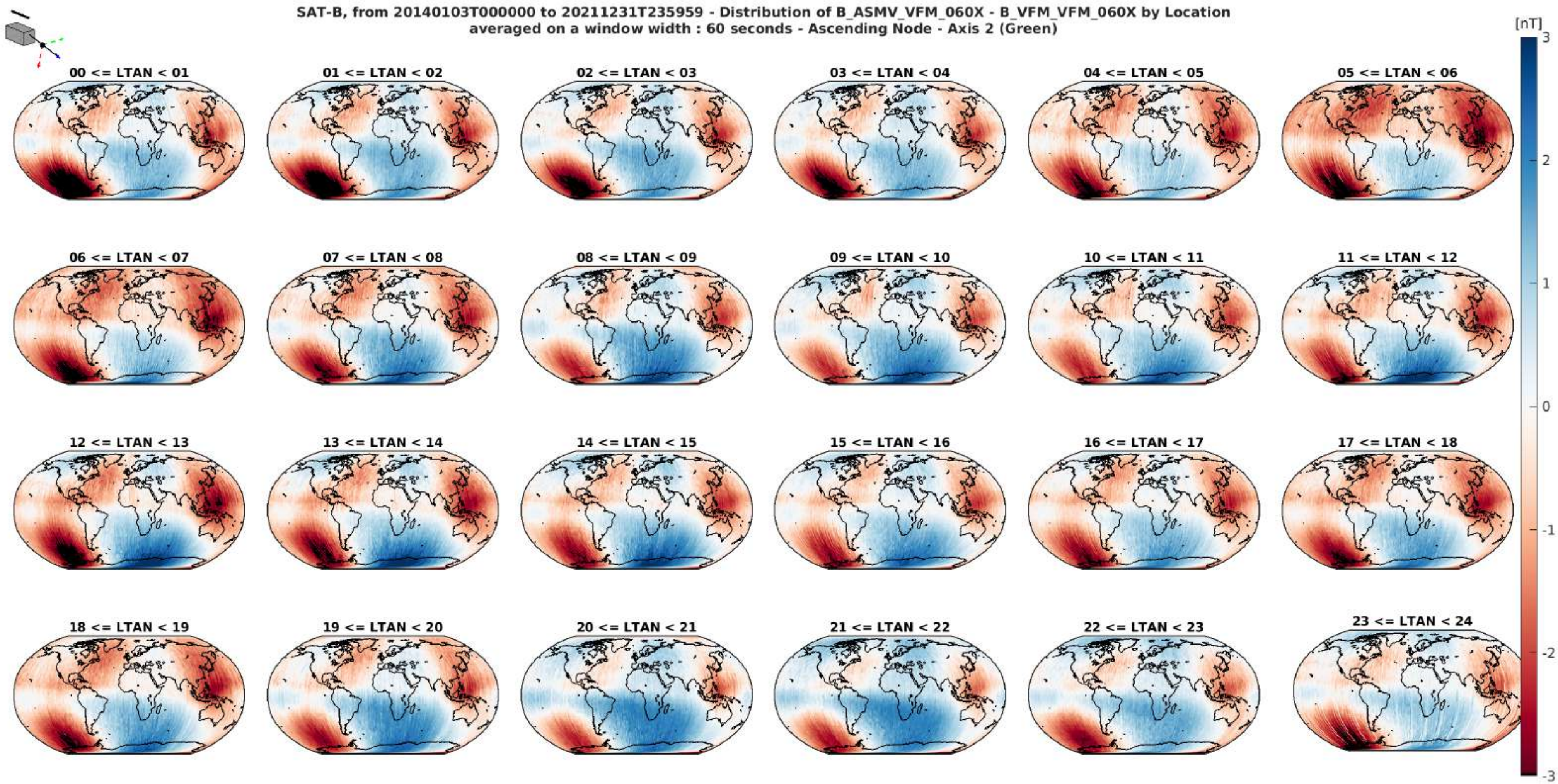
Tests using ASM-V data





- This first showed that **the boom linking the ASM to the optical bench (VFM and STR) is remarkably stable** (great design, thanks !)
- Only small seasonal variations were observed in daily alignments, with amplitude of 40 arcsec, but with **less than 4 arsec deformations within 10 consecutive days**.

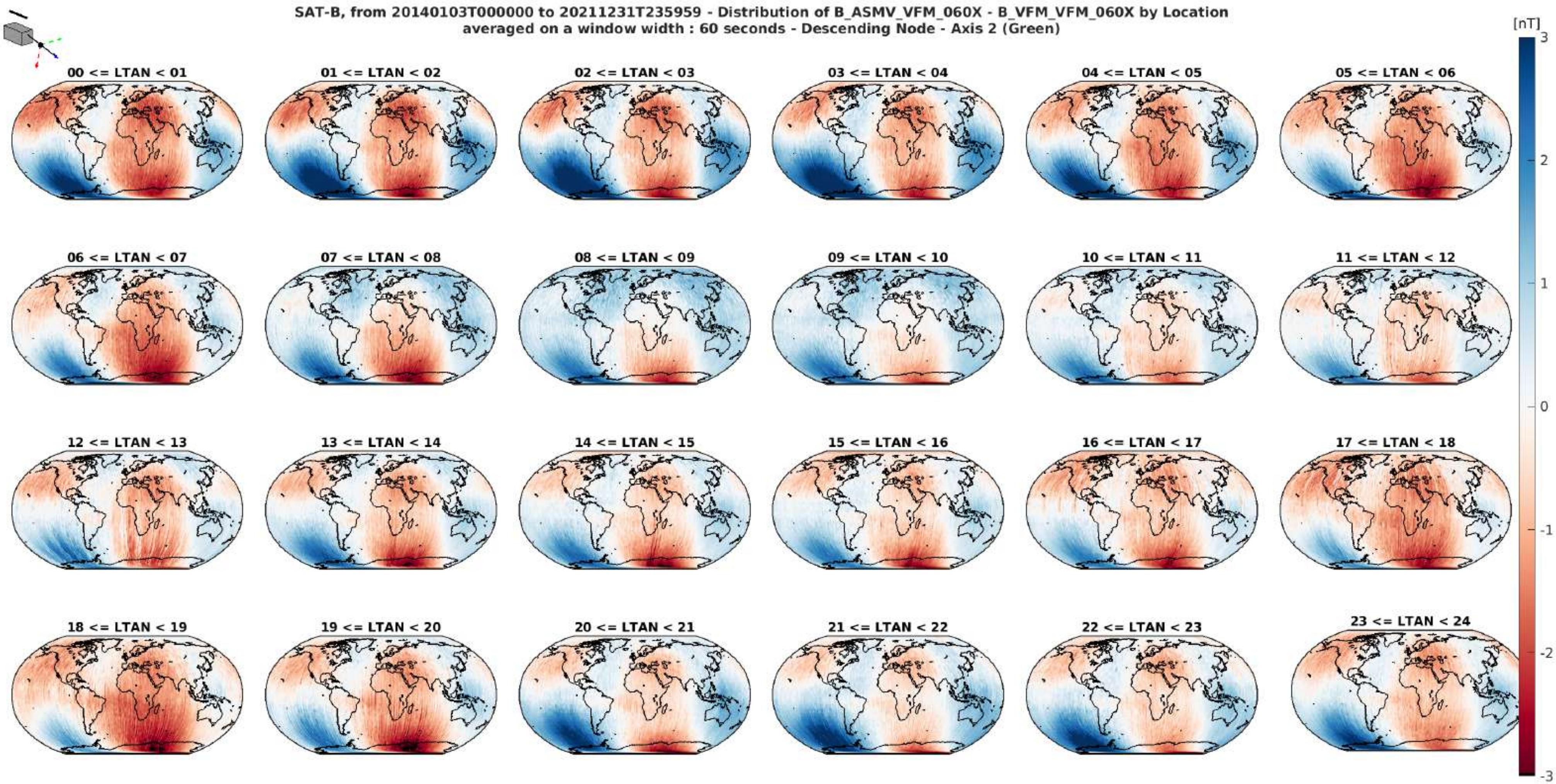
Agreement between B_ASMV and B_VFM, Y component (VFM frame)



- **Differences between Y (East-West) component of B_ASMV and B_VFM versions 06XX are of order +/- 3 nT for Bravo** (here mapped for **ascending orbits**, separated by LTAN). **Very little dependence on LT, and changes sign between ascending and descending orbits.**

- **Similar maps and same conclusion for Alpha (+/- 3 nT)**

Agreement between B_ASMV and B_VFM, Y component (VFM frame)



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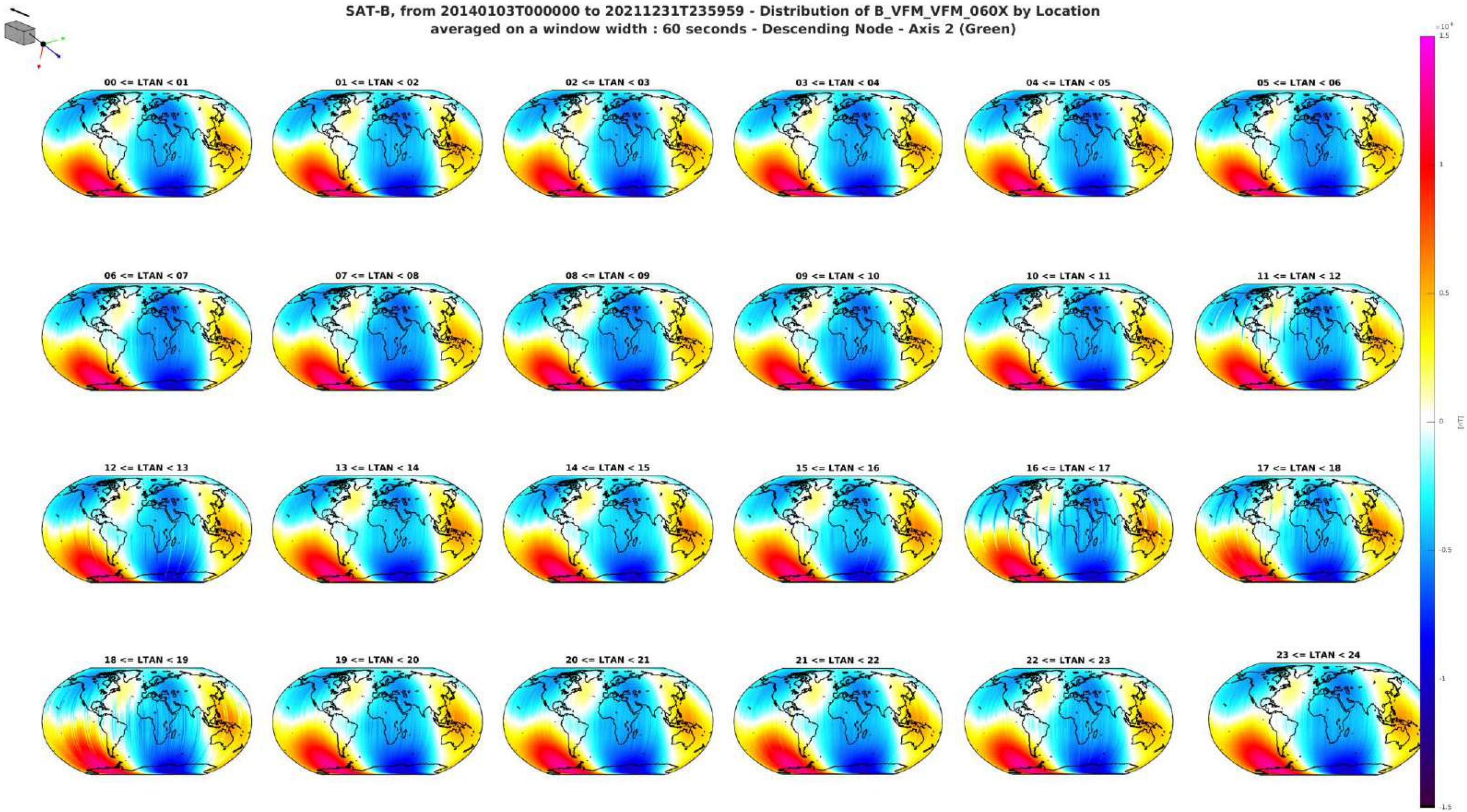
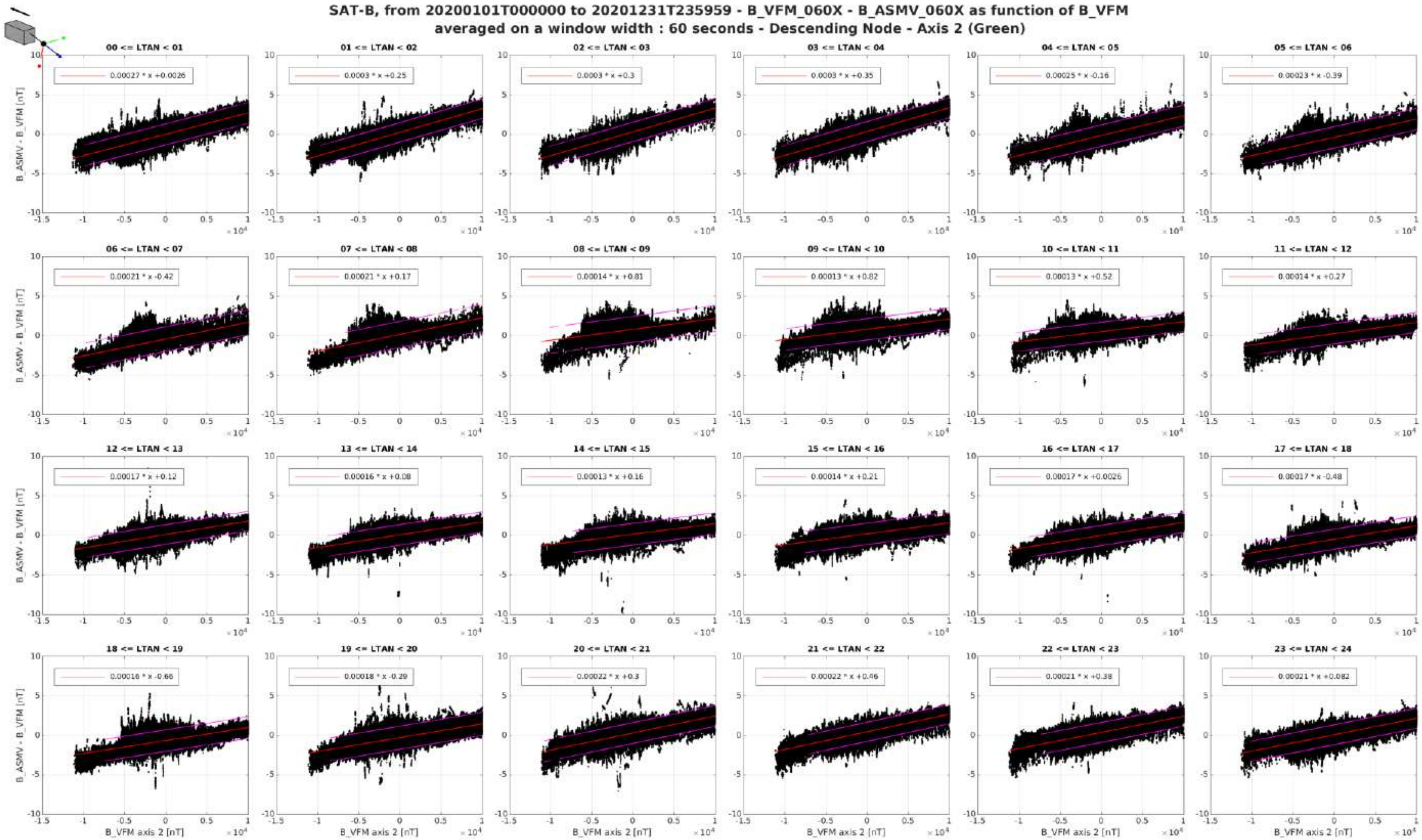
- **Similar maps and same conclusion for Alpha (+/- 3 nT)**

Comparison with Y component of the full signal



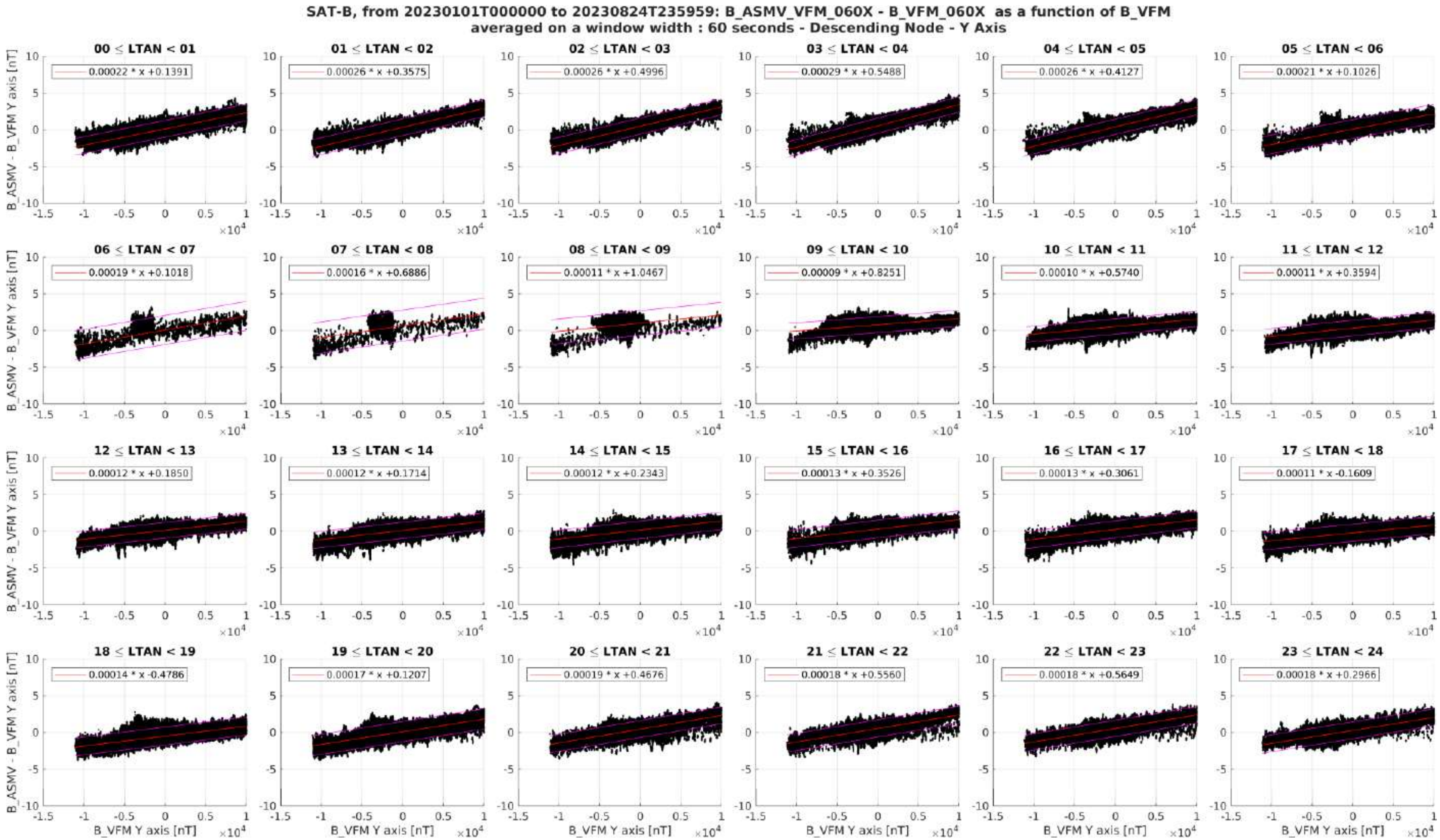
- **Comparison with the full Y signal seen on the VFM (or the ASM) suggests differences in the Y component are mainly proportional to the (common Main Field) signal seen by each instrument**.

Calibration issue on B_ASMV or B_VFM Y components



- **Correlations (here for Bravo, descending node in 2020) with the full Y signal seen on the VFM (or the ASM) suggests a remaining calibration issue on the Y component of either the VFM (too weak) or the ASM (too strong) or both !**
- **This is the least excited axis of the instruments and the most difficult to calibrate.**

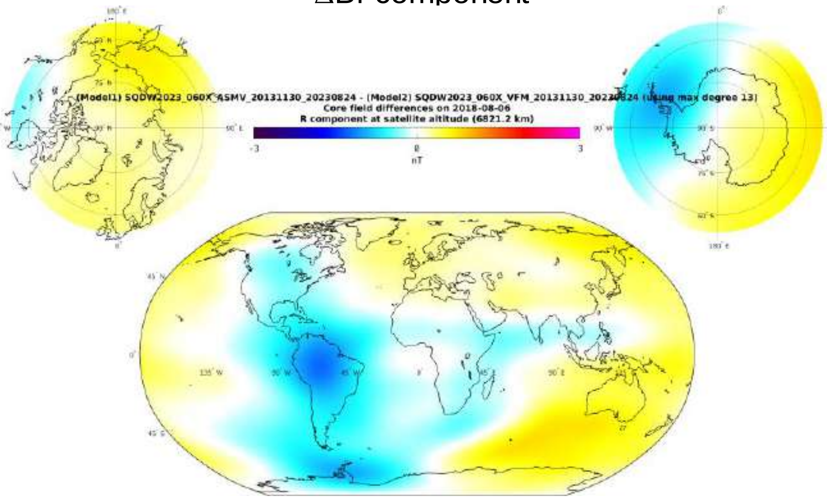
Calibration issue on B_ASMV or B_VFM Y components



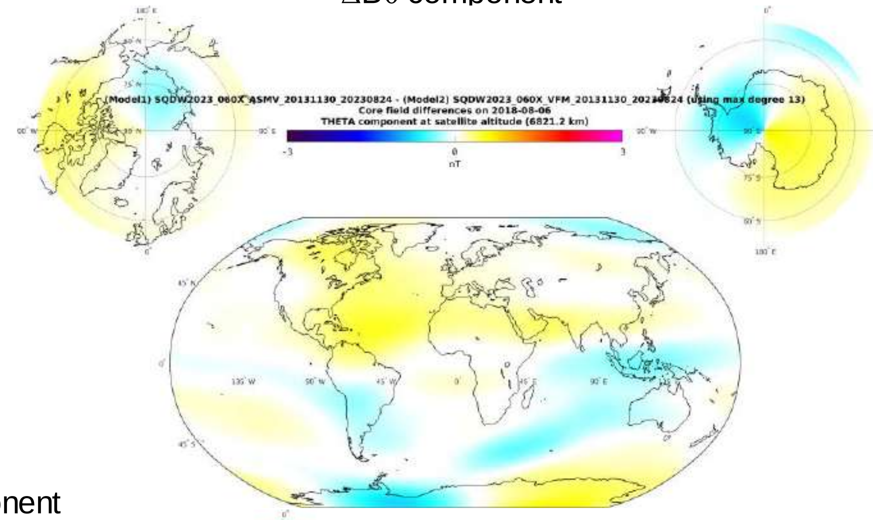
- **Correlations with the full Y signal on the VFM (or the ASM) suggests a remaining calibration issue on the Y component of either the VFM (too weak) or the ASM (too strong) or both !.**
- **Still holds for the latest data (here for Bravo, descending node, January to August 2023)**

Tests using twin (VFM versus ASM_V) field models

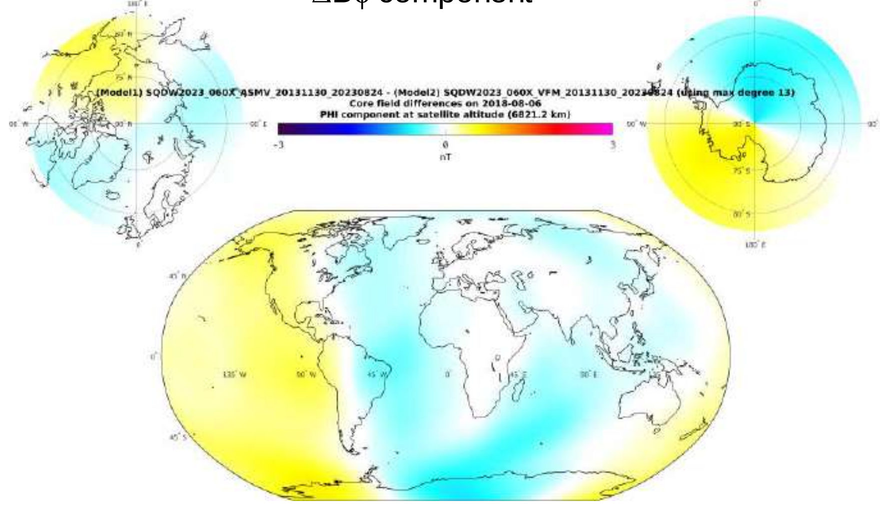
ΔB_r component



ΔB_θ component



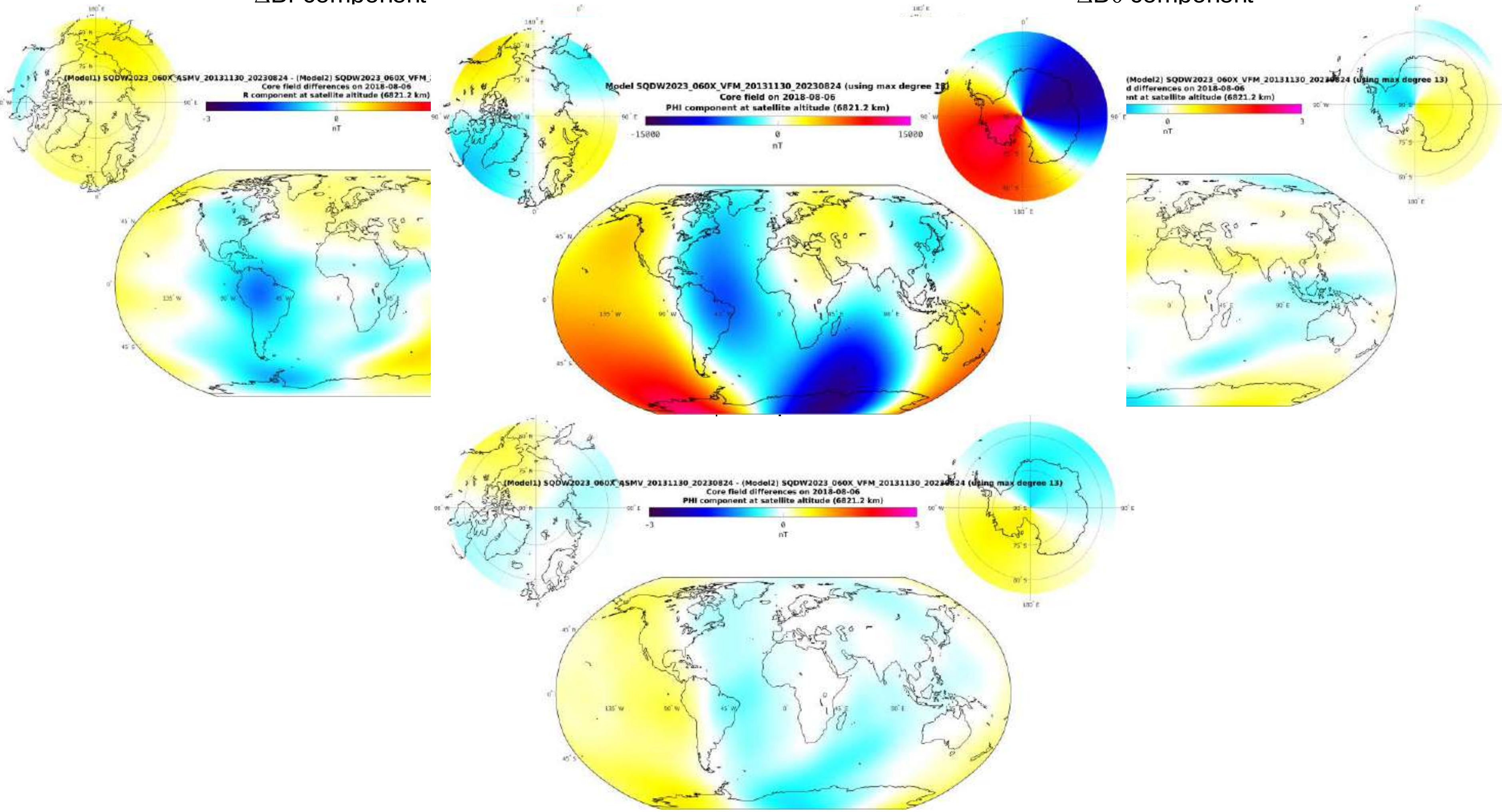
ΔB_ϕ component



- **Comparing twin models built with VFM and ASM_V data using the approach of Vigneron et al., EPS, 2021 show that this calibration issue appears to be the main cause of differences between predictions of such twin field models (here for updated data versions 06XX) at satellite altitude on 06-08-18)**

Tests using twin (VFM versus ASM_V) field models

ΔBr component VFM model Bϕ component ΔBθ component



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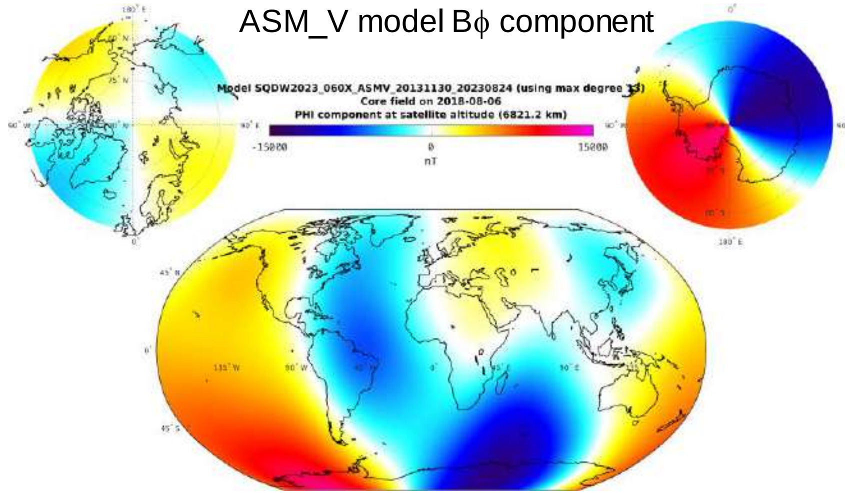
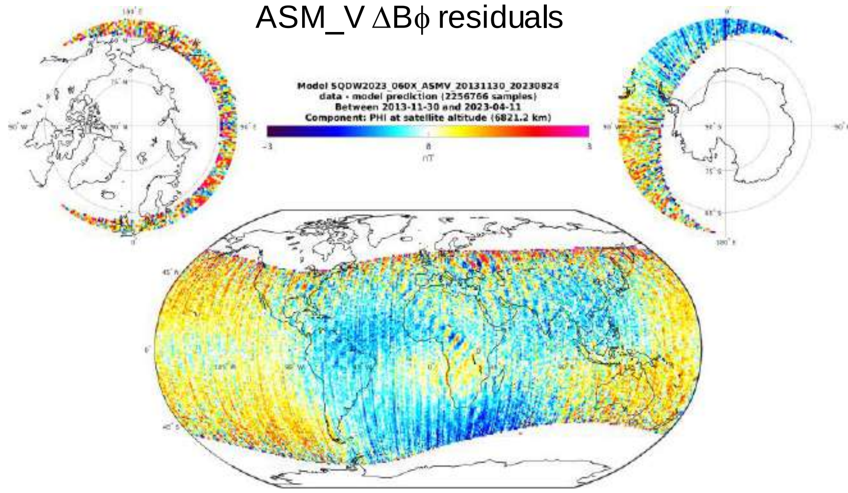
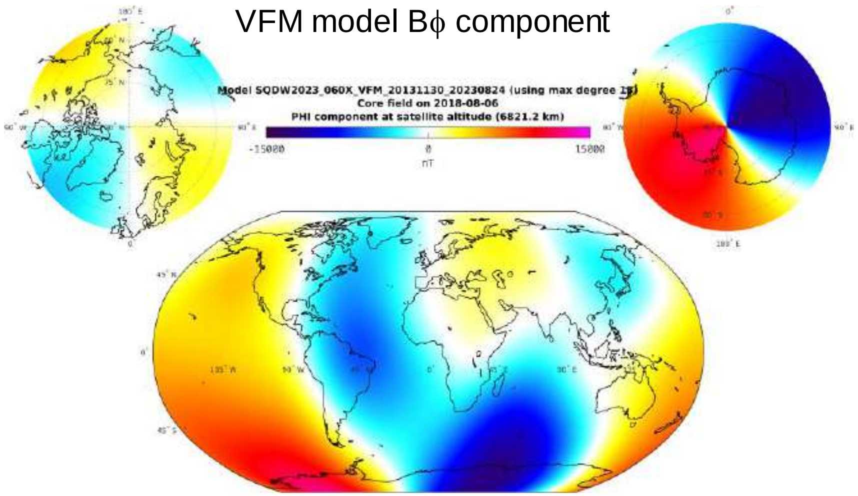
Tests using ASM_V residuals wrt ASM_V model

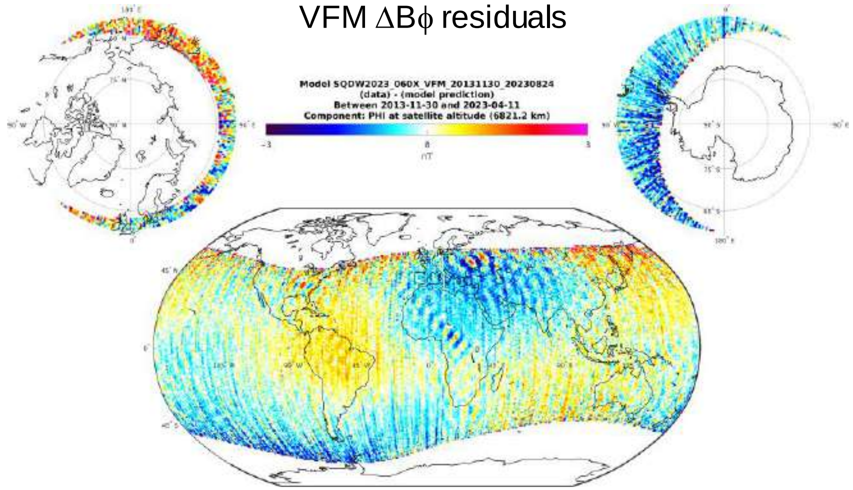




- **Clear field signal remains in the ASM_V Y component residuals, showing that the ASM_V Y component is stronger than ASM_V model prediction for this component (consistent with this component being "too strong")**
- **Confirms calibration issue on the ASM_V Y component**

Tests using VFM residuals wrt VFM model

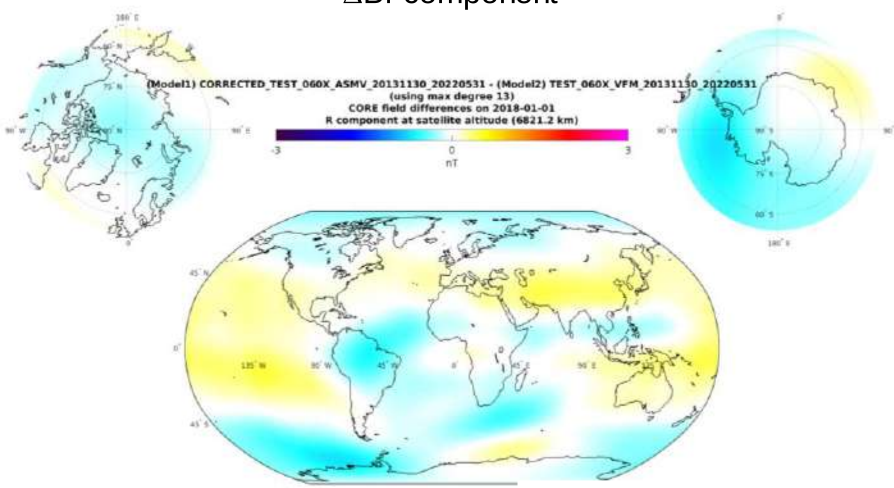




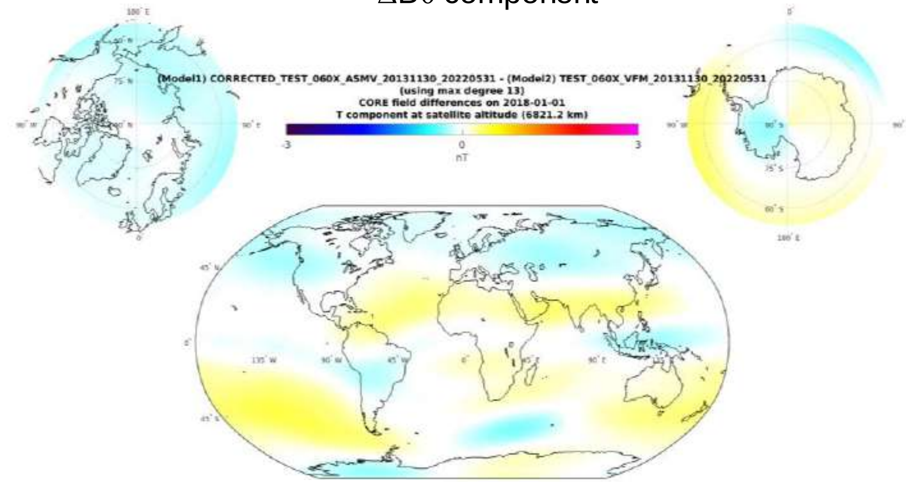
- **Field signal remains in the VFM Y component residuals, showing that the VFM Y component is weaker than VFM model prediction for this component (consistent with this component being “too weak”)**
- **ALSO suggests calibration issue on the VFM Y component !**

Tests using twin (VFM versus *rescaled* ASM_V) field models

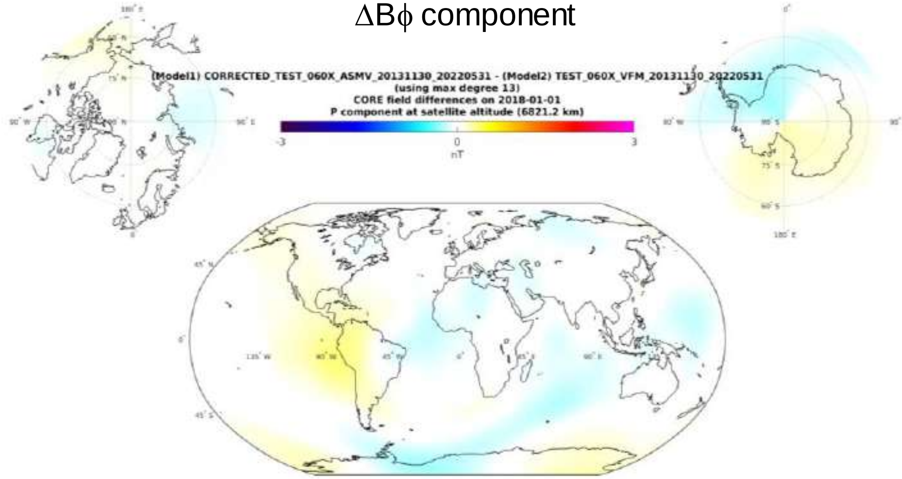
ΔBr component



ΔBθ component

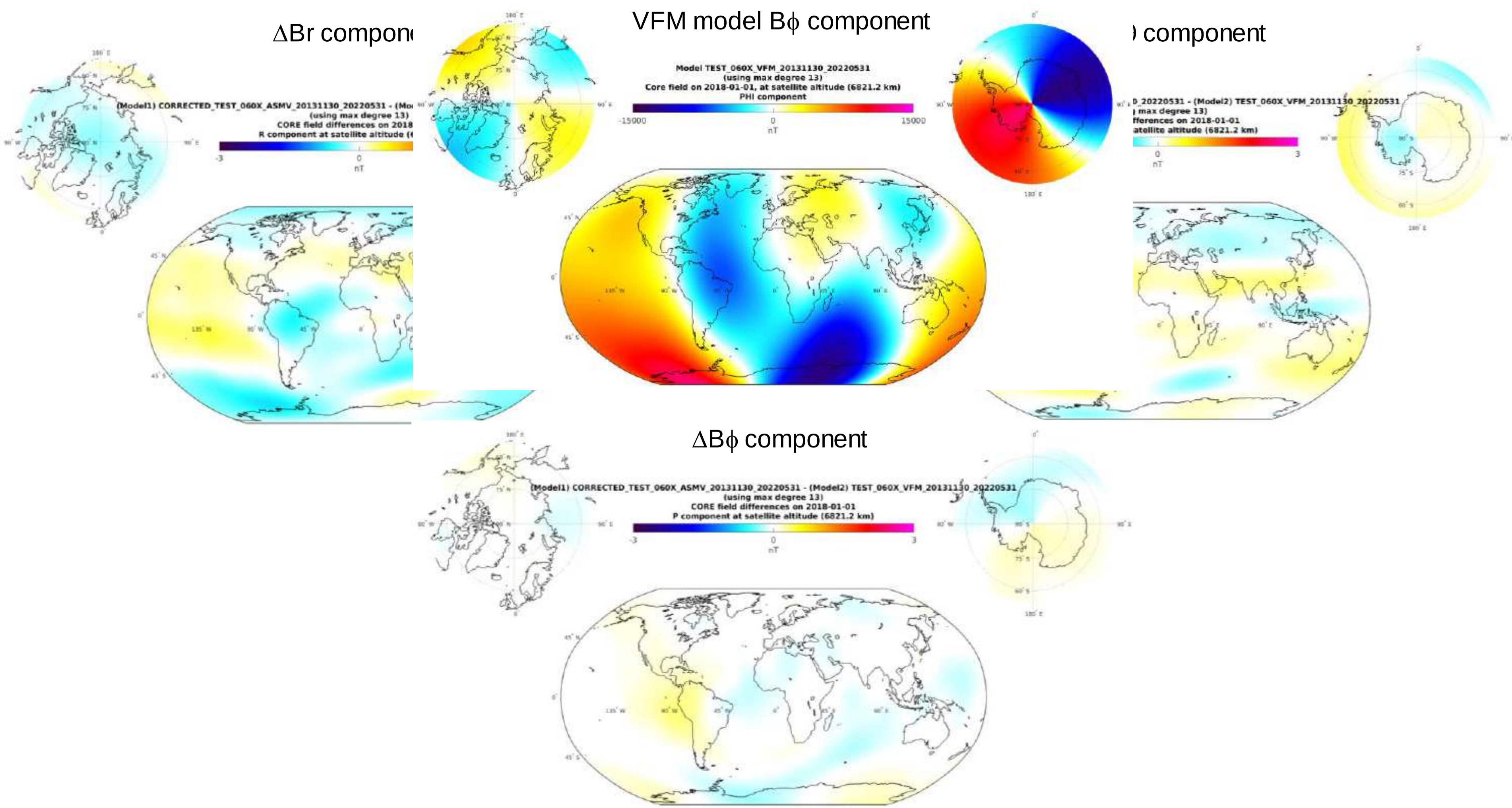


ΔBϕ component



- **ASM_V Y component divided by 1.0002, all rest (including F_ASMV) being untouched**
- **Much better agreement between predictions of twin field models built with VFM and *rescaled* ASM_V data for 06XX data (here at satellite altitude on 01-01-2018)**

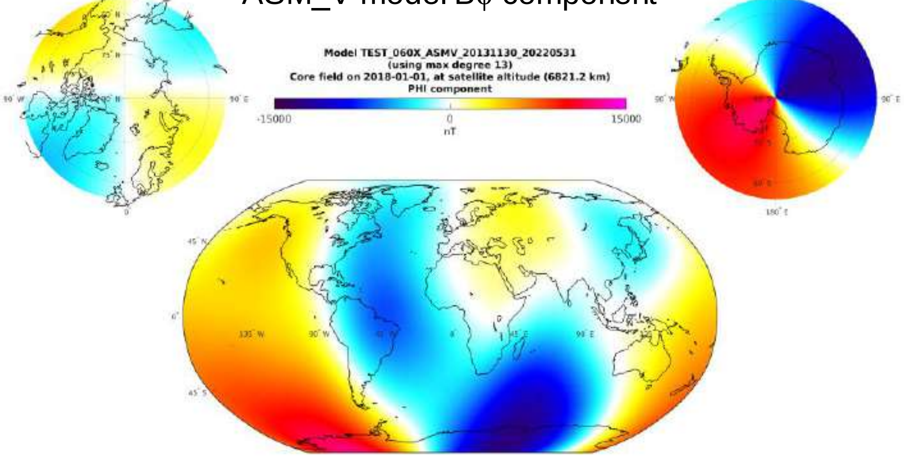
Tests using twin (VFM versus *rescaled* ASM_V) field models



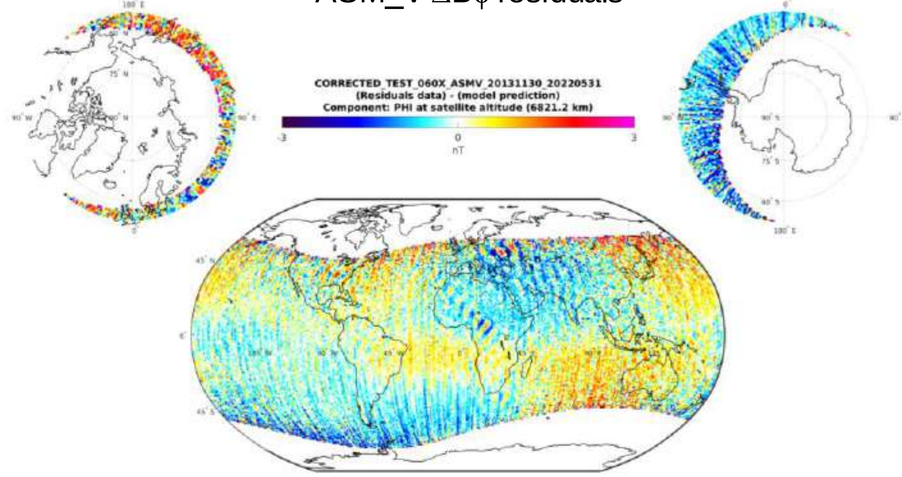
- **ASM_V Y component divided by 1.0002, all rest (including F_ASMV) being untouched**
- **Much better agreement between predictions of twin field models built with VFM and *rescaled* ASM_V data for 06XX data (here at satellite altitude on 01-01-2018)**
- **Signature of the Y component of the field has disappeared**

Tests using ASM_V residuals wrt to corresponding ASM_V field model after *rescaling* of ASM_V Y component

ASM_V model Bϕ component



ASM_V ΔBϕ residuals



- **Clear field signal remains in *rescaled* ASM_V Y component residuals (here for 06XX data, same thing holds for 05XX data), but now showing that the *rescaled* ASM_V Y component is WEAKER than ASM_V model prediction for this component (this component being NOW "TOO WEAK")**
- **Re-scaling of the ASM_V Y component was too strong**
- **Joint rescaling of ASM_V and VFM Y components needed !**

Conclusions from ASM-V and VFM data and model comparisons

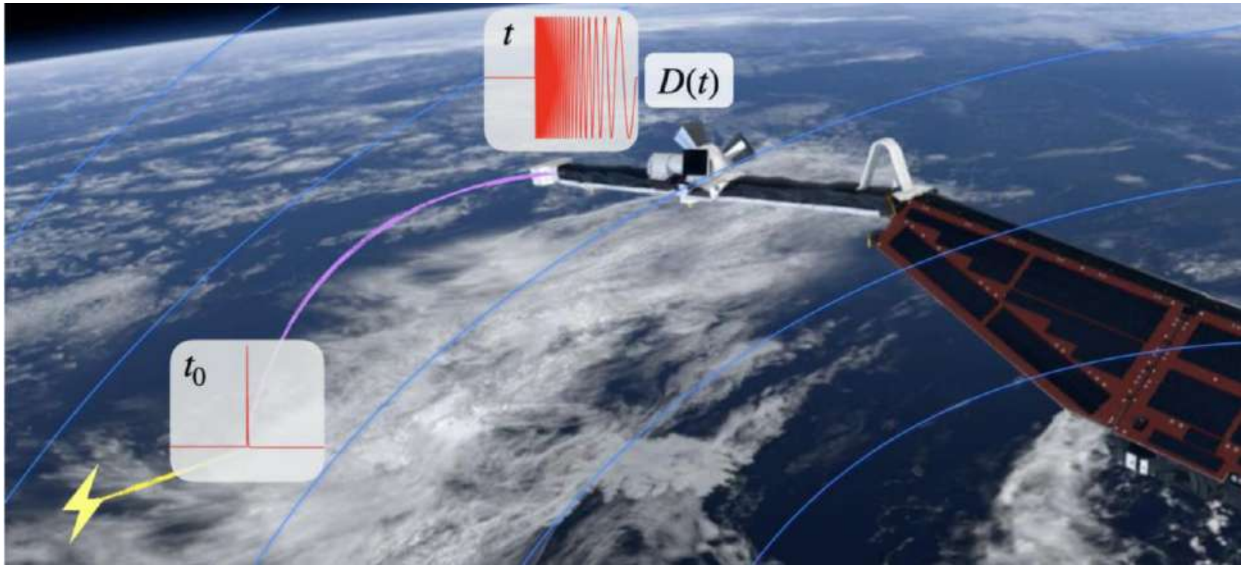
- Twin field modelling shows that **models built using B_VFM and B_ASMV data** mainly **disagree on Bϕ component** (roughly parallel to Y VFM and ASM components) **with the same geographic pattern as the Bϕ field component** -> shows that the **Y calibration issue is the main cause of disagreement between models.**
- **Bϕ** field component **residuals between data and corresponding twin models show the same geographic pattern as the Bϕ field component** -> shows that the **Y calibration issue affects both the B_VFM and B_ASMV data** (but in opposite ways) **for both 05XX and 06XX data versions.**
- **Rescaling the Y component removes most of the large scale twin model disagreement (degrees 1-3)**
- **Improvement in calibration parameters on the Y component of BOTH the VFM and ASM instruments is likely the next step to substantially improve BOTH the B_VFM versus B_ASMV data**
- **Comparison of B_VFM and B_ASMV data, as well as twin model comparisons and residual checks provide means to do this !**
- **Bonus conclusion: ASM-V data are very good, establishing the value of the vector mode principle (to be run on the MAM instruments on board NanoMagSat, see talk this afternoon).**

Swarm ASM Burst mode data

- **Burst mode Initially run briefly during commissioning for testing purposes (end of 2013)**
- **Further tested in 2014**
- **Led to the discovery of the possibility of monitoring ELF whistlers produced by lightning (and other signals, see poster by A. Emsley et al.)**
- **Now run since end of 2019, one week per month on Alpha and Bravo** (usually not at the same time, but occasionally so)
- **Now produced as an official Swarm product (ASMxBUR_1B L1B product)**
- **Also led to the production of an official Swarm Whistler product (WHIxEVT_2 Level 2 product)**
- **Also prompted the decision of running a similar mode on NanoMagSat (using MAM and HFM now up to 2kHz with both scalar and vector data !)**

Swarm WHIxEVT_2 whistler L2 product

- The WHIxEVT_2_ product contains **information about the Extremely Low Frequency (ELF) portion of whistlers** detected during ASM Burst Mode sessions
- These whistlers are detected randomly when the satellites approach regions of active thunderstorms and **can be used to probe the ionosphere (recall talk by M. Jenner et al. yesterday)**



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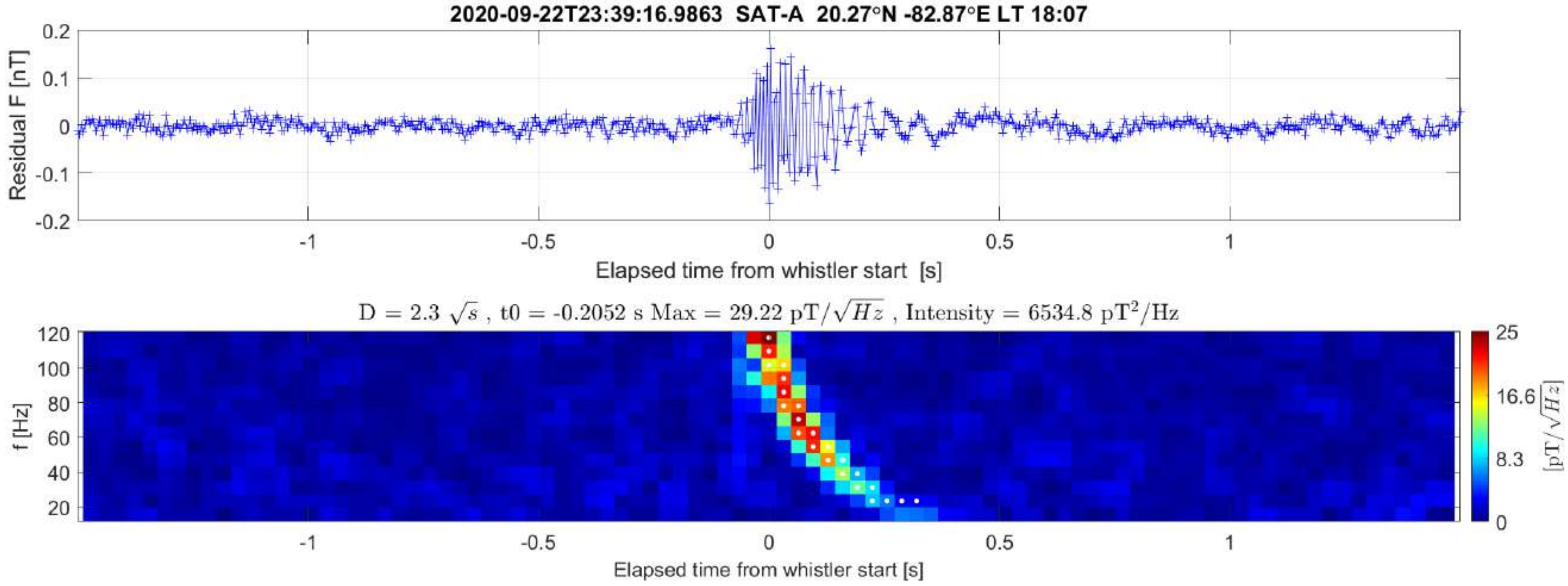
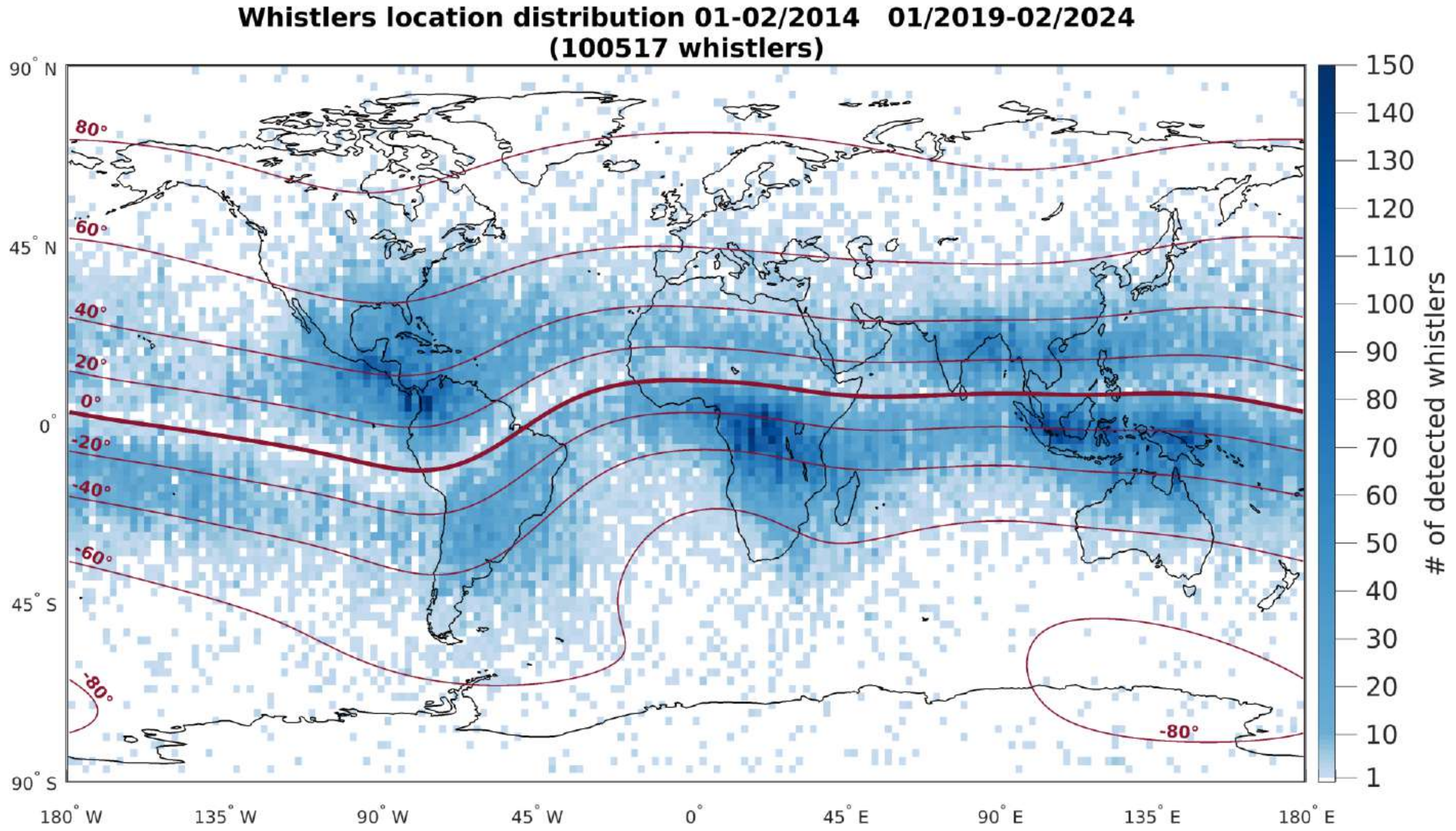


More than 100 000 whistlers detected so far !



Check poster by **Coïsson et al. !**

The CNES-CFI CEA-Leti ASM instrument on board Swarm is a great success !

Many thanks:

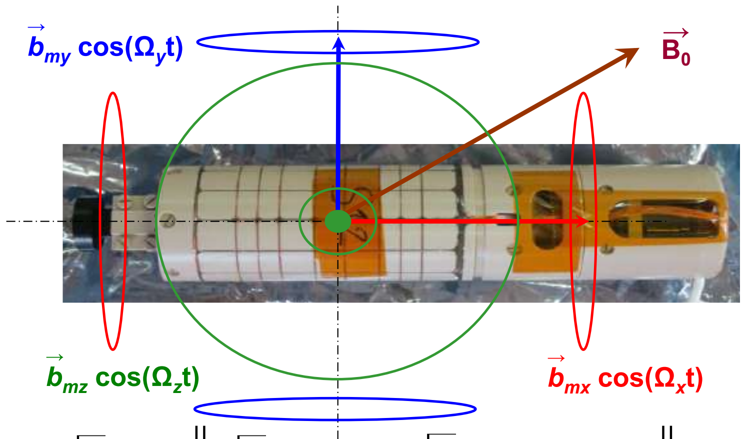
- to CNES for funding the ASM development

- to ESA for allowing this to happen

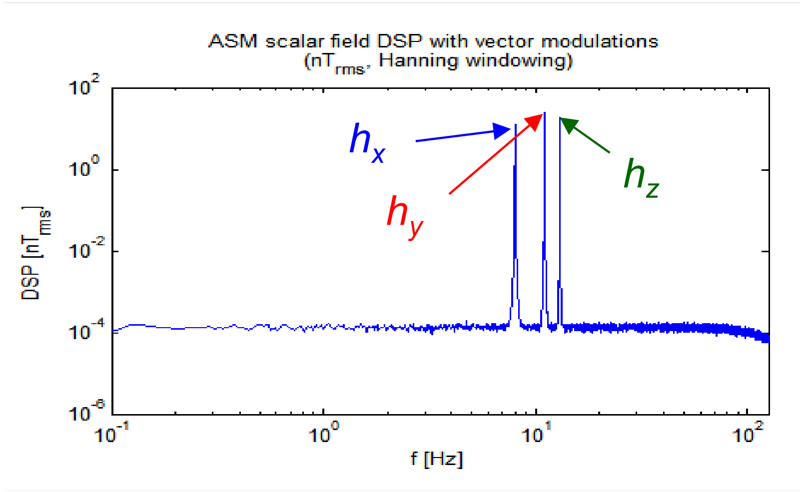
- to the late Eigil Friis-Christensen for initiating the project and inviting me to join him and Hermann Lühr on such a great adventure !

Eigil Friis-Christensen (1944 – 2018)

ASM vector mode principle



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



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**.