Swarm: Recent Progress in Analysis of the Sun Induced Magnetic Disturbance

Lars Tøffner-Clausen[1], Vincent Lesur[2], Peter Brauer[1],
Nils Olsen[1], Enkelejda Qamili[3], and Christopher C. Finlay[1]

[1]DTU Space, Technical University of Denmark; [2]Institut de Physique du Globe de Paris, France; [3]Serco for ESA, ESA/ESRIN, Italy

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Introduction

The ESA *Swarm* mission consisting of the three satellites named *Alpha*, *Bravo*, and *Charlie* was launched in November 2013 with the objective to provide the best ever survey of the geomagnetic field and its temporal evolution. Each spacecraft carries an **A**bsolute **S**calar **M**agnetometer (ASM) for measuring Earth's magnetic field intensity, a **V**ector **F**luxgate **M**agnetometer (VFM) measuring the direction and strength of the magnetic field, and a three-head **S**tar **TR**acker (STR) mounted close to the VFM to obtain the attitude needed to transform the vector readings to an Earth fixed coordinate frame. One of the purposes of the absolute scalar magnetometer is to provide the necessary absolute magnetic data to calibrate the vector magnetometer (VFM). Unfortunately, soon after launch of *Swarm* it became clear that the magnetic field vector measurements on all three spacecraft could not be calibrated using the traditional methods used for previous missions such as Ørsted and CHAMP; unforeseen, highly systematic disturbances contaminated the measurements. Following intense investigations and analysis by a dedicated *Magnetic Measurements Expert Group* a method was devised for successfully characterising a model of the disturbance thereby re-enabling a traditional calibration of the VFM instrument, and subsequently providing fully calibrated and corrected magnetic vector measurements to the *Swarm* user community.

Here we present the latest results and developments of the calibration and characterisation method for the *Swarm* magnetometry package.

Basic Model Parameterisation and Estimation

The general model for the calibration and disturbance-correction of the *Swarm* vector field magnetometer (VFM) measurements, $\vec{B}_{\mathrm{VFM}}$, is:

$$\vec{B}_{\mathrm{VFM}}(t) = \underline{\underline{P}}^{-1}(\mathbf{m})\ \underline{\underline{S}}^{-1}(\mathbf{m}, t, \ldots)\ \vec{B}_{\mathrm{pre-flight}}(t) - \delta\vec{B}_{\mathrm{Sun}}(\mathbf{m}, \alpha, \beta)$$

where

$\vec{B}_{\mathrm{pre-flight}}$ are the VFM measurements calibrated using the pre-flight parameters and corrected for the pre-flight determined spacecraft disturbance fields

$\mathbf{m}$ is the model parameter vector

t is the time instant of the measurement

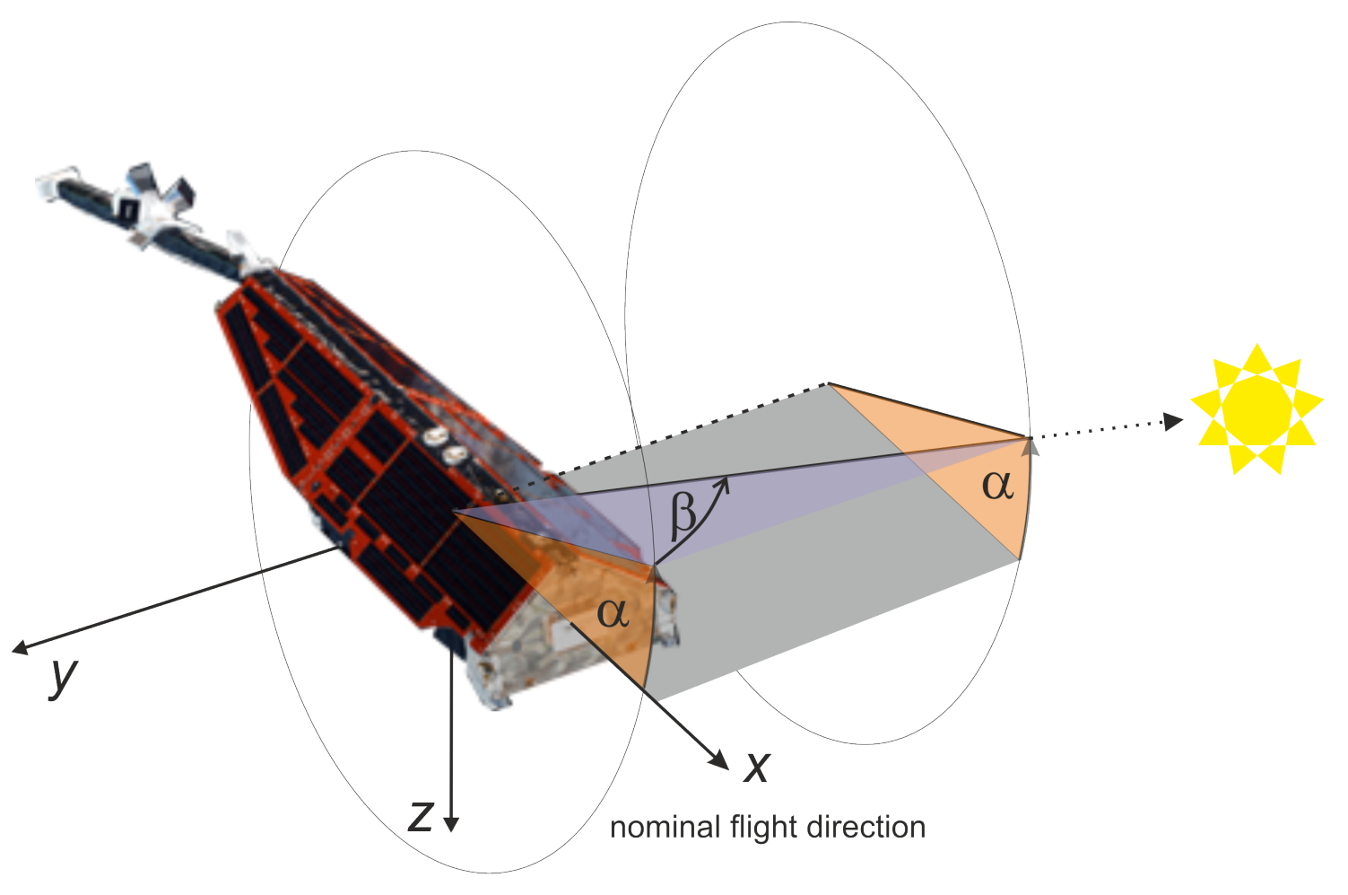
α, β are the Sun incident angles (see below)

$\delta\vec{B}_{\mathrm{Sun}}$ is the Sun induced disturbance vector, see below

$$\underline{\underline{S}} = \begin{pmatrix} s_1(\mathbf{m}, t, \ldots) & 0 & 0 \\ 0 & s_2(\mathbf{m}, t, \ldots) & 0 \\ 0 & 0 & s_3(\mathbf{m}, t, \ldots) \end{pmatrix}$$ is the diagonal scaling matrix

$$\underline{\underline{P}} = \begin{pmatrix} 1 & 0 & 0 \\ -\sin u_1 & \cos u_1 & 0 \\ \sin u_2 & \sin u_3 & \sqrt{1 - \sin^2 u_2 - \sin^2 u_3} \end{pmatrix}$$ is the non-orthogonality correction matrix, $u_i = \mathbf{m}_{k_u(i)}$

The Sun induced magnetic disturbance vector has been found to be well described by three spherical harmonic expansions (of degree 25), one for each field component, parameterised by the Sun incident angles on the spacecraft, denoted α and β, cf. figure to the left. I.e.



$$\delta\vec{B}_{\mathrm{Sun}} = \sum_{n=0}^{25} \sum_{m=0}^{n} \left(\vec{u}_n^m \cos m\alpha + \vec{v}_n^m \sin m\alpha\right) P_n^m(\sin\beta)$$

Note that $\delta\vec{B}_{\mathrm{Sun}}$ is not directly dependent on time (however indirectly through the Sun incident angles, α and β).
The scaling matrix, $\underline{\underline{S}}$, is currently the main focus point. The elements $s_j(\mathbf{m}, t, \ldots)$ describe the temporal evolution of the VFM instrument sensitivity and includes both thermal as well as pure temporal effects (e.g. aging). The various parameterisations of $s_j(\mathbf{m}, t, \ldots)$ are described later.

The model parameter vector, $\mathbf{m}$, is estimated using a *scalar calibration* minimizing the scalar residuals, $\Delta F = \left|\vec{B}_{\mathrm{VFM}}\right| - F_{\mathrm{ASM}}$, using an Iteratively Reweighted Least Squared (IRLS) approach.

Huber weights are used to reduce the effect of outliers. Since $\delta\vec{B}_{\mathrm{Sun}}$ is over-parameterised the actual inversions are performed using truncated singular value decompositions with 700-800 degrees of freedom (out of the $2,000+$ elements of $\mathbf{m}$).

Present, Implemented Model

The current model, which is the basis for the *Swarm* magnetic Level 1b products baseline 04, uses the following s_j:

$$s_j(\mathbf{m}, t, T_{\mathrm{sensor}}, \beta) = s^{\mathrm{B-spline}}(\mathbf{m}, t) + \delta s_{j,\mathrm{Tsensor}} T_{\mathrm{sensor}} + s_{j,\beta}\beta$$

where

$s^{\mathrm{B-spline}}$ is a quadratic B-spline in time with 3-month knot separation (common for all three components of the magnetic field)

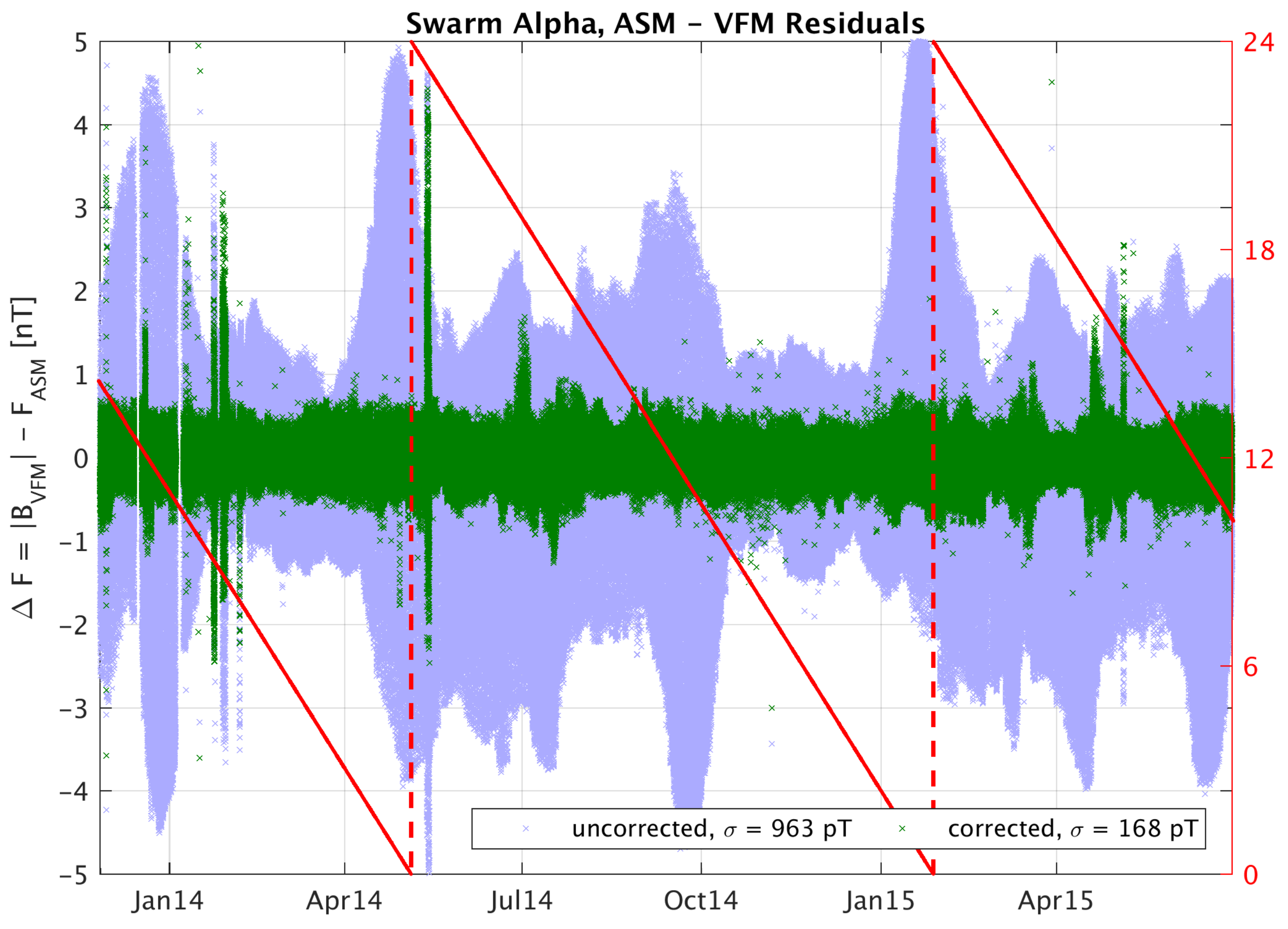
$\delta s_{j,\mathrm{Tsensor}} = \mathbf{m}_{k_T(j)}$ is an adjustment of the pre-flight estimated dependency of the VFM sensitivity on its sensor temperature

T_{sensor} is the actual VFM sensor temperature

$s_{j,\beta} = \mathbf{m}_{k_\beta(j)}$ is an empirical β-scaling parameter

β is the Sun incident angle (as above)

Applying this model to the first 19 months of data from *Swarm Alpha* reduces the scalar residuals between the VFM and ASM instruments as seen in the figure to the left: The light blue markers are the uncorrected residuals whereas the green markes show the residuals after applying the model. The weighted rms of the scalar residuals reduces from 963 pT to 168 pT.



New Model

The temporal characteristics of the current model, i.e. the parabolic B-spline function, is somewhat heuristic and do not reflect the physical properties of the VFM sensor and hence not the expected evolution of the VFM instrument sensitivity. Rather, an exponential saturation of the sensitivity is expected, therefore the new model of s_j has the following form:

$$s_j(\mathbf{m}, t, T_{\mathrm{sensor}}, T_{\mathrm{elec}}, \beta) = s_{\mathrm{exp}} e^{-\frac{t-t_0}{\tau}} + \delta s_{j,\mathrm{Tsensor}} T_{\mathrm{sensor}} + s_{j,\mathrm{other}}(\mathbf{m}, T_{\mathrm{elec}}, \beta)$$

where

$s_{\mathrm{exp}} = \mathbf{m}_{k_e(j)}$ is the exponential decay factor

t_0 is some intial time

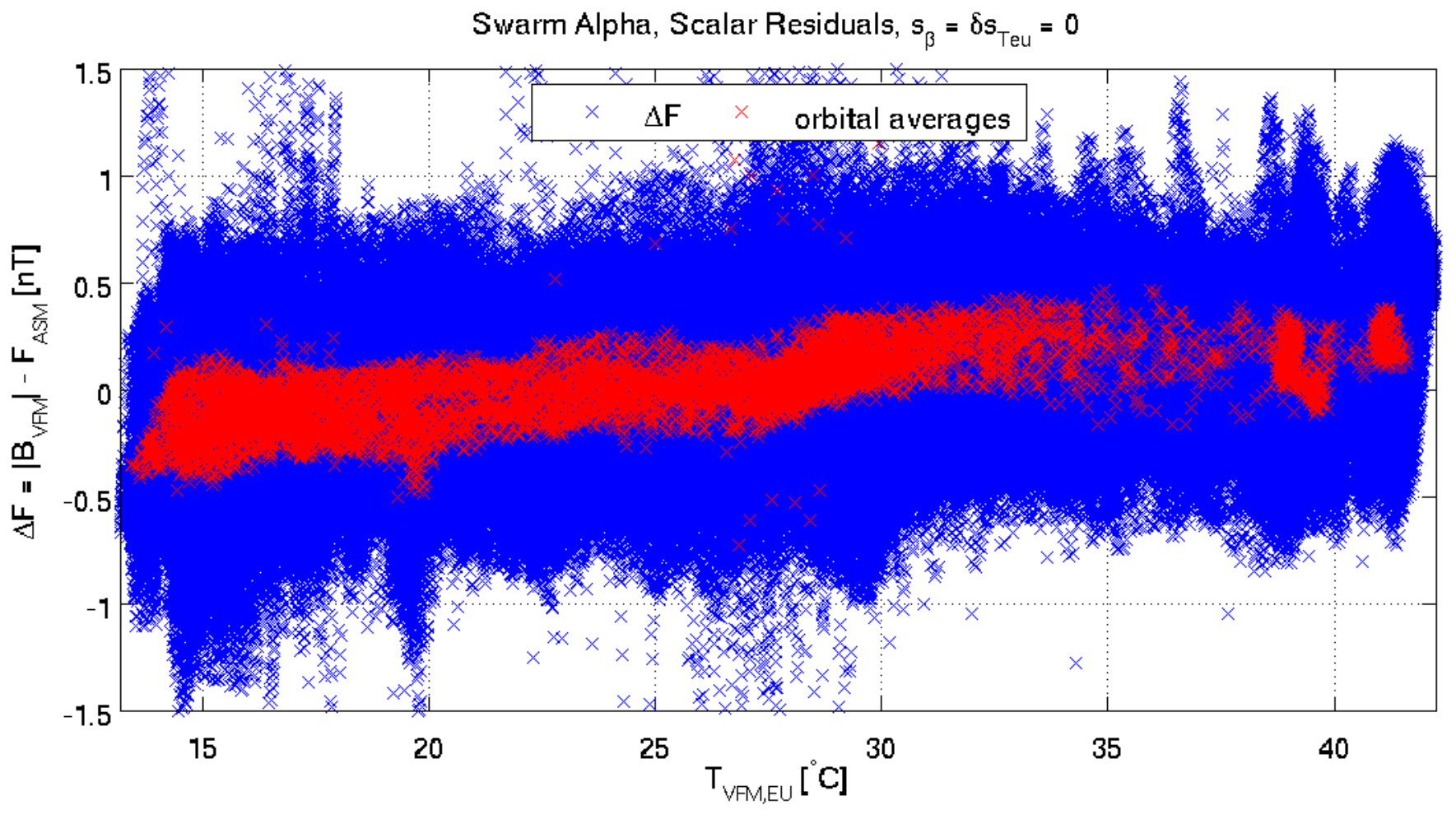
$\tau = \mathbf{m}_{k_\tau(j)}$ is the exponential time constant

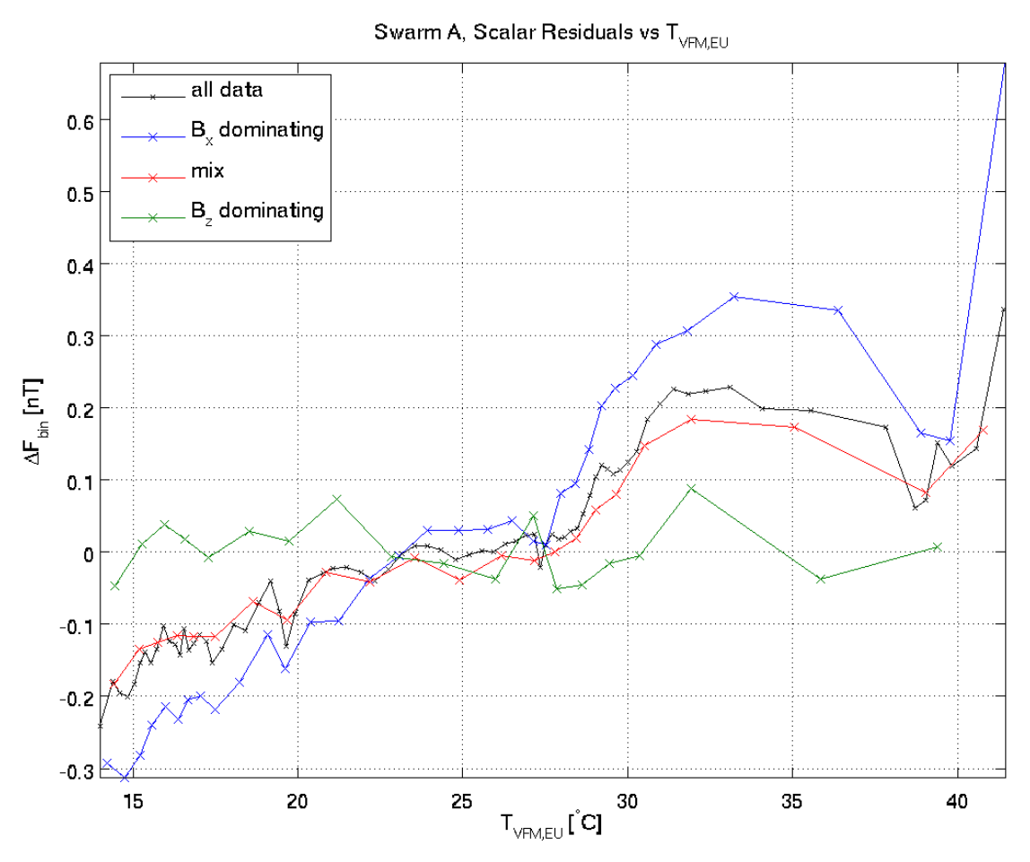
$s_{j,\mathrm{other}}$ is some residual part of the sensitivity wihch is still under investigation (see below)

T_{elec} is the actual VFM electronic unit temperature (unit located inside the spacecraft body)

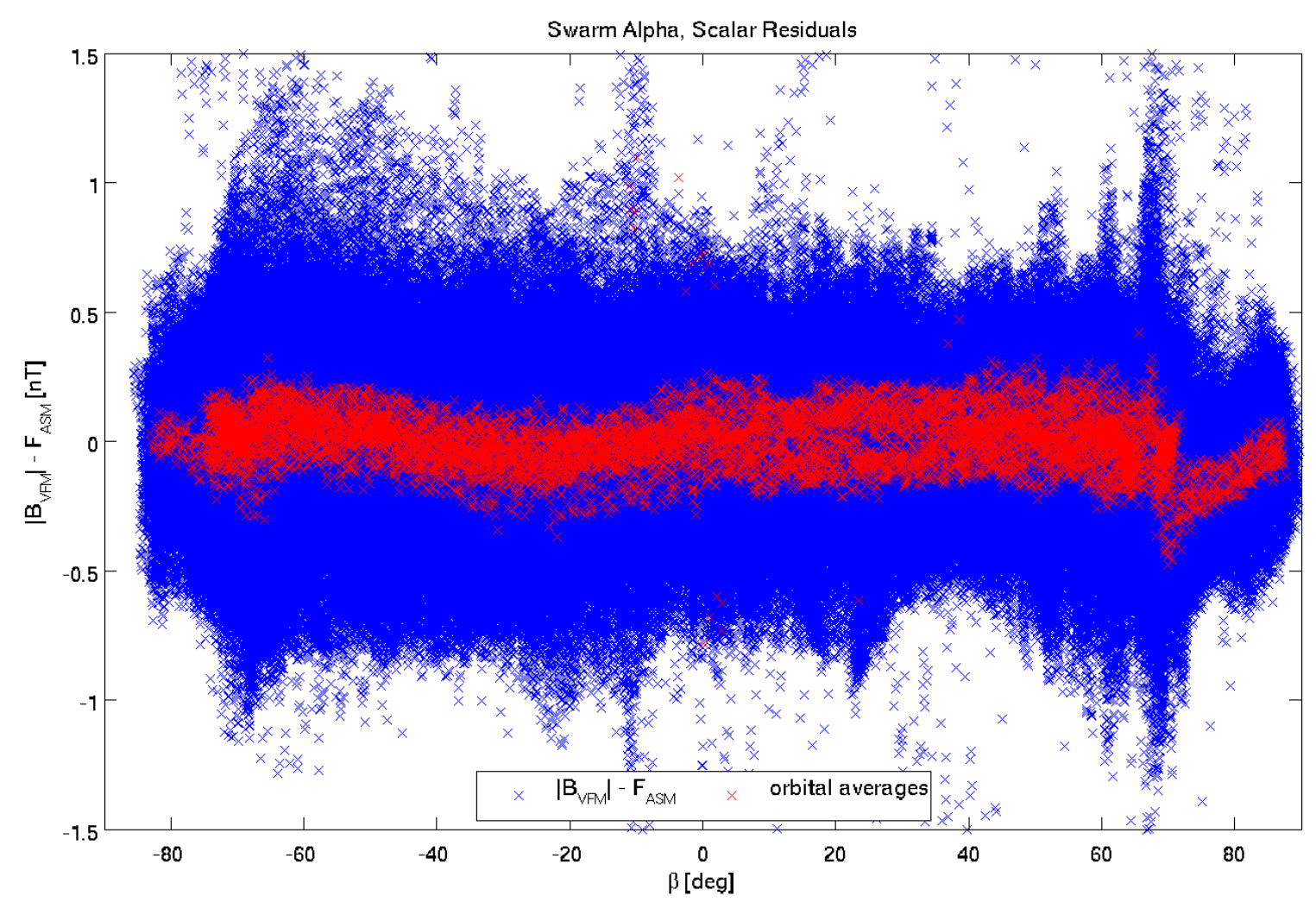
Beta Angle or Electronic Unit Temperature Dependency ?

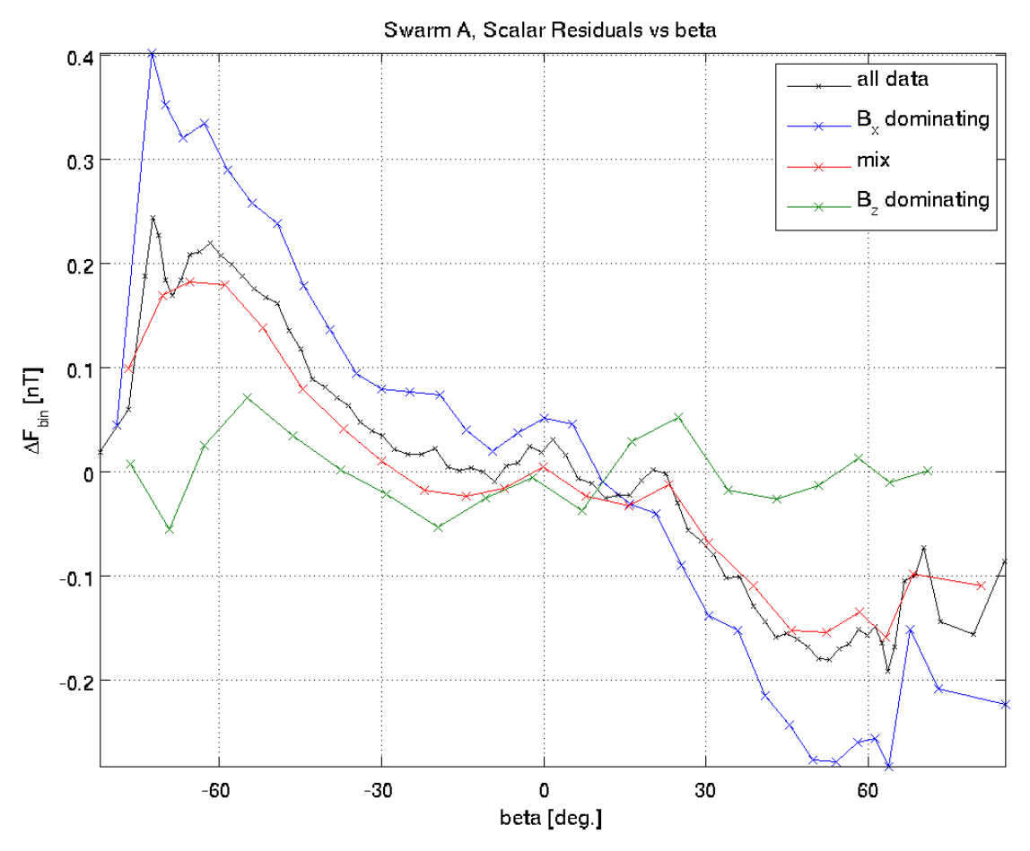
The $s_{j,\mathrm{other}}$ factor in the equation above is not yet clearly characterised. When omitting this parameter from the estimation process, some systematic residuals arise. Below to the left, these residuals are plotted as a function of the VFM electronic unit temperature (individual samples in blue, orbital averages in red). There seem to be some kind of hysteresis effect with a notch around 30°C. In the figure on the right the residuals are binned according to temperature and dominating component of the magnetic field vector as seen by the VFM. From this, the B_x component of the VFM seems to be the most affected.





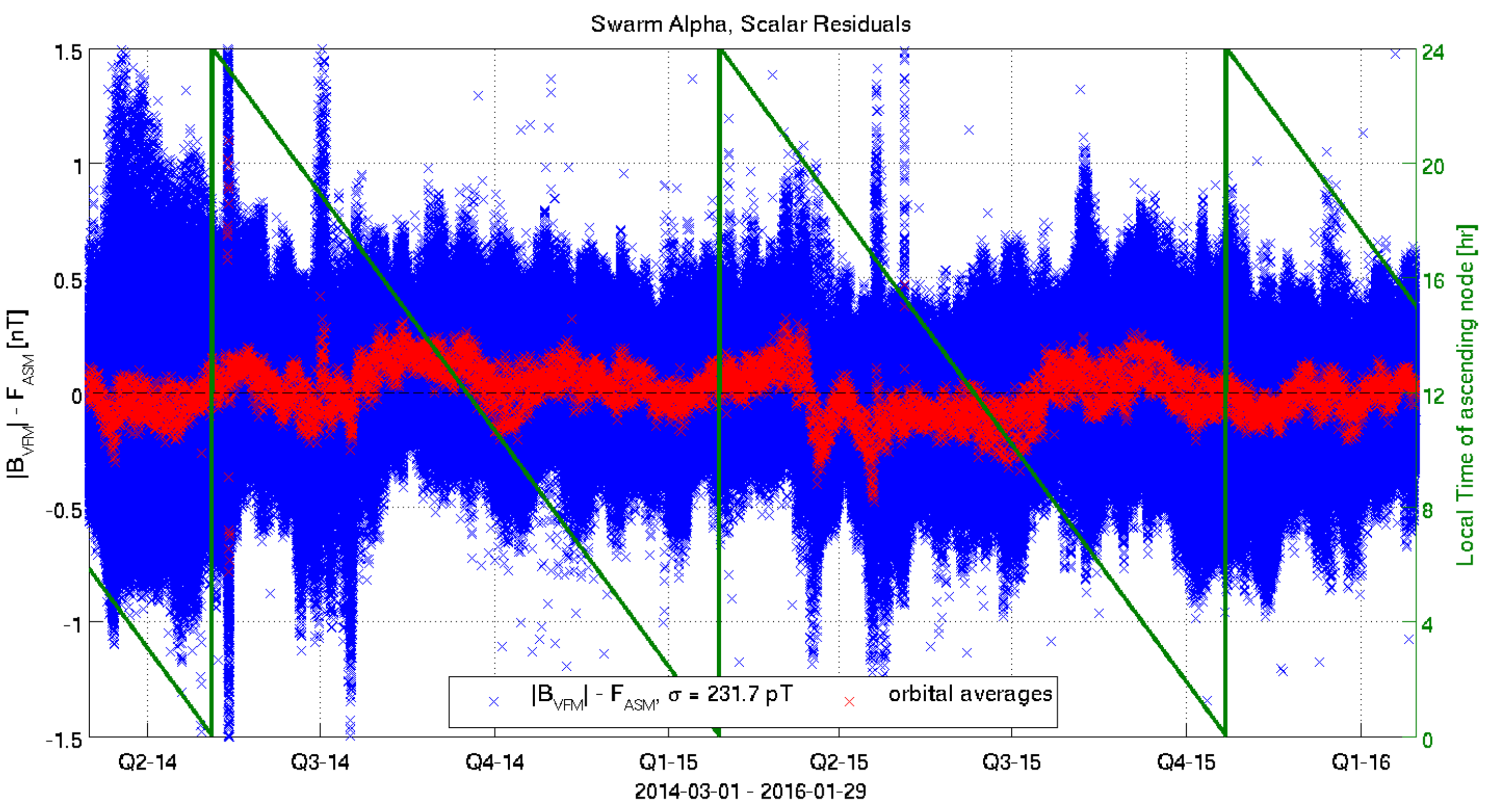
Plotting the same residuals as function of β reveals somewhat less system behaviour although the natural high correlation between the T_{elec} and β parameters naturally results in some similarities.

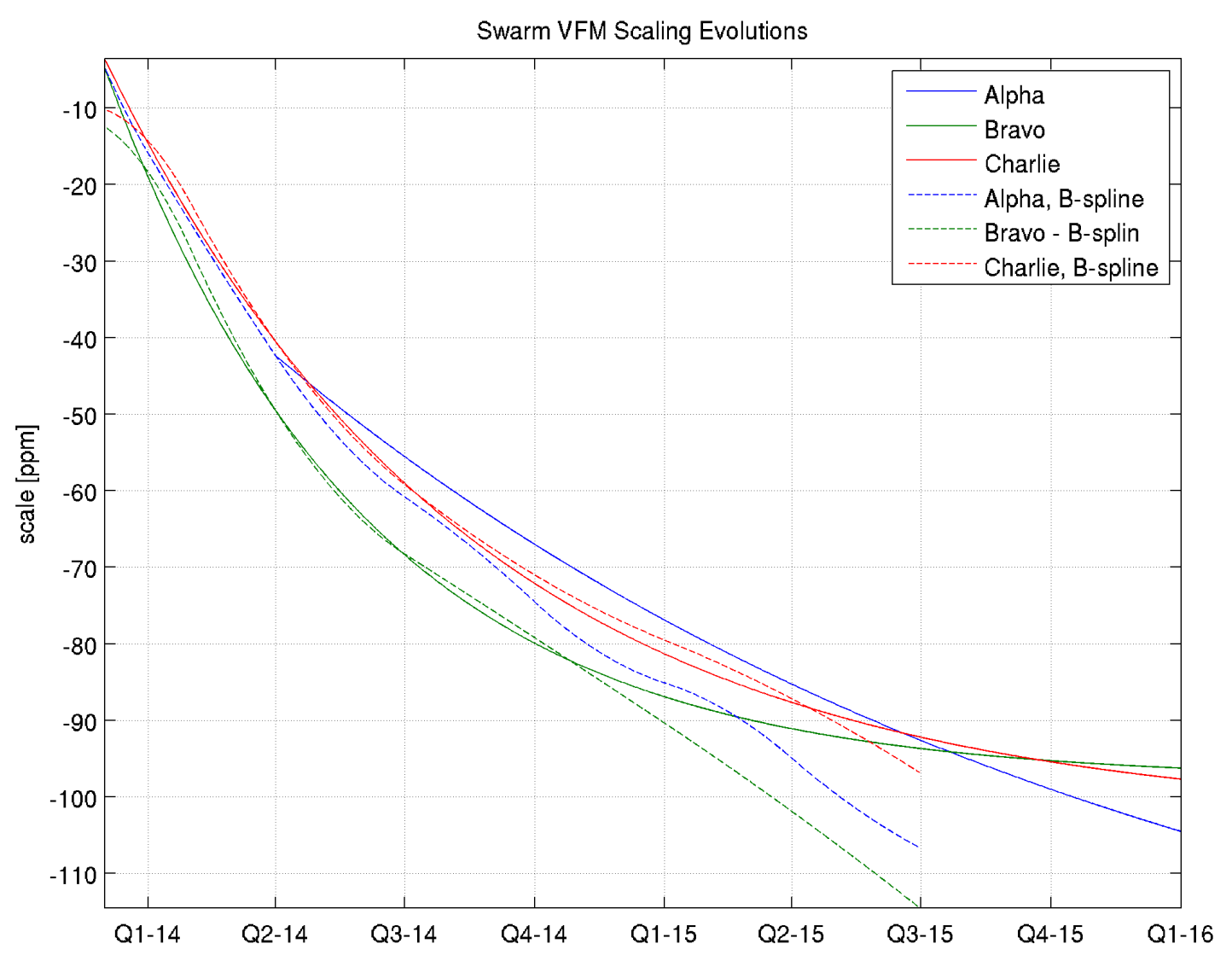




Preliminary Results

Based on the plots above, a model with $s_{j,\mathrm{other}} = \delta s_{\mathrm{Telec}}\ T_{\mathrm{elec}}$ for $T_{\mathrm{elec}} \leq 30°\mathrm{C}$ has been tested. The scalar residuals of this model for *Swarm Alpha* for the first 26 months of the mission is shown in the figure below. Residuals are shown in blue, in red are shown the orbital averages. Local time of the ascending node is shown in green. For this model, the weighted rms of the residuals is 232 pT, i.e. somewhat larger than for the present, implemented model, but this new model is thought to be a more valid representation of the VFM instrument behaviour.





To the left, plots of $s^{\mathrm{B-spline}}$ vs. $s_{\mathrm{exp}} e^{-\frac{t-t_0}{\tau}}$ for all three *Swarm* satellites are shown; B-splines are the dashed lines, the exponential functions are the solid lines. Note that for *Swarm Alpha*, the exponential function starts in March 2014 ("Q2-14"). The curves are similar, in particular for *Swarm Charlie* (in red) whereas *Alpha* (blue) and *Bravo* (green) show some deviations after late 2014.

Conclusion

The present model for the calibration and disturbance correction of the *Swarm* magnetic measurements has proven quite effective. However, this model is not reflecting the physical properties of the VFM instrument, and it is by nature not good for predictions of the VFM sensitivity; hence new models of the VFM sensitivity are being tested with promising results.

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Department of Geomagnetism, DTU Space, Technical University of Denmark, Diplomvej 371, 2800 Kgs. Lyngby, Denmark
lastec@space.dtu.dk