Polar cap currents: Perspectives from internal field modelling using Swarm and CHAMP data

Chris Finlay

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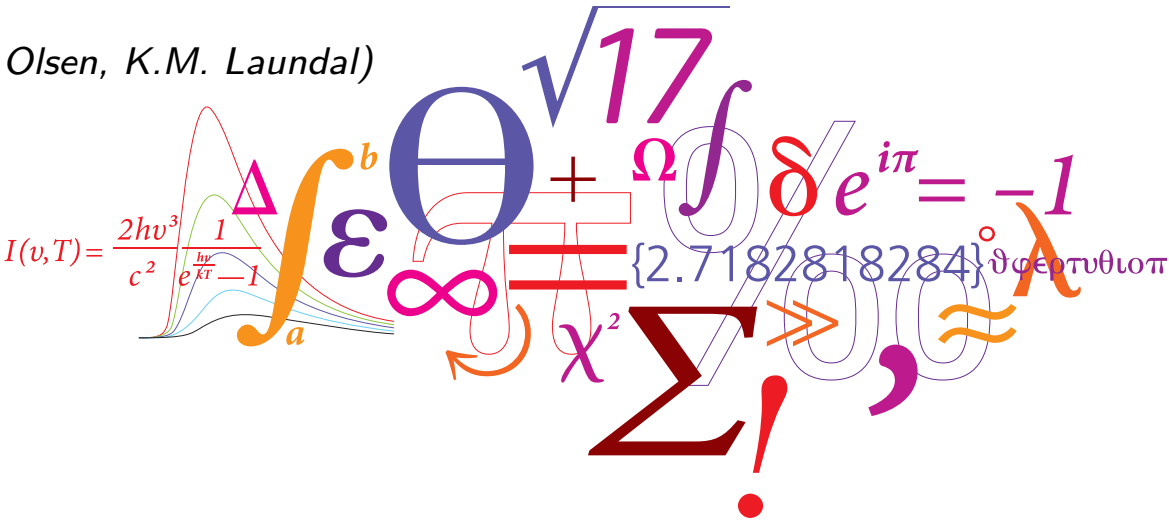
(with thanks to: E. Friis-Christensen, N. Olsen, K.M. Laundal)



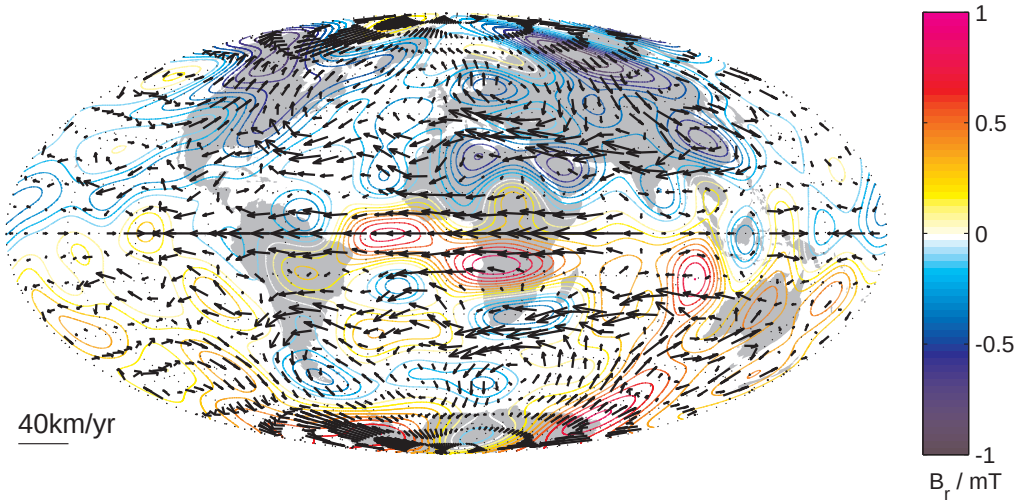
DTU Space
National Space Institute

Outline

1. **Internal field modelling**
2. Unmodelled signals at polar latitudes
3. Discussion
4. Summary

Challenges for internal field studies

- Origin of decreasing dipole field strength?
- Evolution of South Atlantic anomaly?
- What causes pulses of field acceleration?



Involve MHD process in Earth's core governed by:

$$\underbrace{\frac{\partial \mathbf{B}}{\partial t}}_{\text{Secular variation}} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Advection \& stretching by core flow}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{Ohmic diffusion}}$$

Progress requires internal field models with:

- Higher spatial resolution $>$ SH degree 15 of time varying internal field
- Higher time resolution of the SV $<$ 1-2 yrs

- This talk: CHAOS model (Olsen et al., 2006, 2014; Finlay et al., 2015) taken as example

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- **(2) Only data from dark regions**
  - Sun 10 deg below horizon
- **(3) Use only scalar intensity data $> \pm$55 deg quasi-dipole latitude**
  - If E_m averaged over preceding 2hrs $\leq 0.8\text{mV/m}$

where $$E_m = 0.33 v^{4/3} B_t^{2/3} \sin^{8/3}(|\Theta|/2)$$ (Newell et al., 2007)

v: solar wind speed
$B_t = \sqrt{B_Y^2 + B_Z^2}$ is IMF magnitude in the $Y - Z$ plane
$\Theta = \arctan(B_Y/B_Z)$ is the IMF clock angle

Model parameterization I

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.

- The internal part of the potential takes the form

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m \cos m\phi + h_n^m \sin m\phi\right) \left(\frac{a}{r}\right)^{n+1} P_n^m \left(\cos\theta\right)$$

- And further expanded in time as

$$\begin{aligned} g_n^m(t) &= \sum_l g_{n,l}^m \cdot M_l(t) && \text{for } n = 1 - 20 \\ &= g_n^m(t_0) \quad (\text{const.}) && \text{for } n = 21 - 80 \end{aligned}$$

where $M_l(t)$ are order 6 B-splines with 0.5 yr spacing

Model parameterization II

- Define external potential in SM and GSM co-ordinate systems, with θ_d and T_d being dipole co-lat. and dipole local time

$$
\begin{aligned}
V^{\mathrm{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d\right) \left(\frac{r}{a}\right)^n P_n^m(\cos\theta_d) \\
&+ a \sum_{n=1}^{2} q_n^{0,\mathrm{GSM}} R_n^0(r,\theta,\phi).
\end{aligned}
$$

- The degree-1 coefficients in *SM* coordinates are further expanded, for example

$$
q_1^0(t) = \hat{q}_1^0 \left[\epsilon(t) + \iota(t) \left(\frac{a}{r}\right)^3\right] + \Delta q_1^0(t)
$$

- $\epsilon(t)$ and $\iota(t)$ are external, internal parts of the **RC index**
(Similar to *Dst* but baseline more stable over months to years)

Model estimation

- Work with data in **magnetometer frame** co-estimating Euler angles in 10 day bins

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$$\boxed{\mathcal{J} = [\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}}^{-1} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}}$$

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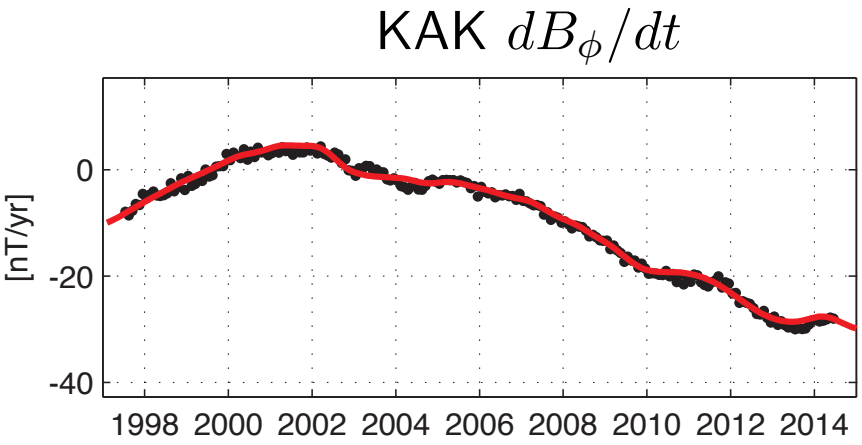
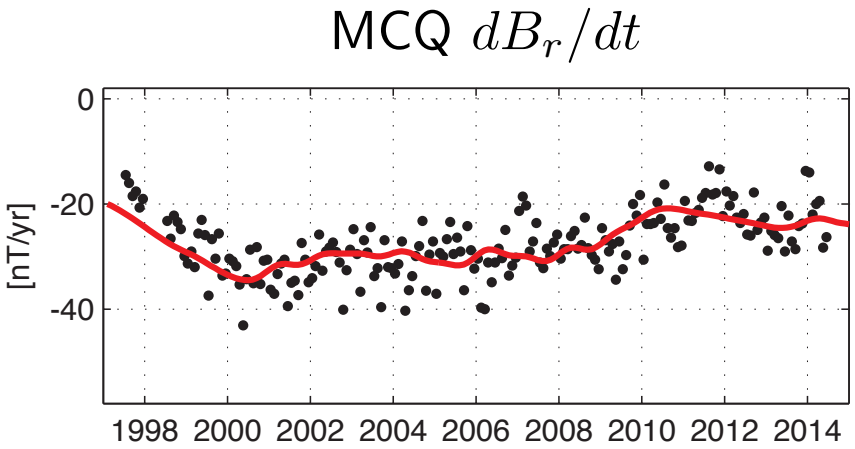
- $\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, updated at each iteration based on residuals
- $\underline{\underline{\mathbf{\Lambda}}}_3$ measures the time-average of $\left|\frac{\partial^3 B_r}{\partial t^3}\right|^2$, integrated over the core surface

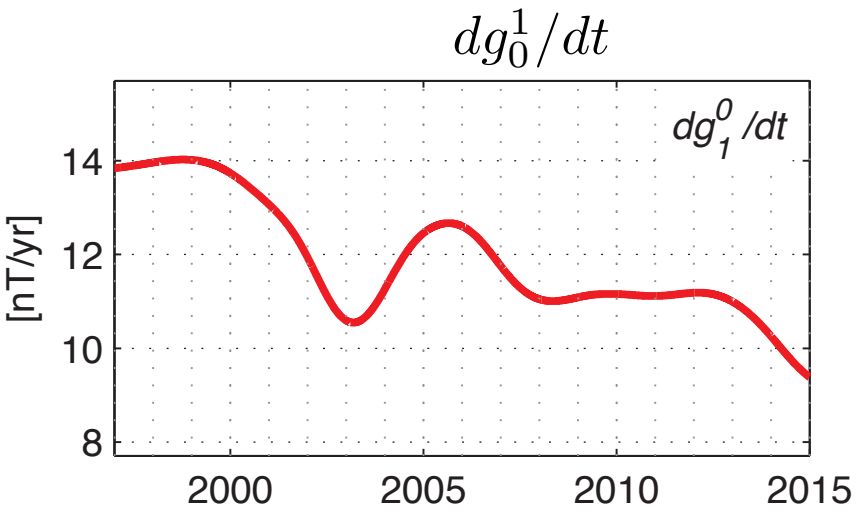
$$\left\langle \left| \frac{\partial^3 B_r}{\partial t^3} \right|^2 \right\rangle = \frac{1}{\Delta t} \int \int \left| \frac{\partial^3 B_r}{\partial t^3} \right|^2 d\Omega_c \; dt = \mathbf{m}^T \underline{\underline{\Lambda}}_3 \mathbf{m}$$

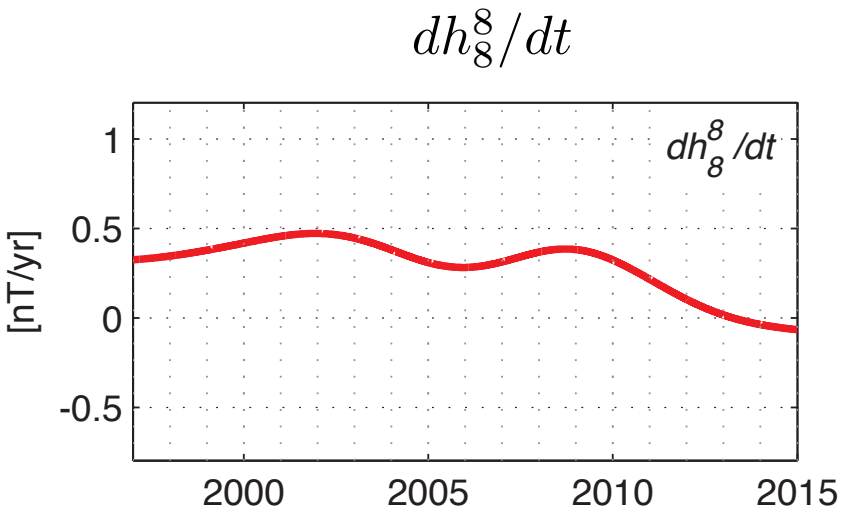
- $\underline{\underline{\mathbf{\Lambda}}}_2$ measures the time averaged of $\left|\frac{\partial^2 B_r}{\partial t^2}\right|^2$, integrated over the core surface, but only at the model endpoints

Example model results: CHAOS-5



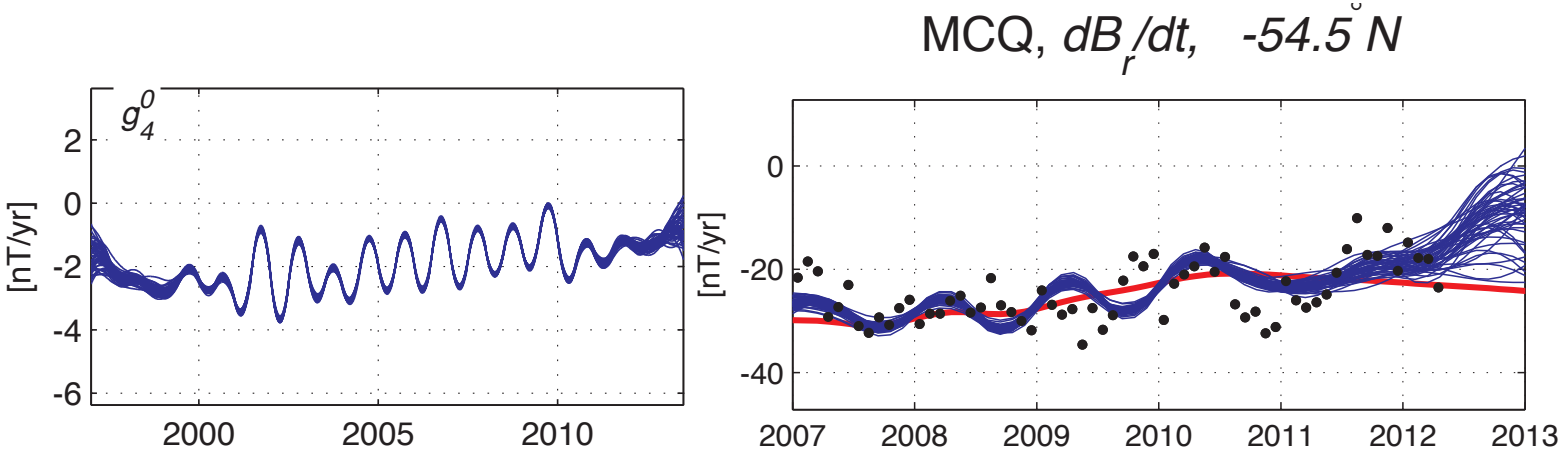






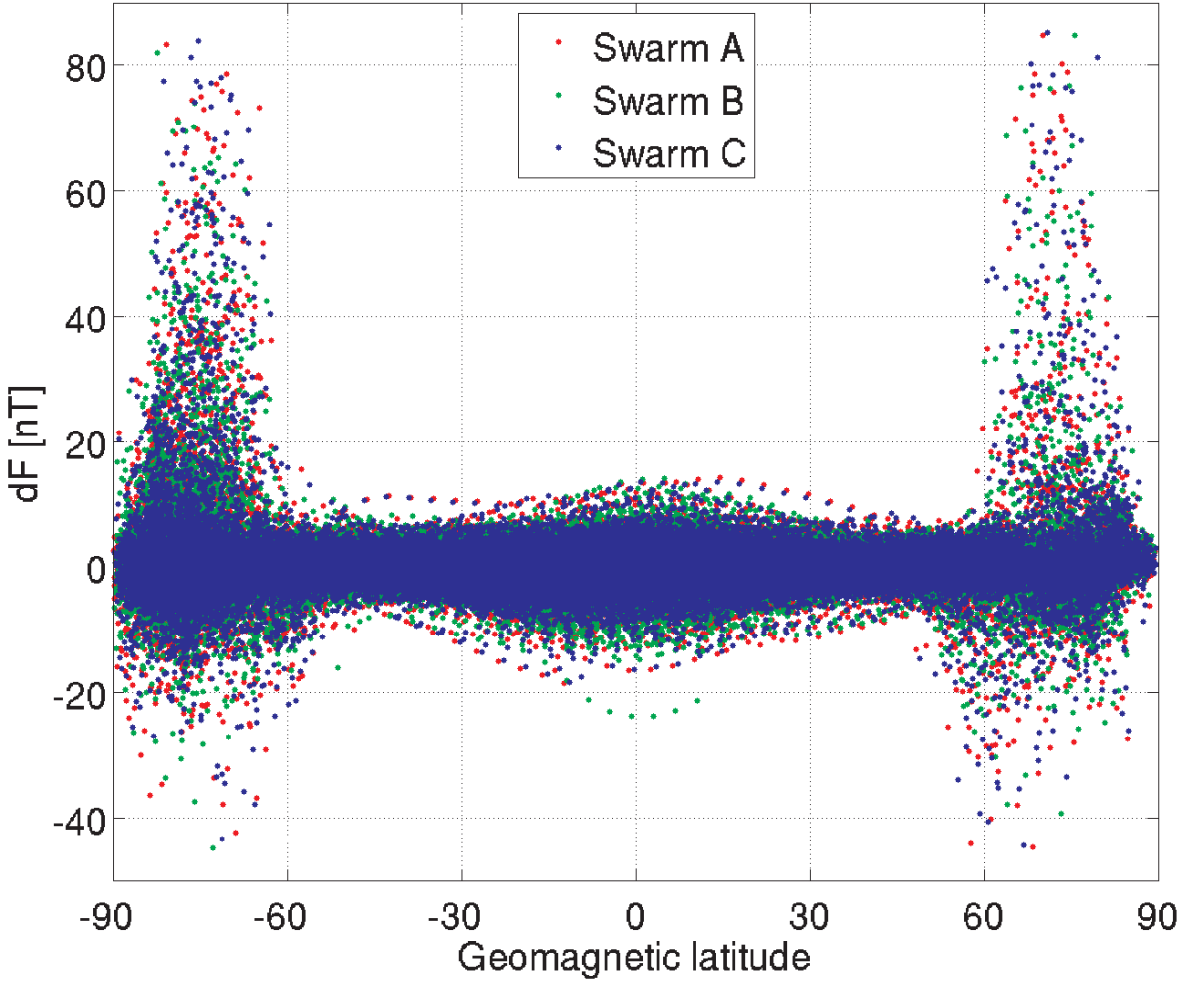
Need for strong temporal regularization

- Experiments relaxing the temporal regularization show large annual oscillations, especially during times with good quality, low altitude, satellite data:



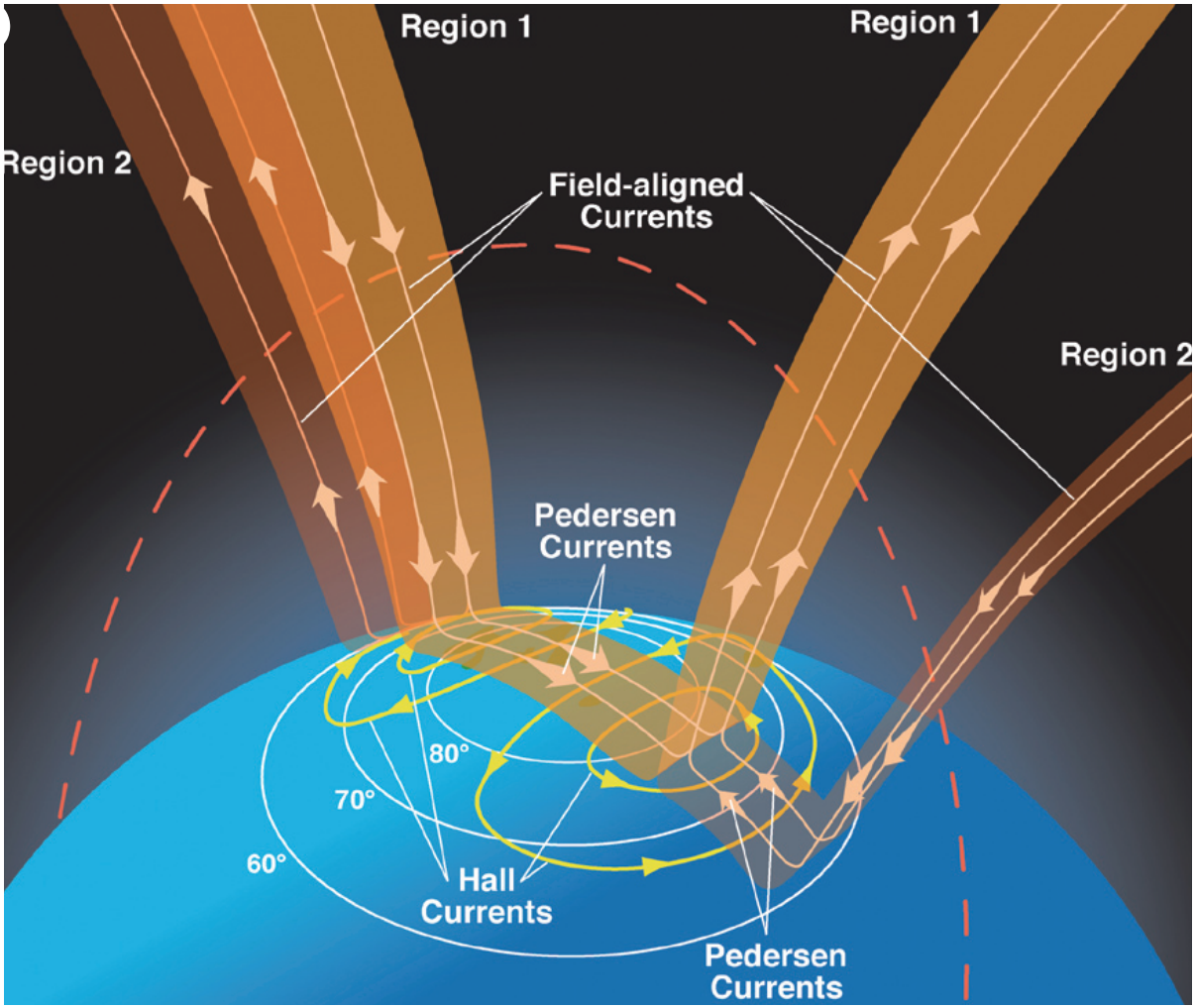
- Strong Oscillations at polar latitudes, especially prominent in dB_r/dt (and dF/dt).

CHAOS-5 Model residuals vs QD latitude



- Largest unmodelled signals in F occur in the polar regions
- Amplitude of dF residuals is generally larger in the southern hemisphere

Polar cap currents (for the purposes of this talk)



(From Le et al., 2015, Terr. Atmos. Ocean. Sci. Vol 26, 11-15)

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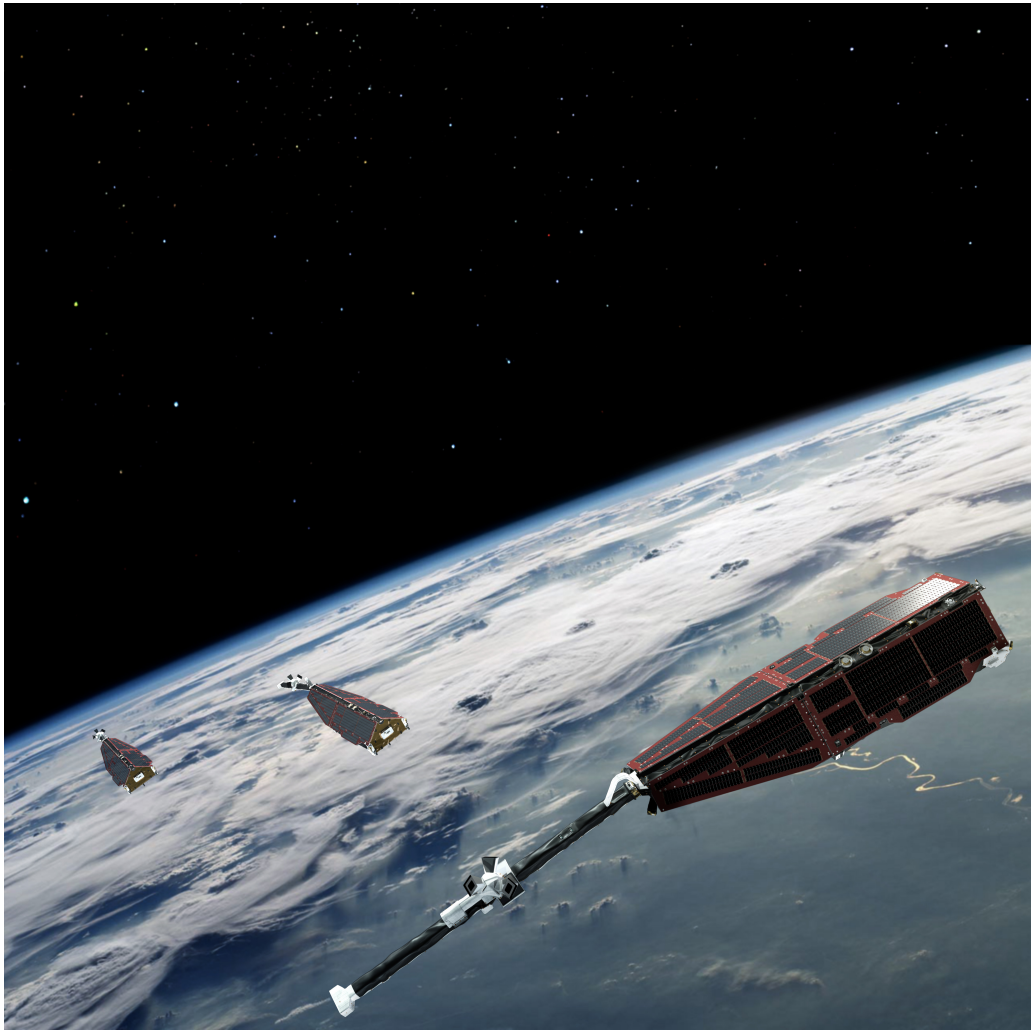
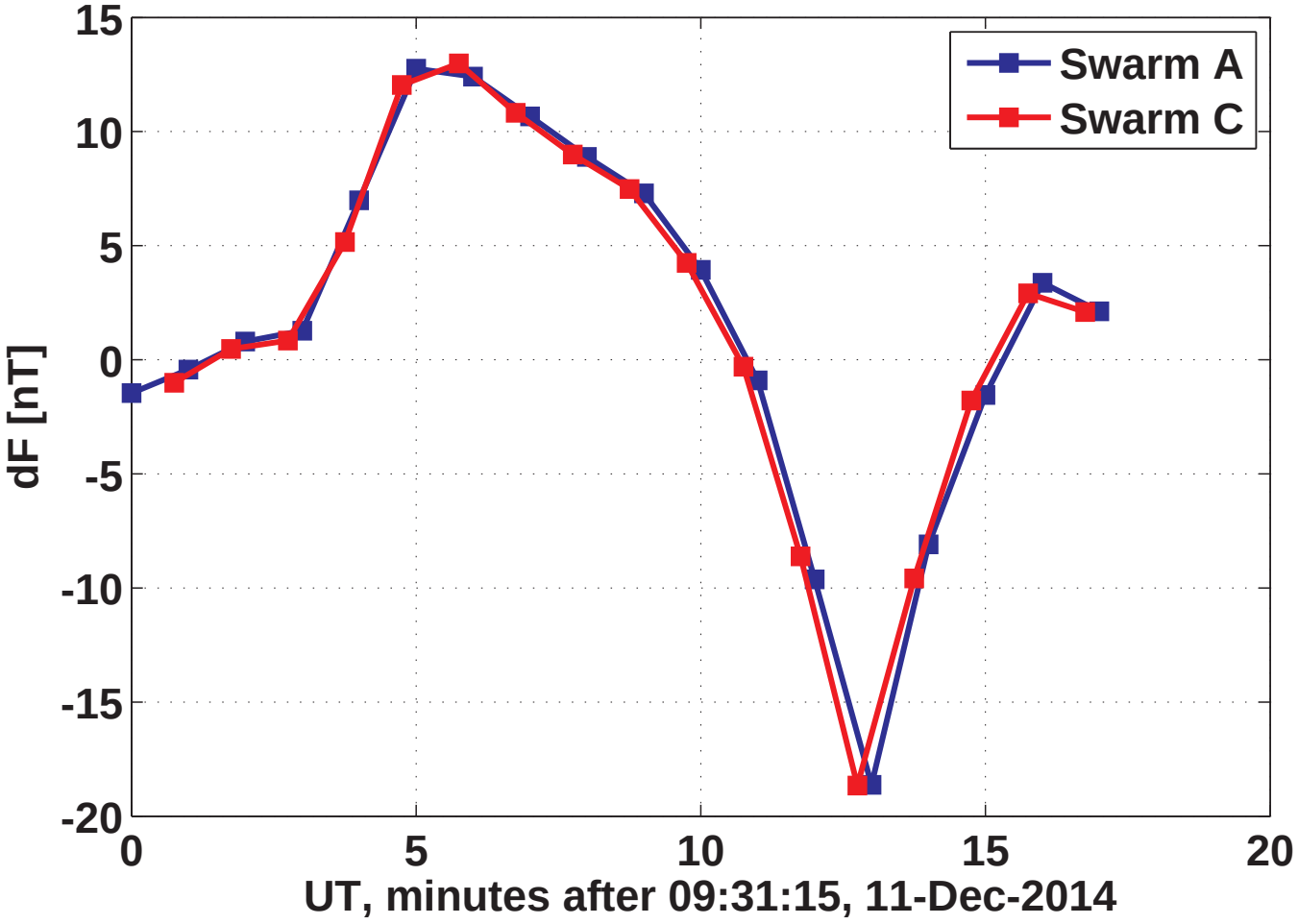
Swarm data: residuals from CHAOS-5x, 2013.9-2015.2



Swarm ΔF: Example polar pass, 11th Dec 2014



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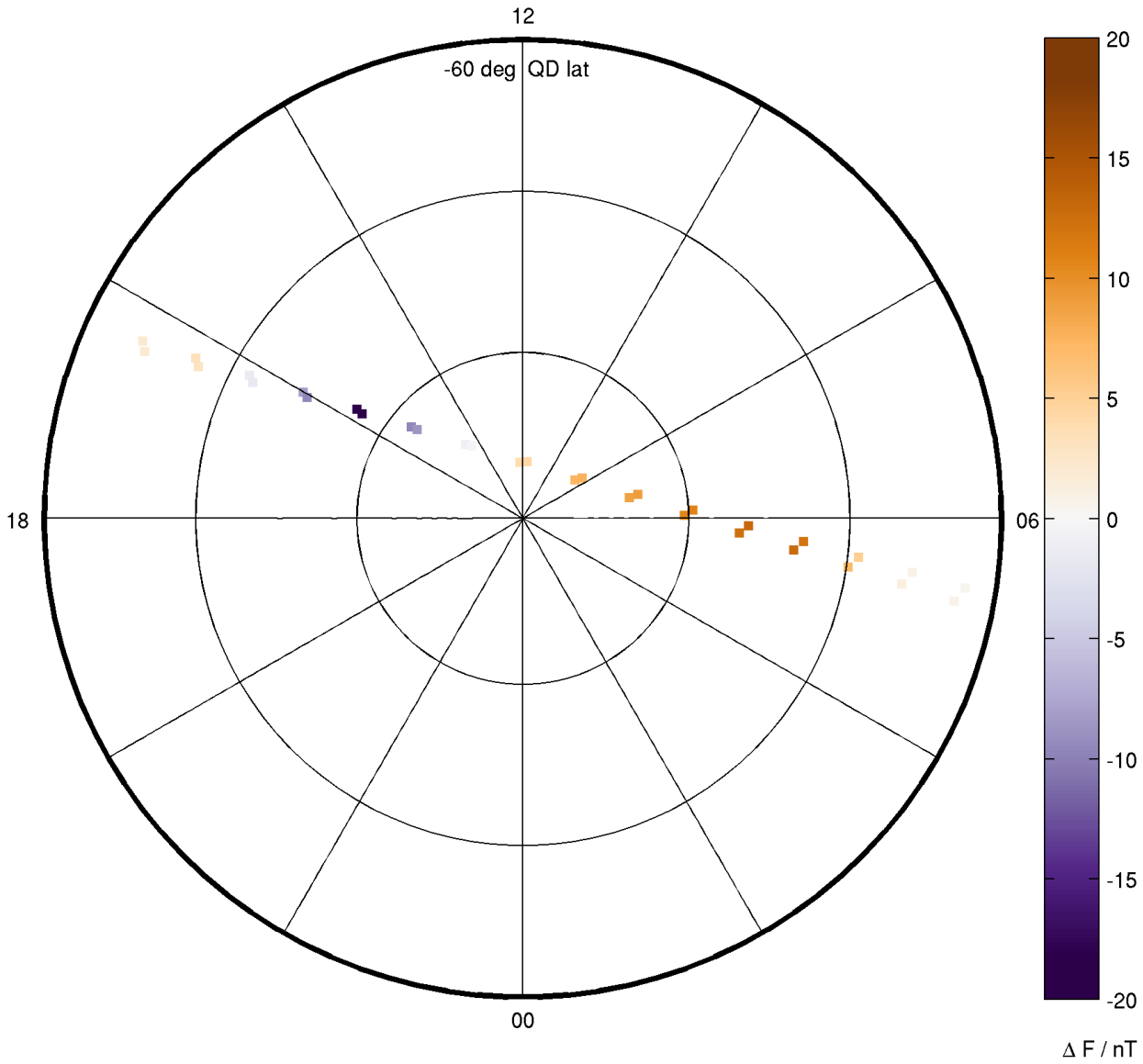
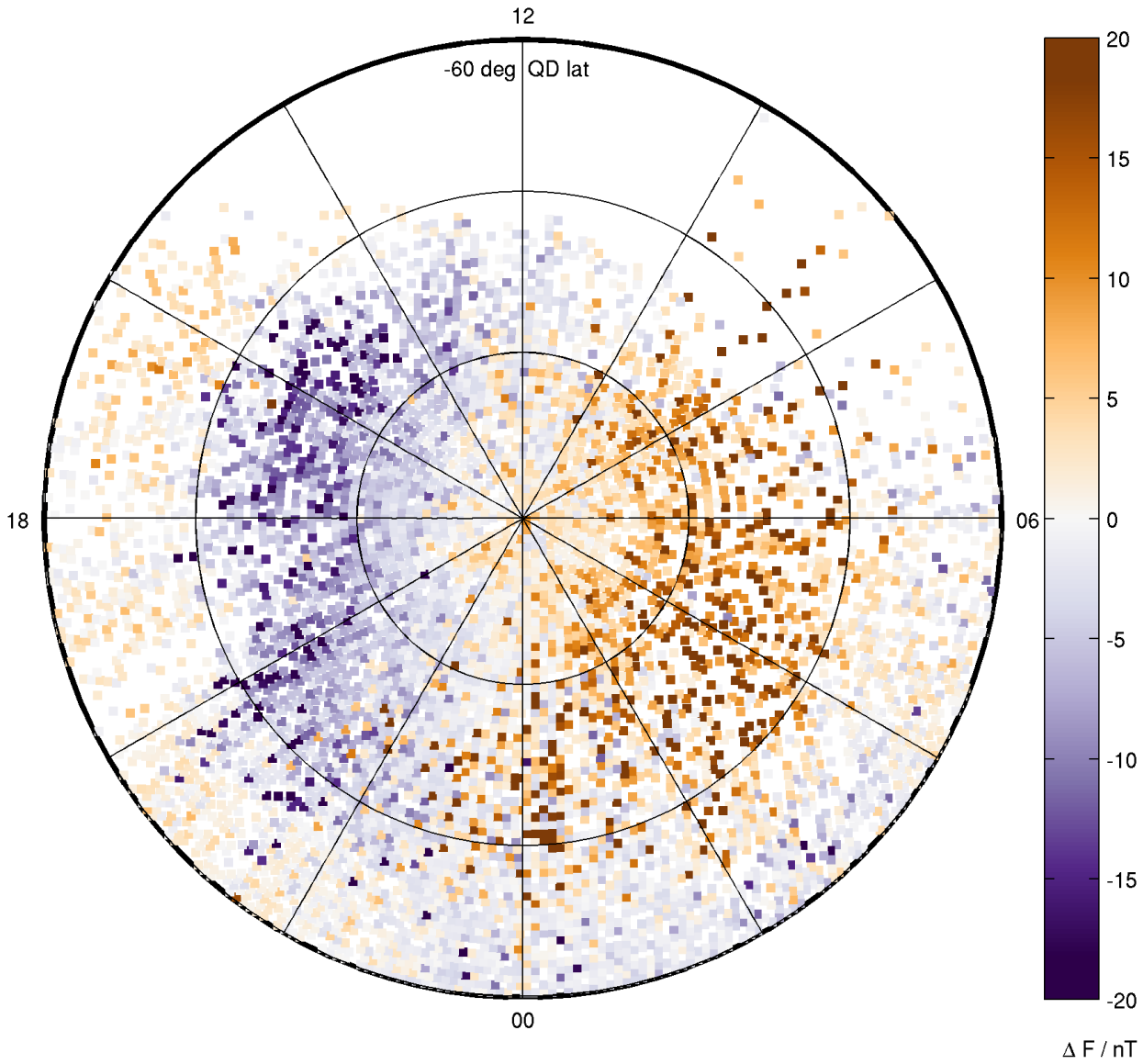
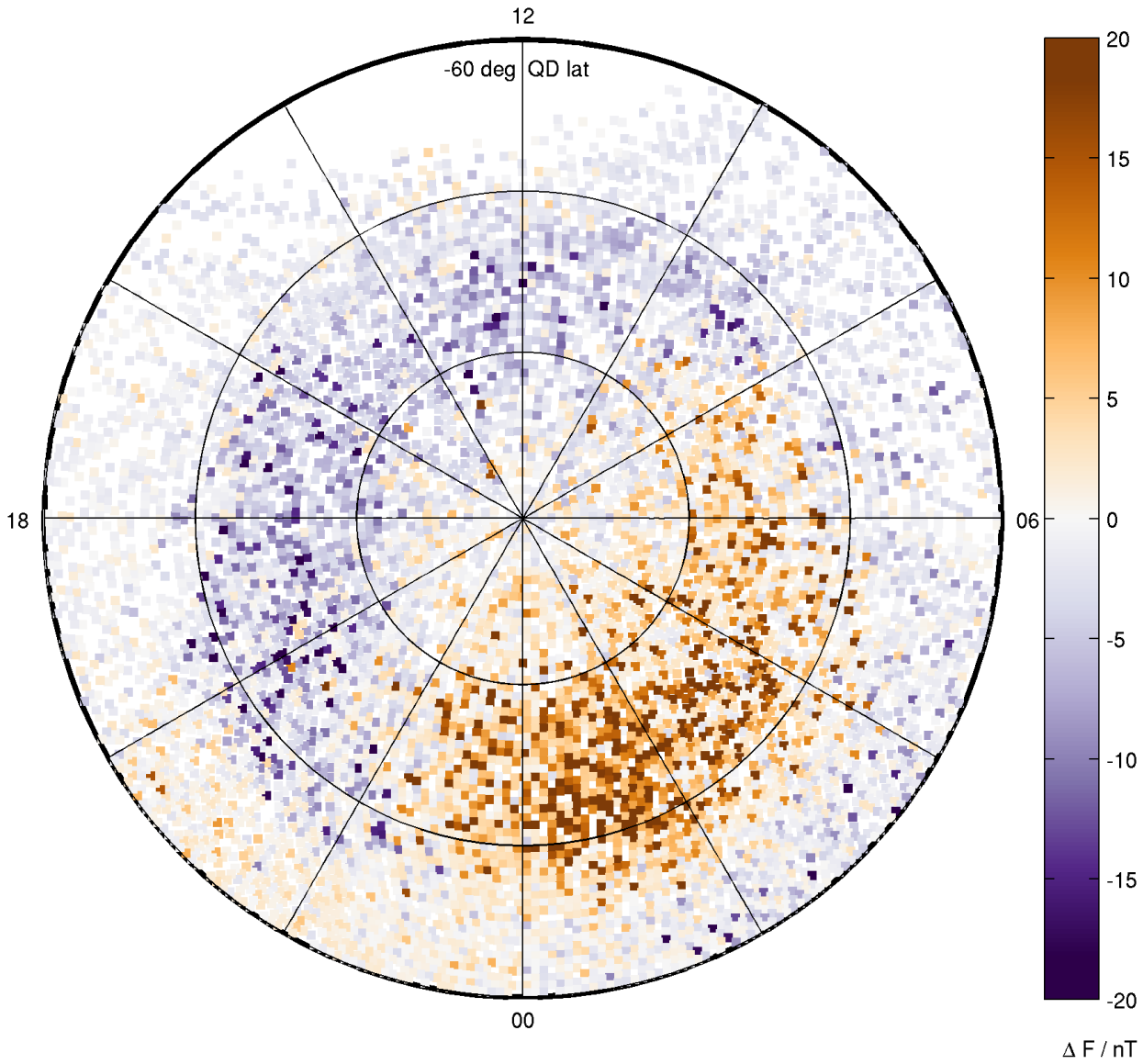


Swarm ΔF, Northern hemisphere

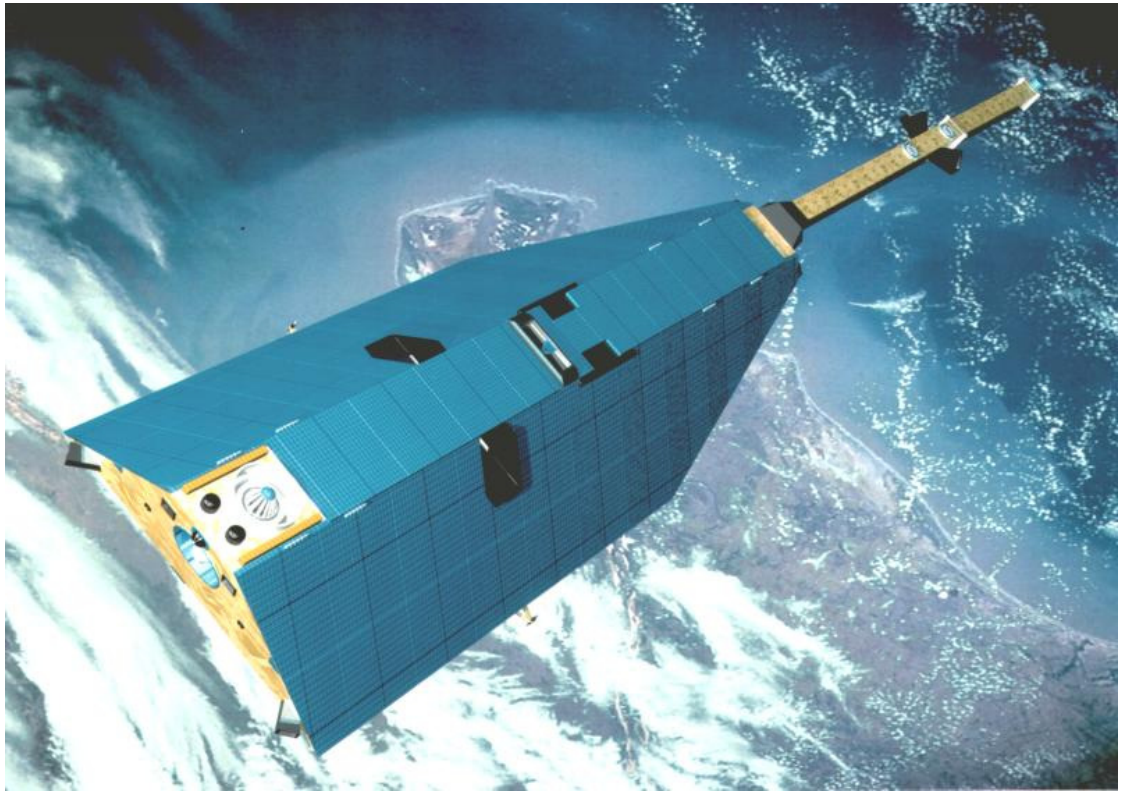


Swarm ΔF, Southern hemisphere

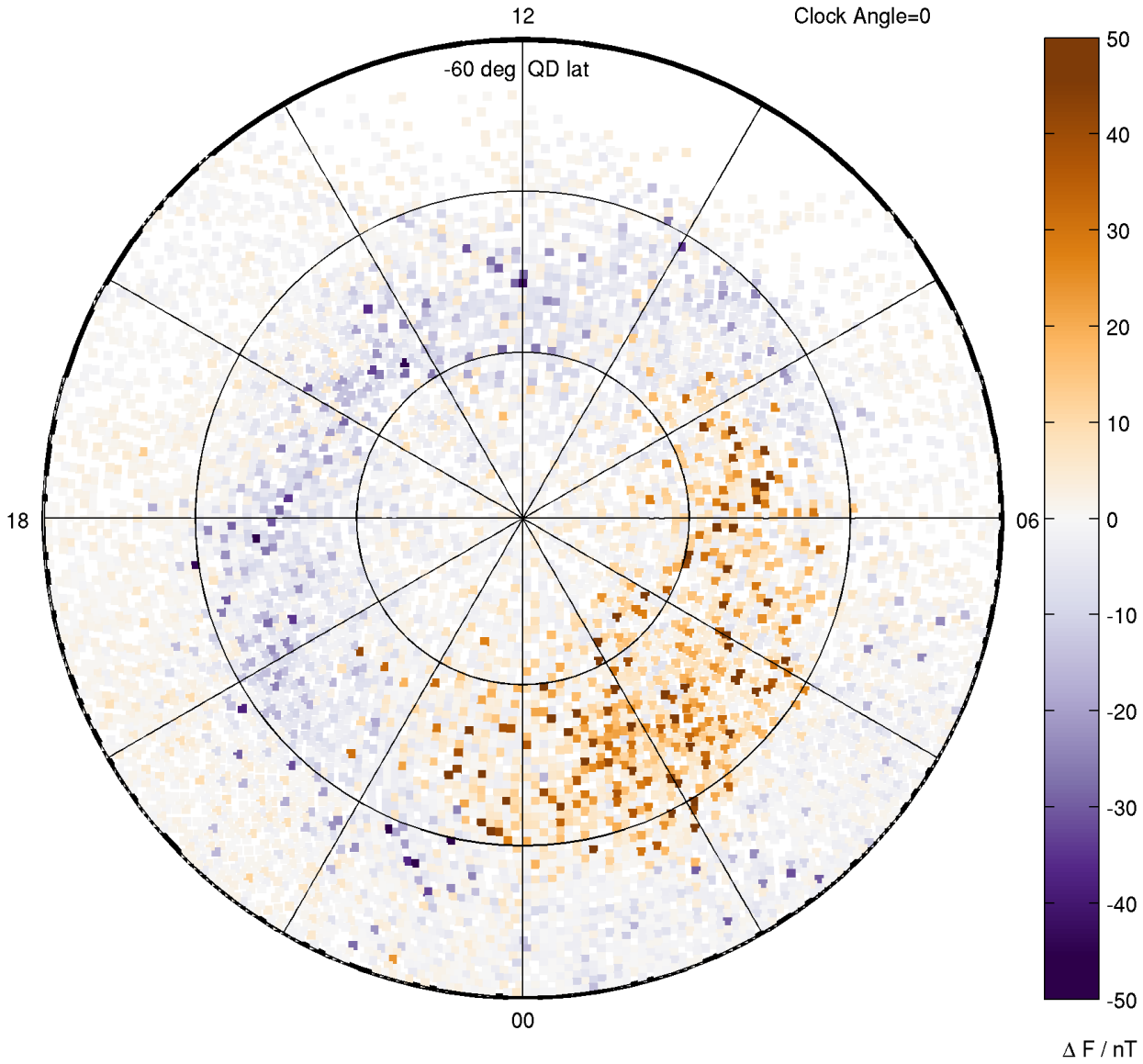


CHAMP data: Residuals from CHAOS-5x, 2008-2010

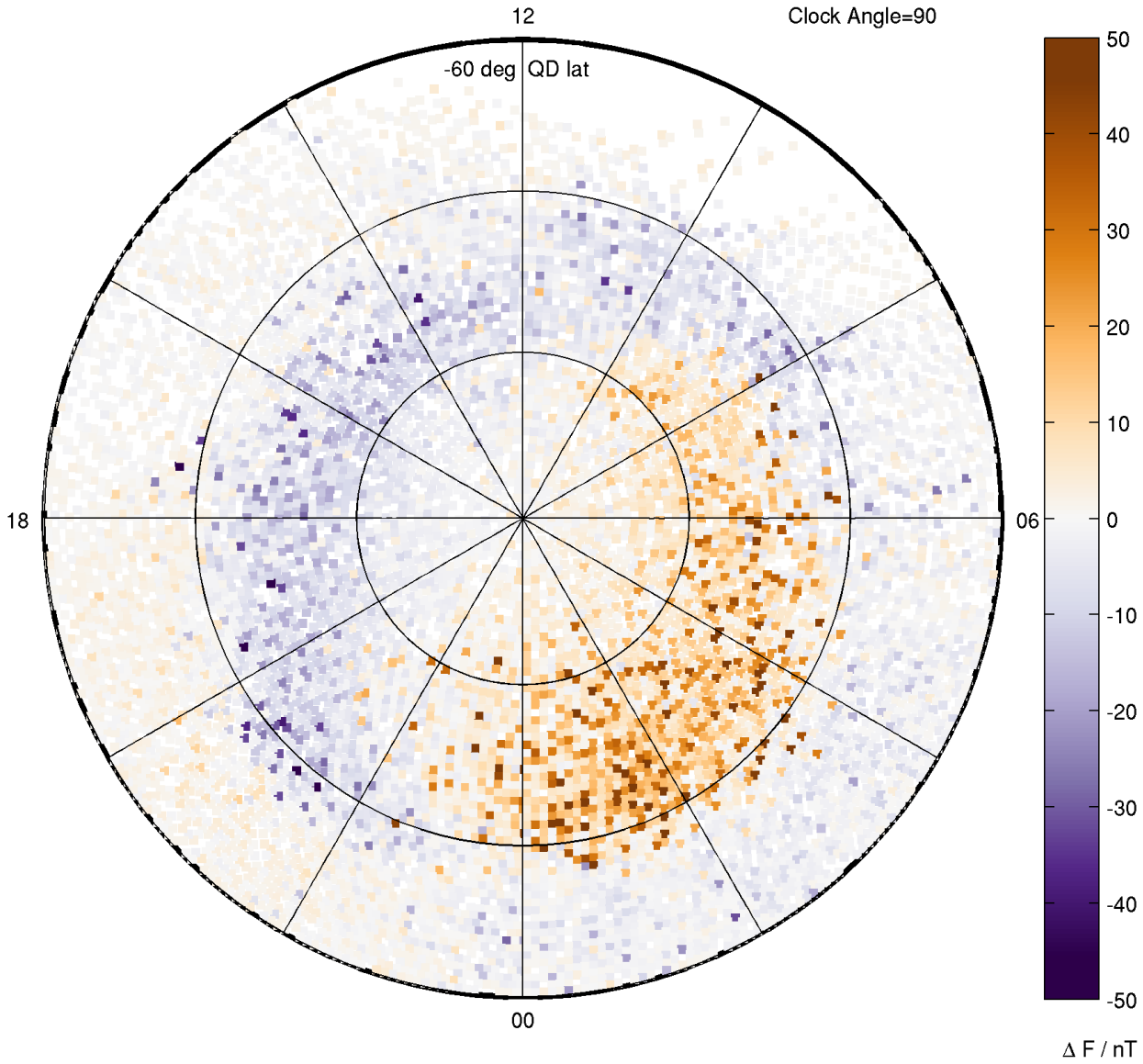
- Lower altitude
- Solar minimum
- Same quiet-time, dark, data selection



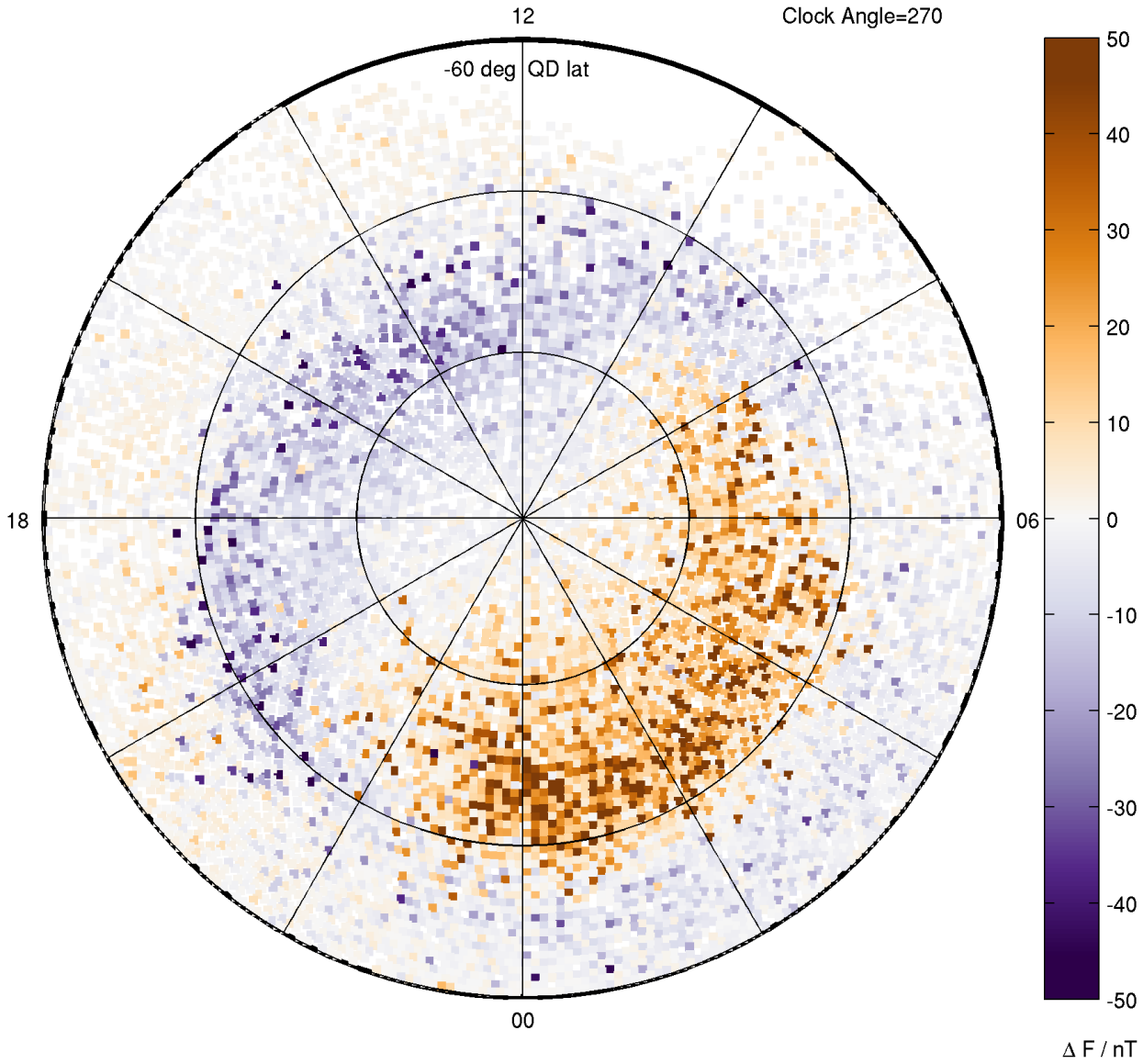
CHAMP, SH, ΔF, IMF clock angle 0 deg



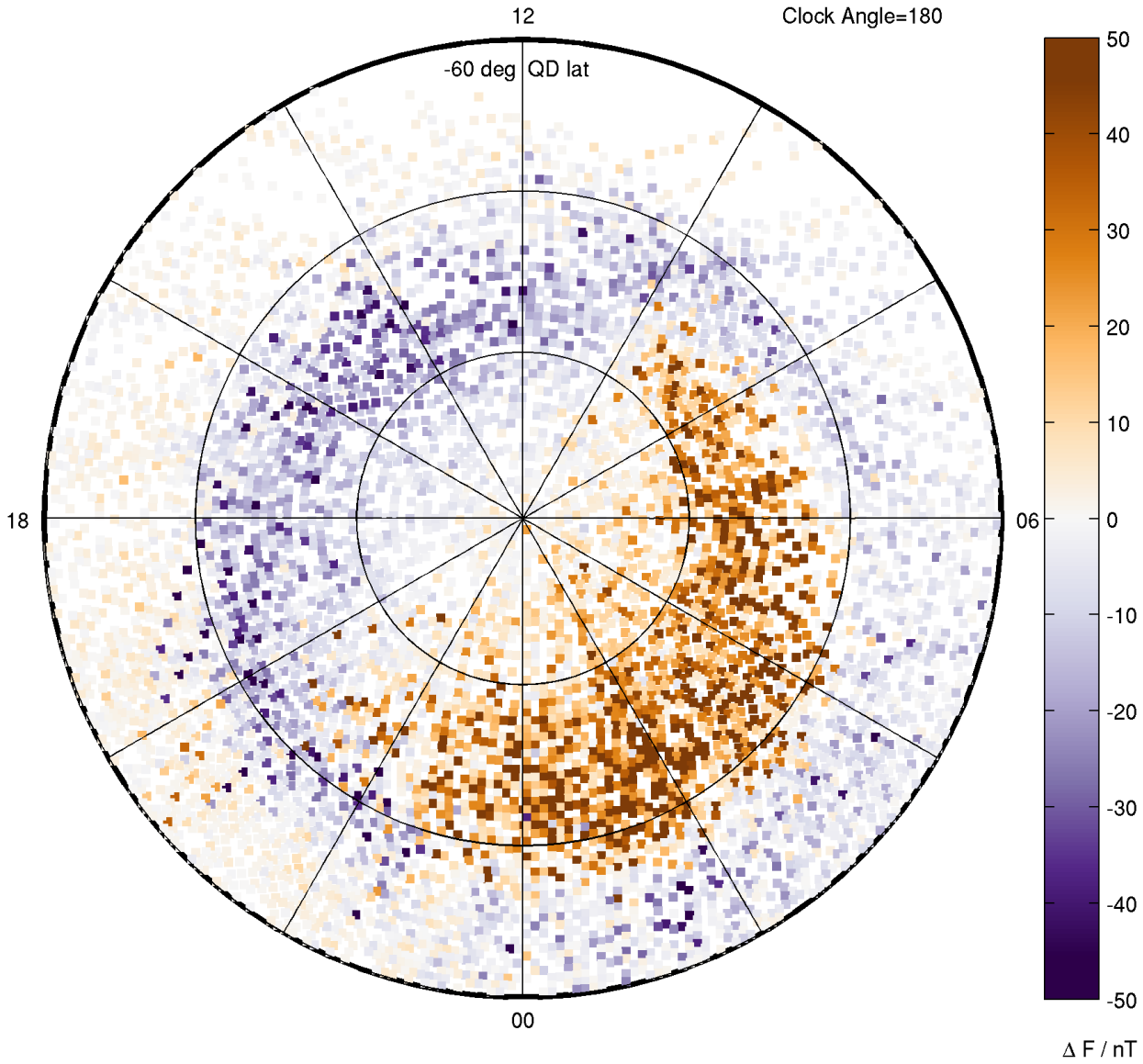
CHAMP, SH, ΔF, IMF clock angle 90 deg



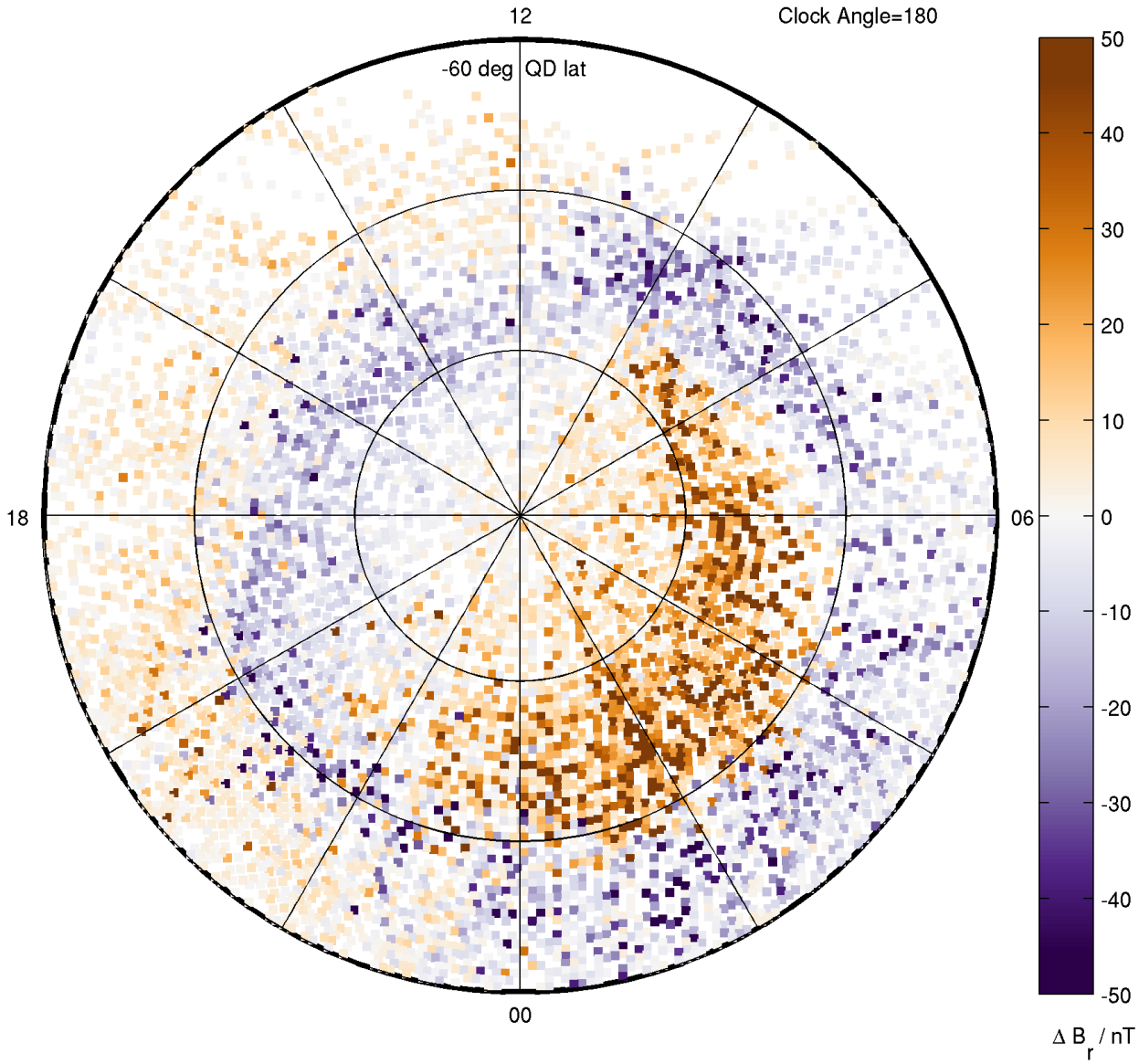
CHAMP, SH, ΔF, clock angle 270 deg



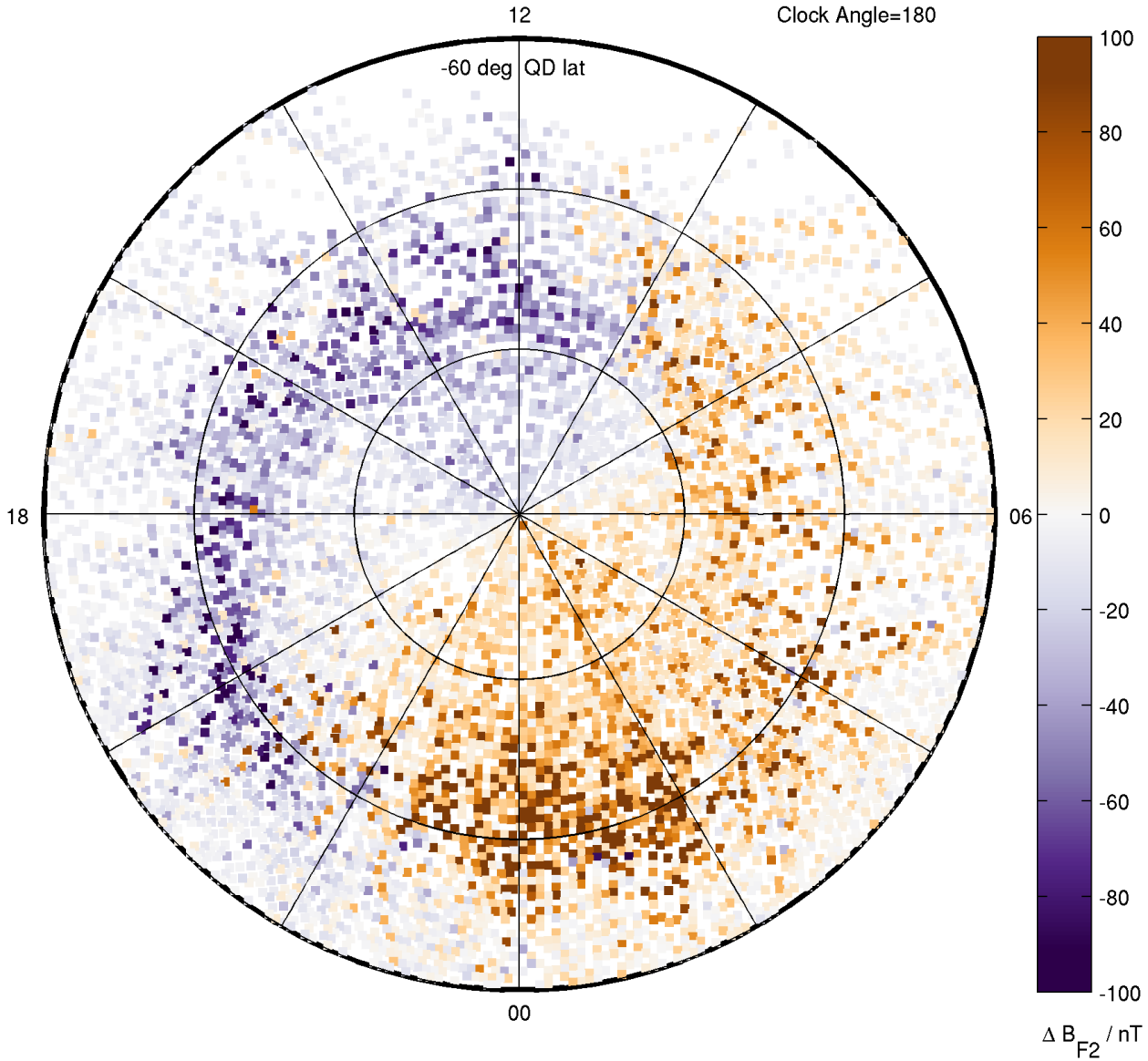
CHAMP, SH, ΔF, IMF clock angle 180 deg



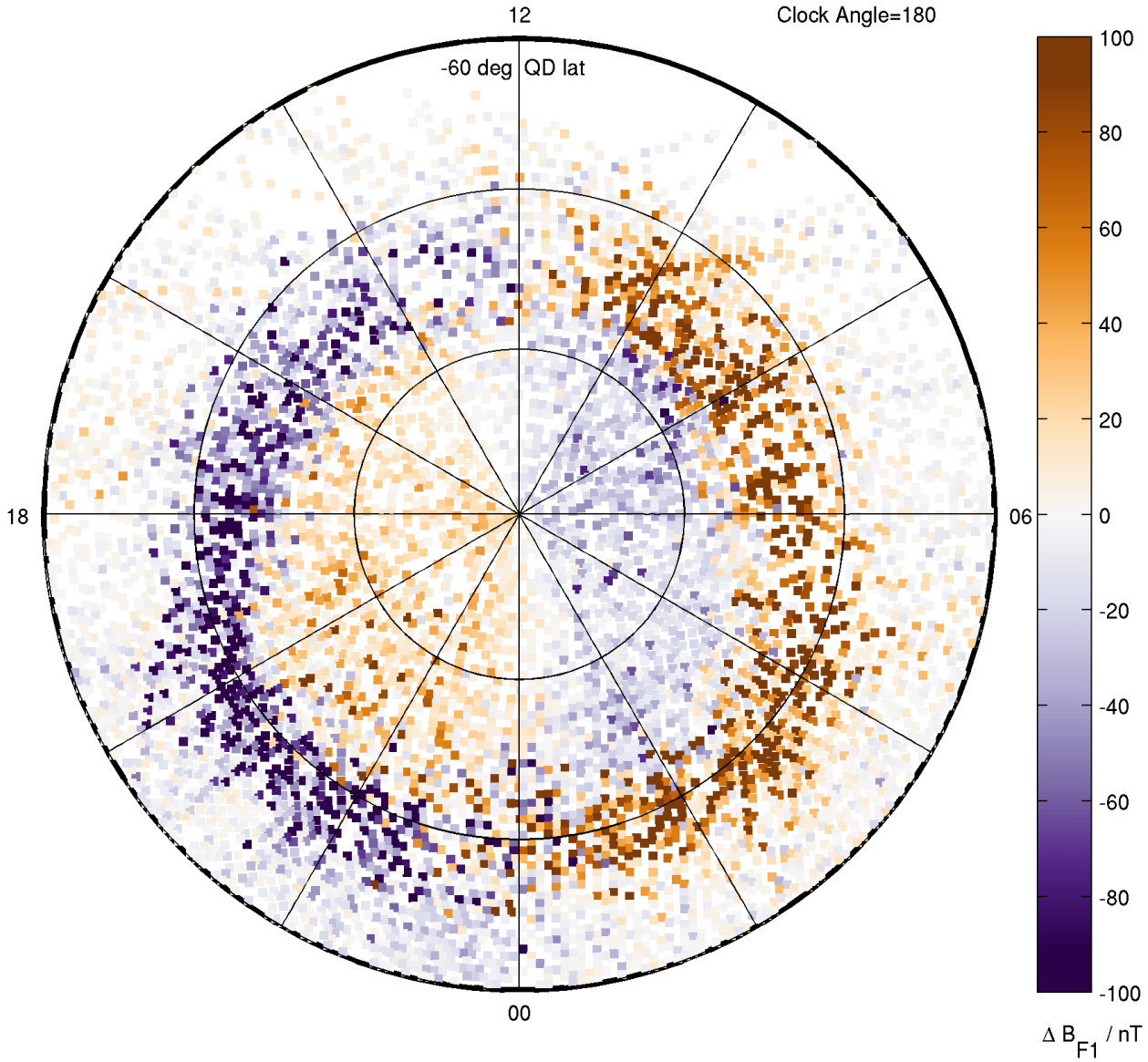
CHAMP, SH, ΔB_r, clock angle 180 deg



CHAMP, SH, ΔB_{QD-NS}, clock angle 180 deg



CHAMP, SH, ΔB_{QD-EW}, clock angle 180 deg



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Shortcomings of existing internal field models

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- **CHAOS model** (Olsen et al., 2006, 2014; Finlay et al., 2015)
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  - Uses all vector components, not just ΔF
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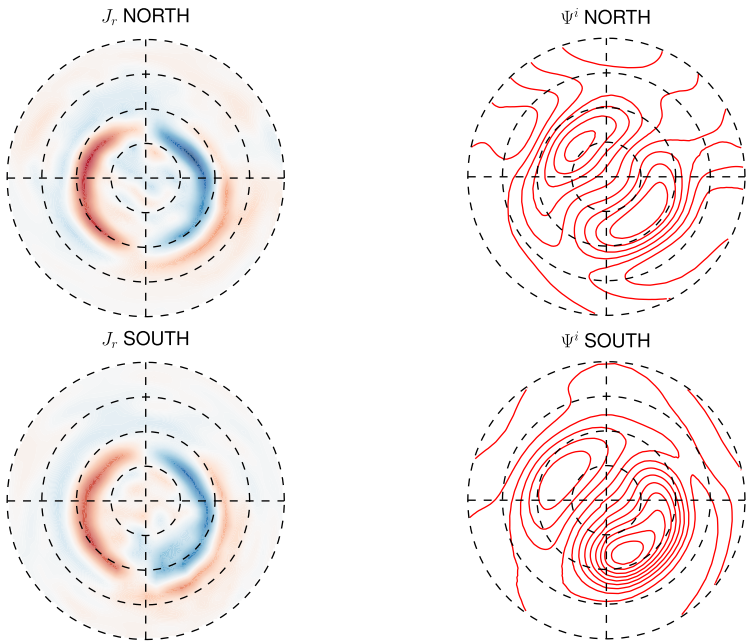
- **CM - Comprehensive model** (Sabaka et al., 2002, 2004, 2015)
  - Ionospheric field explicitly co-estimated in QD, local time frame
  - Primary focus is on SQ rather than polar currents
  - Ionospheric field amplitude scaled with F10.7, but no dependence on IMF
  - Large number of regularization terms (for both internal and ionospheric fields)

How to proceed: Selection, correction or accounting?

- **Data selection/weighting?**
  - Times of large IMF variability
  - Substorm times (e.g. MPB index?)

- **Correction of polar cap data?**
  - Empirical models provide only statistics
  - Physics-based models not yet predictive
  - Significant event-by-event variability

- **Accounting for expected correlations**
  - Derive pol-tor models of $\mathbf{B}$ and $\mathbf{J}$ for given IMF & solar wind conditions (with K.M. Laundal and N. Olsen)
  - Find expected data error correlations
  - Build data covariance matrices



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- Even for 'quiet' conditions: **polar cap disturbance ΔF strong & well-organized**.
- Clear opportunity for detailed studies of polar cap currents with Swarm and CHAMP.
- Challenging 'noise' source for internal field studies despite high quality data.
- Internal field modelling needs to improve to **better reflect the unmodelled sources**.

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Olsen, N., Luehr, H., Finlay, C. C., Sabaka, T. J., & Tø ffner Clausen, L., 2014. The CHAOS-4 geomagnetic field model, *Geophys. J. Int.*, **197**(2), 815–827.

Sabaka, T. J., Olsen, N., & Langel, R. A., 2002. A comprehensive model of the quiet-time, near-earth magnetic field: phase 3, *Geophys. J. Int.*, **151**, 32–68.

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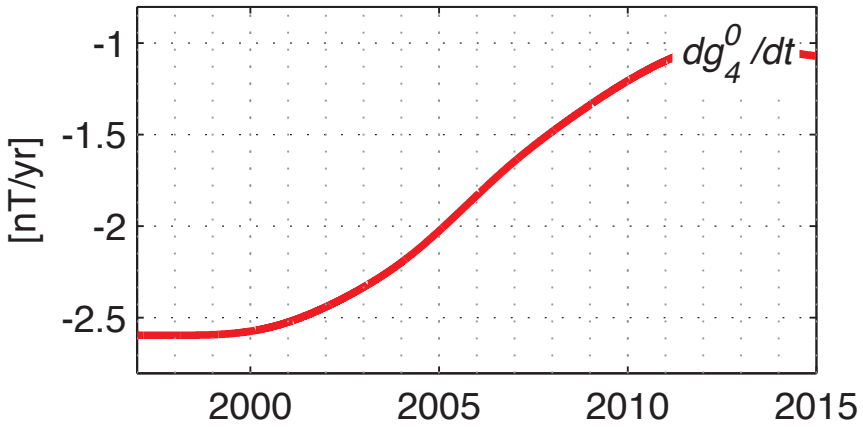
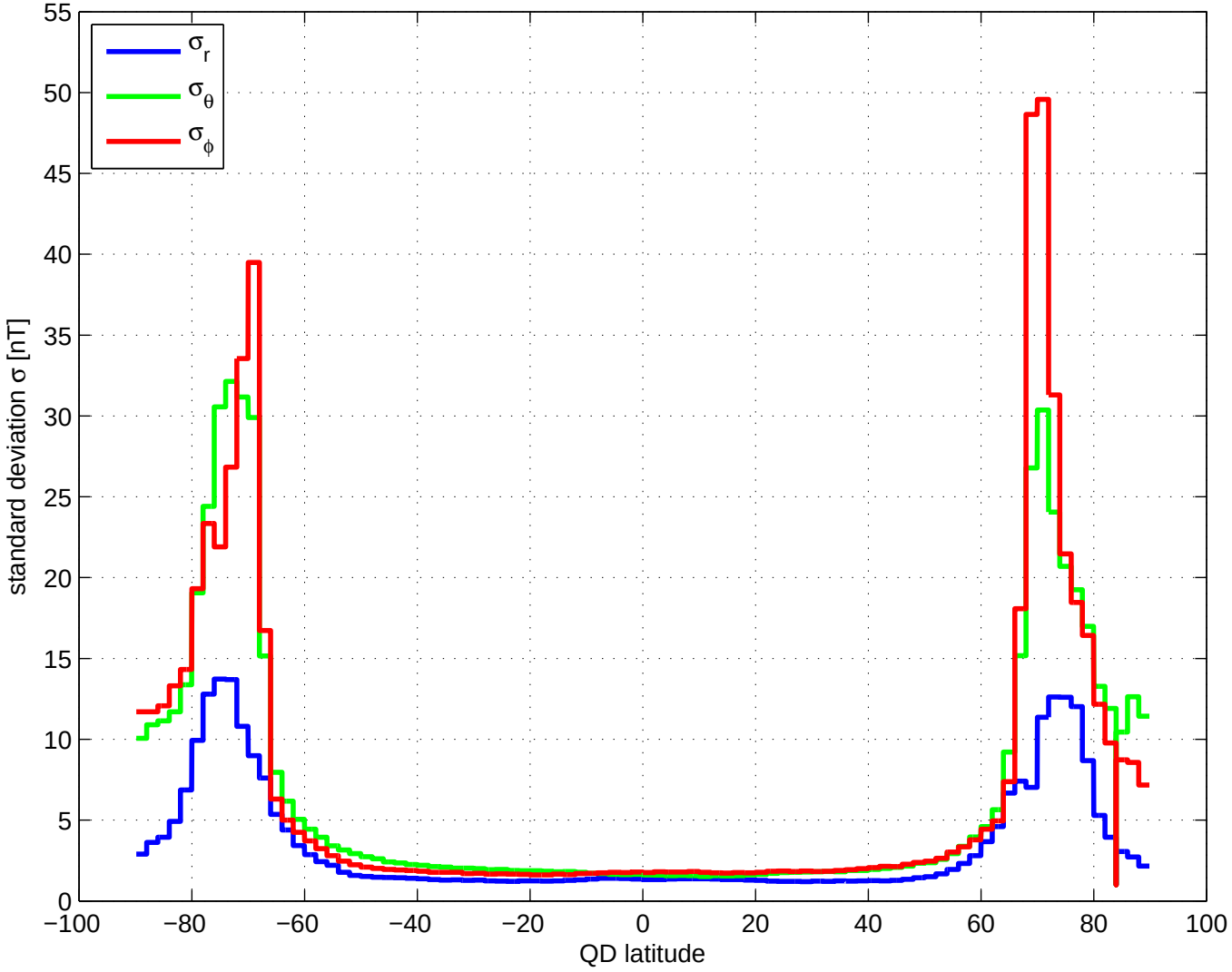
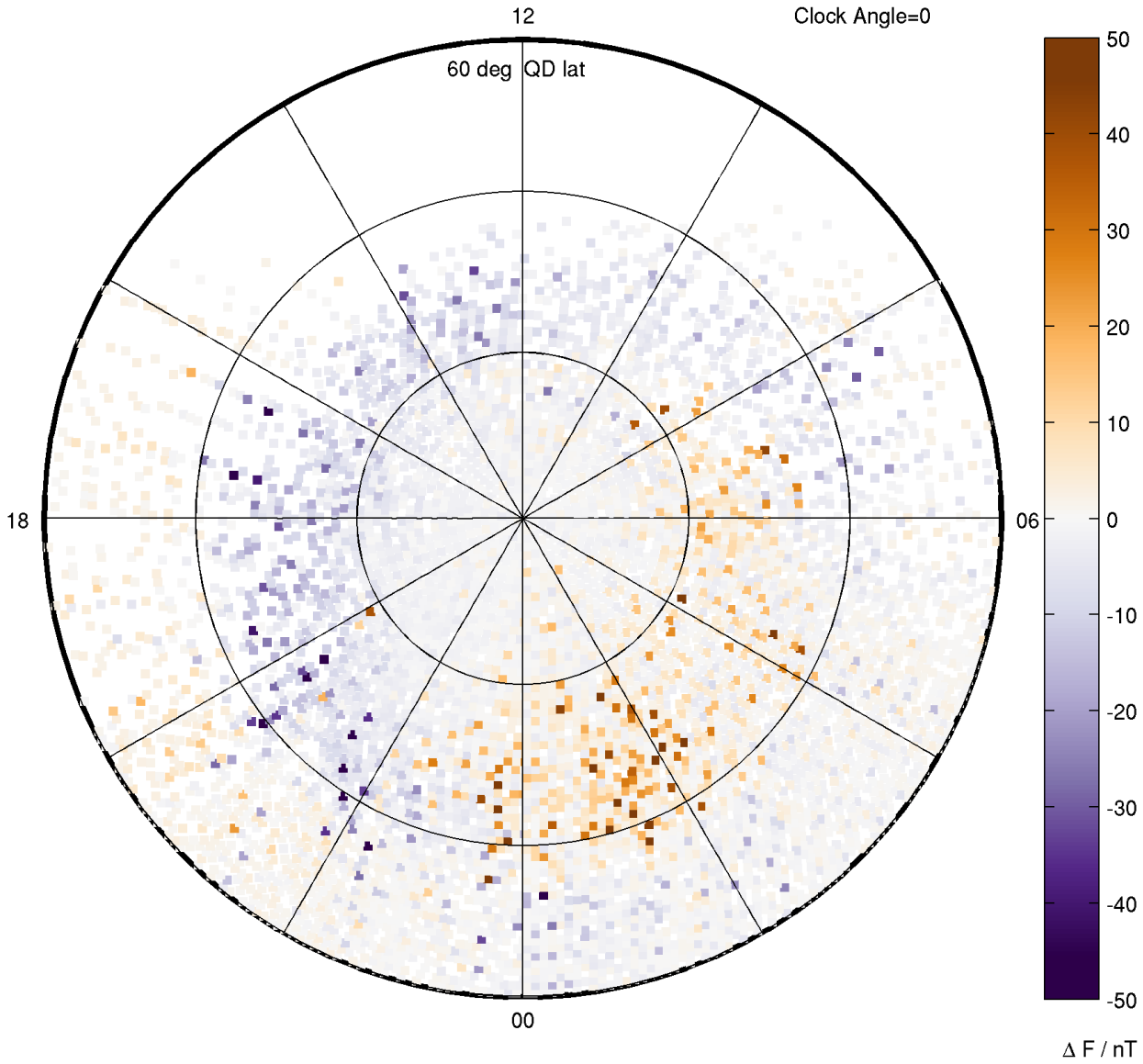


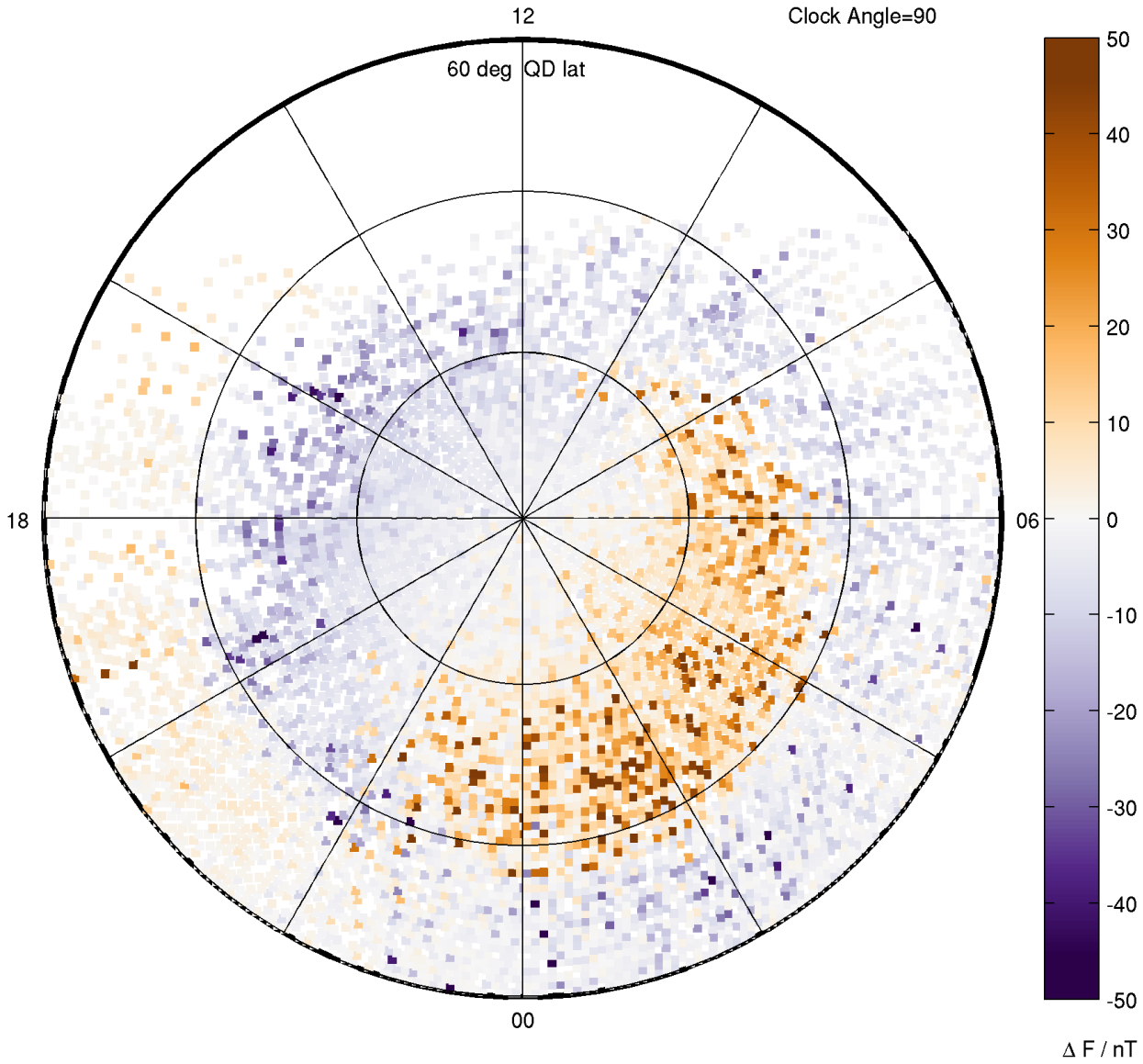
Latitude dependent rms residuals, CHAMP vector data



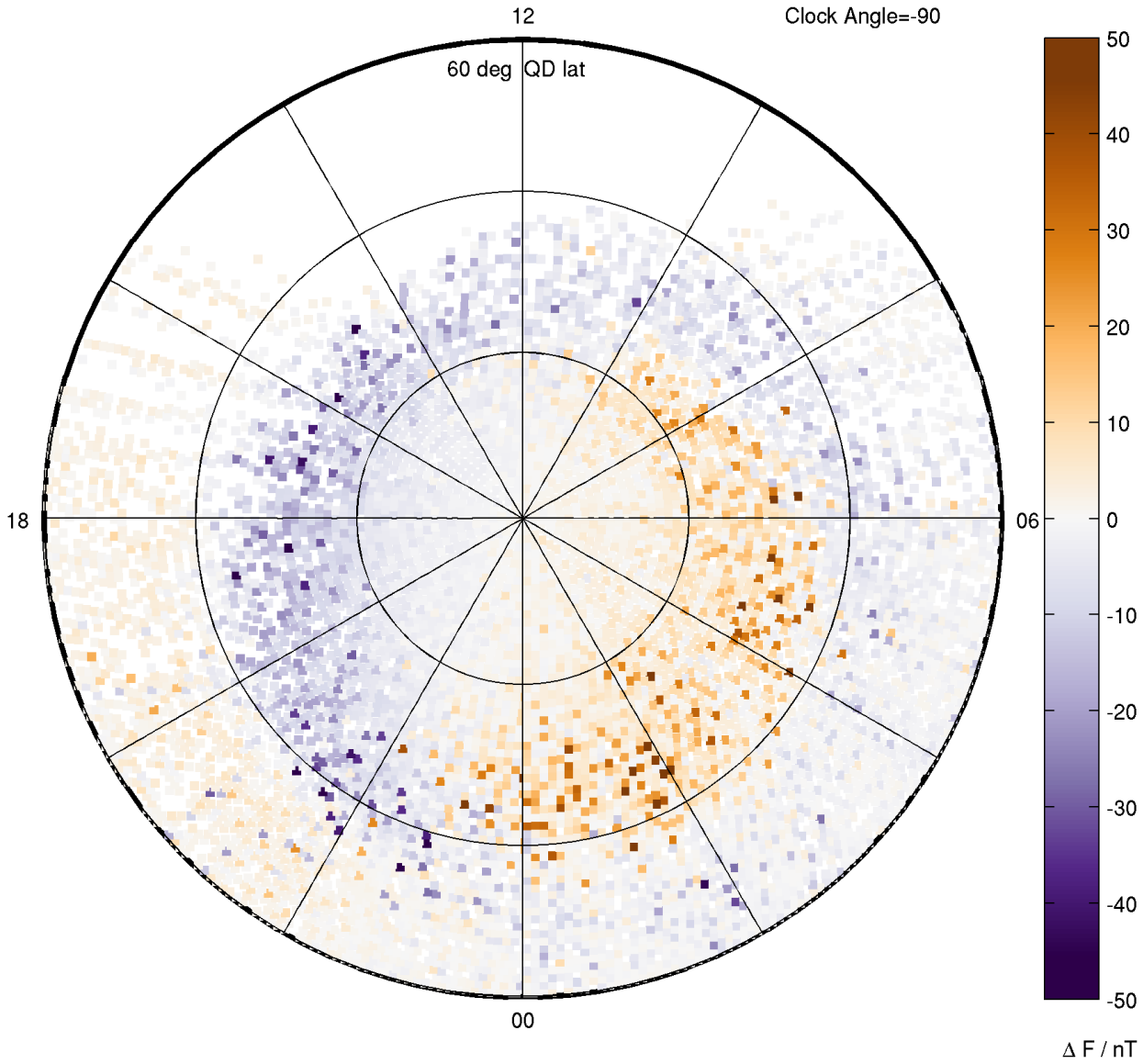
CHAMP, NH, ΔF, IMF clock angle 0 deg



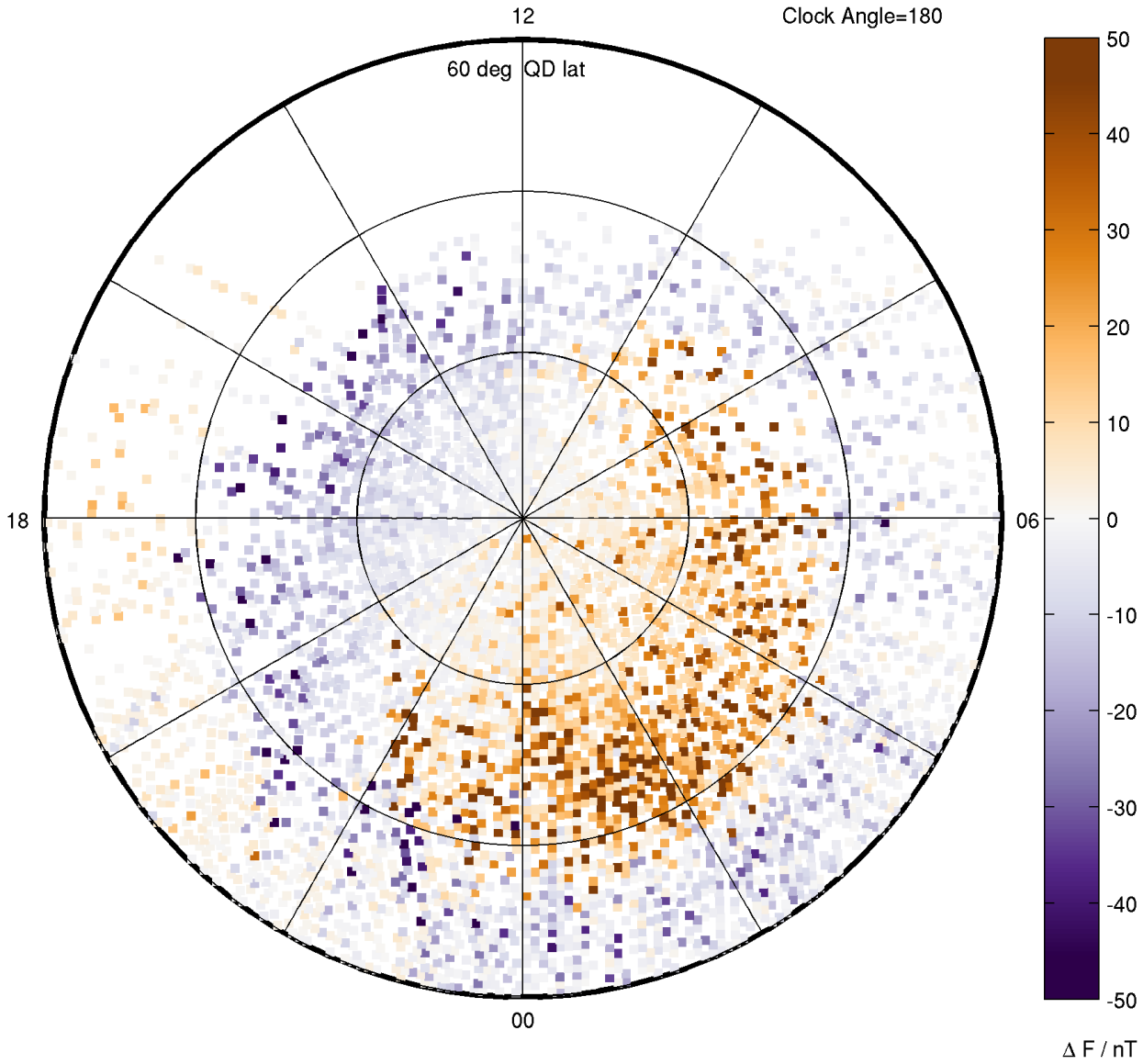
CHAMP, NH, ΔF, IMF clock angle 90 deg



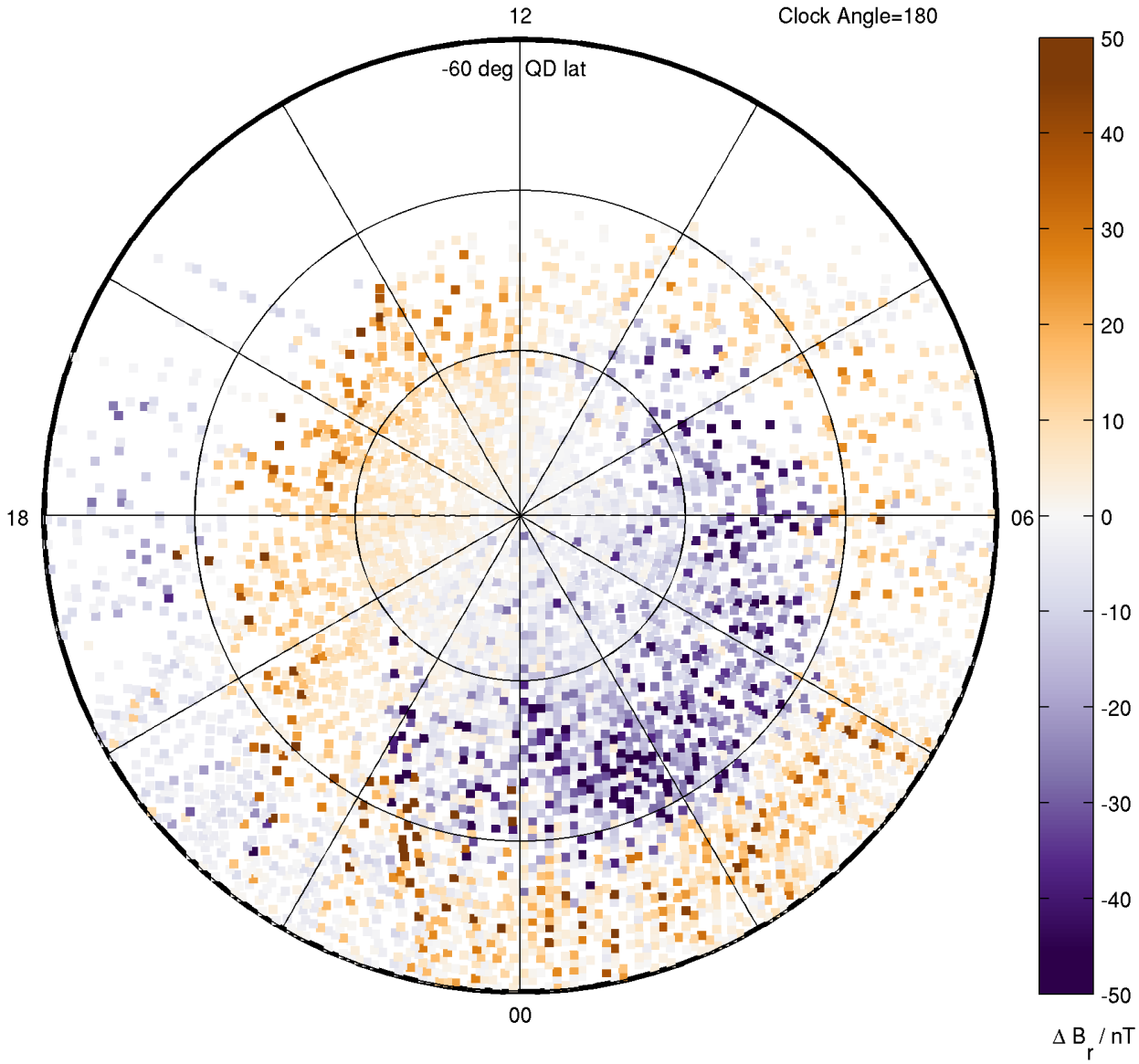
CHAMP, NH, ΔF, clock angle 270 deg



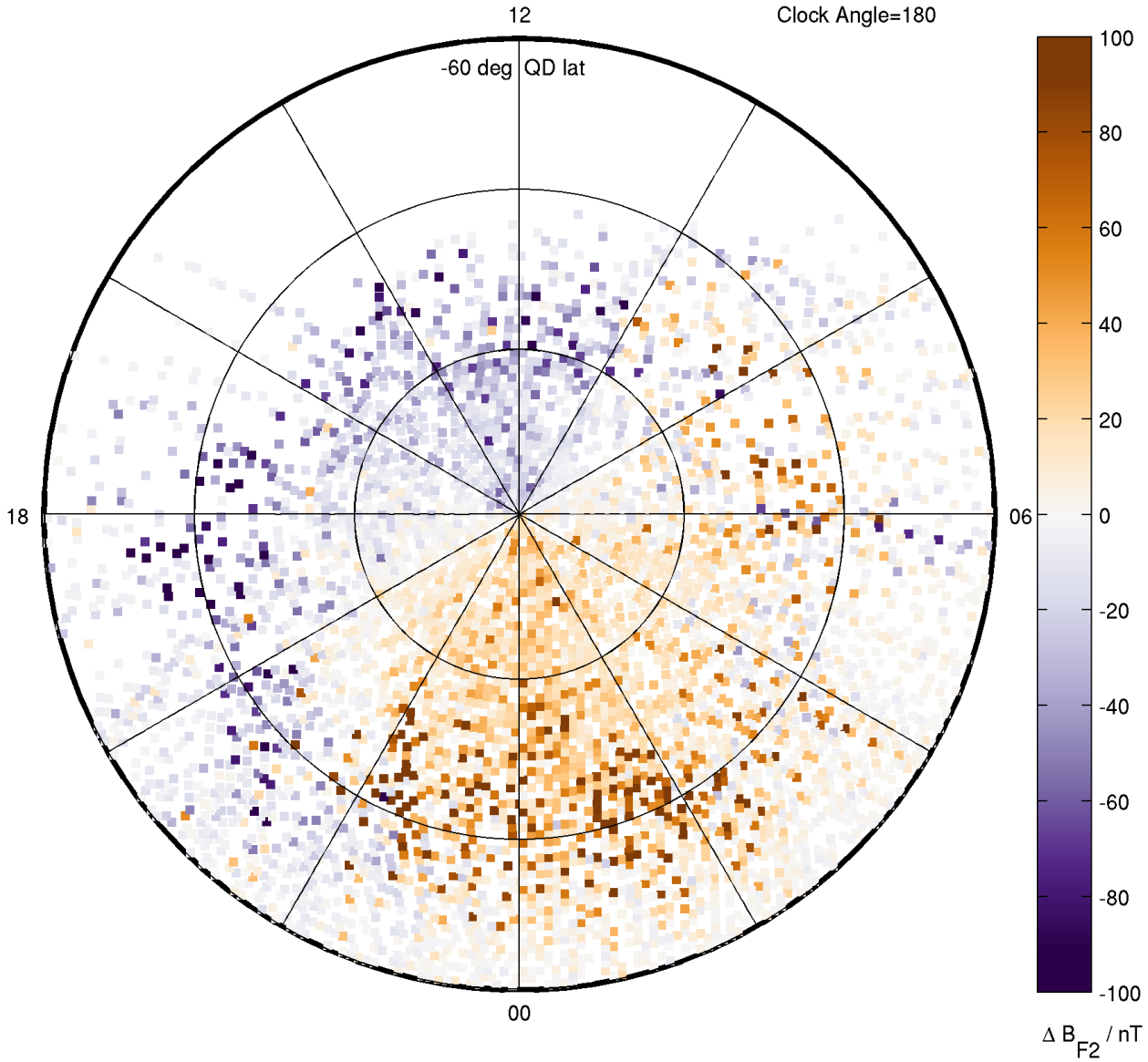
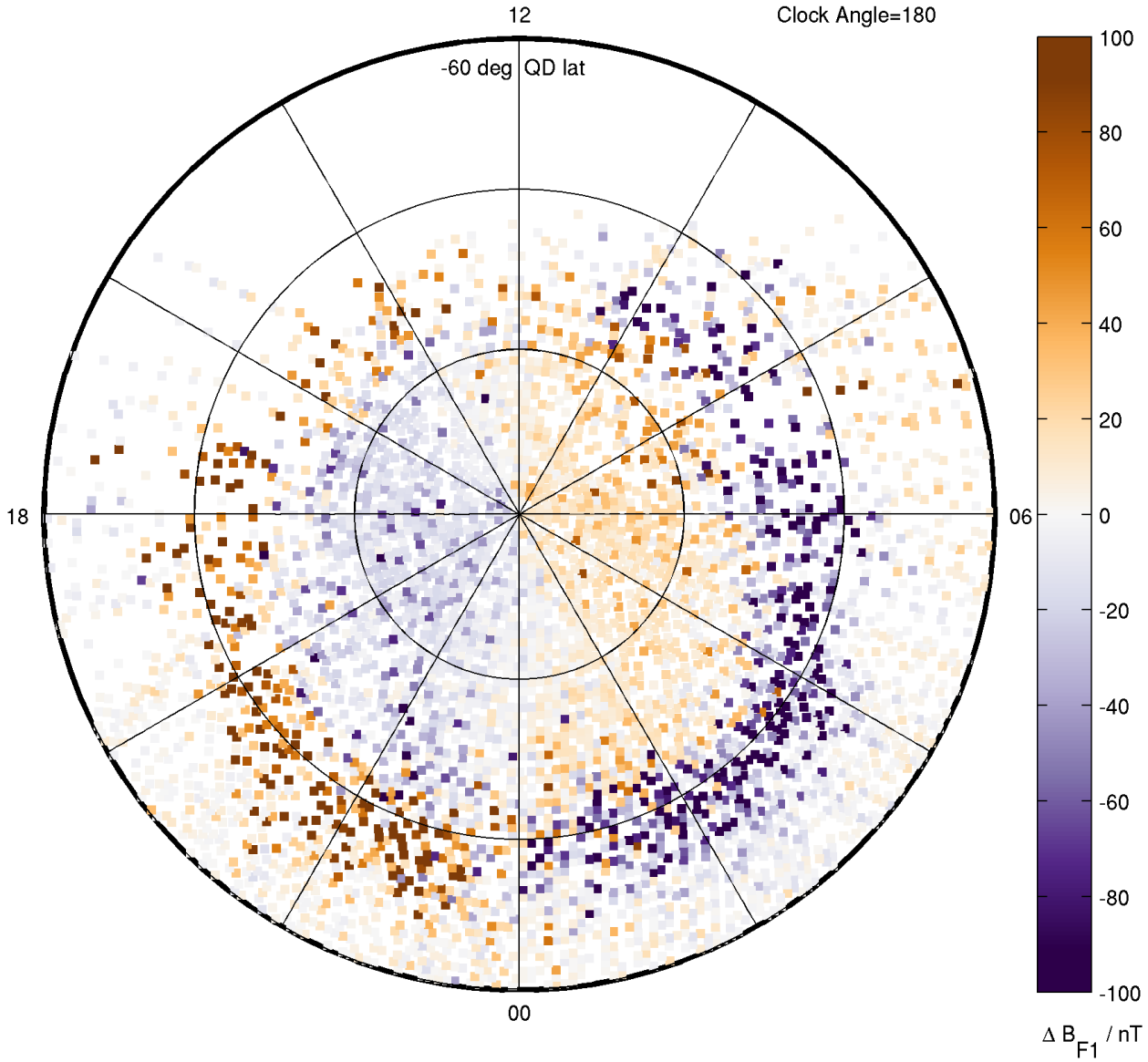
CHAMP, NH, ΔF, IMF clock angle 180 deg



CHAMP, NH, ΔB_r, clock angle 180 deg



CHAMP, NH, ΔB_{QD-NS}, clock angle 180 deg



CHAMP, NH, ΔB_{QD-EW}, clock angle 180 deg