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Core field evolution from a decade of observations by the *Swarm* satellites

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With thanks to: Nils Olsen & Lars Tøffner-Clausen

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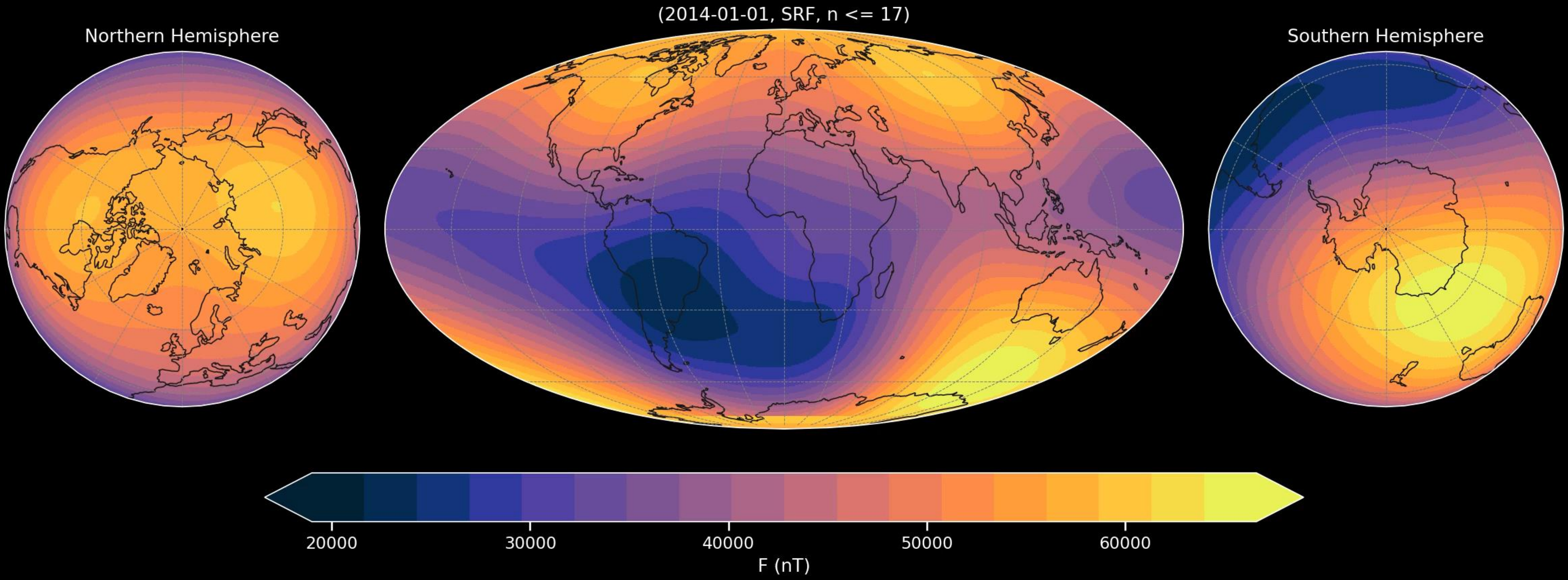
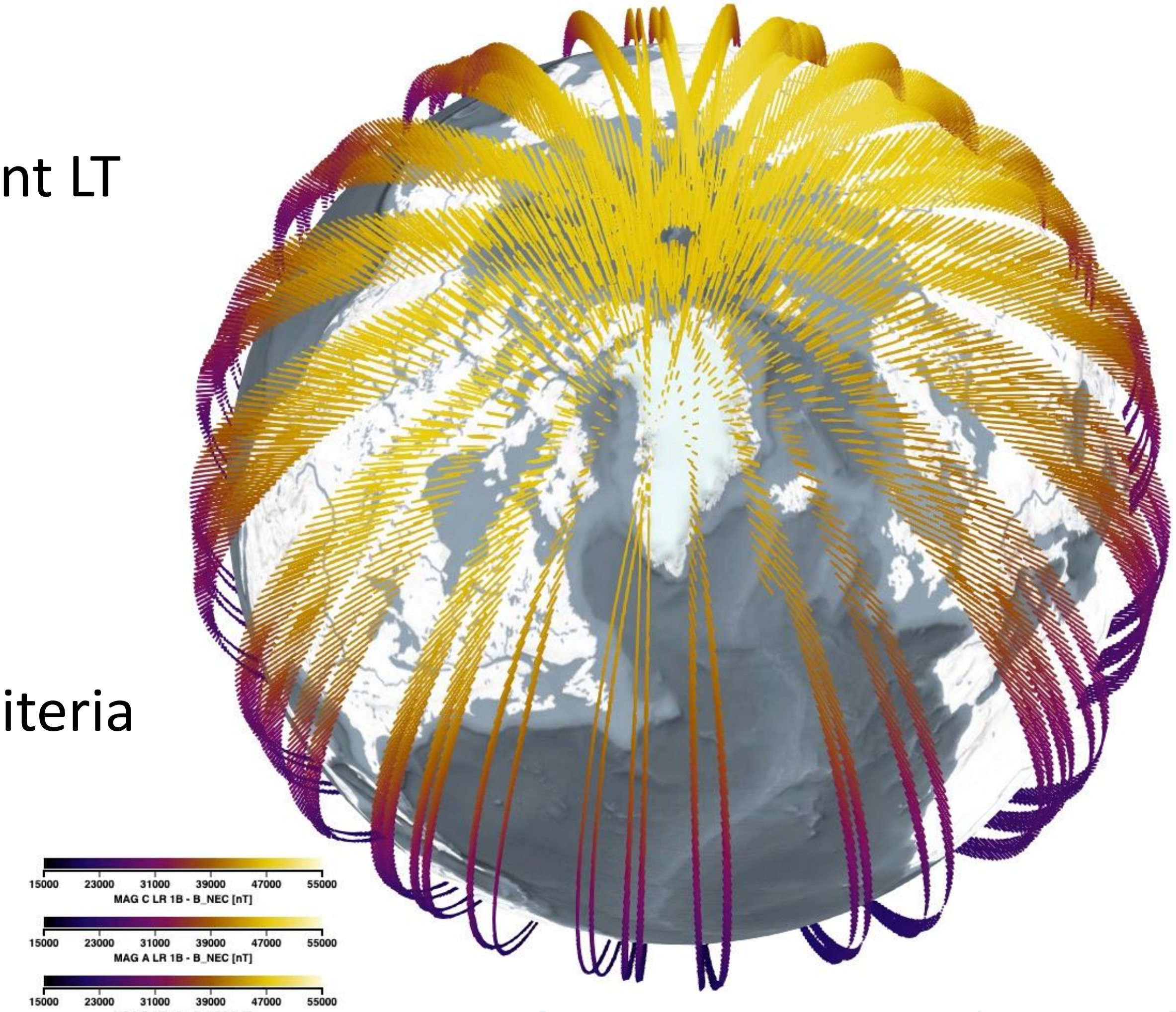
Evolution of magnetic field intensity at Earth's surface



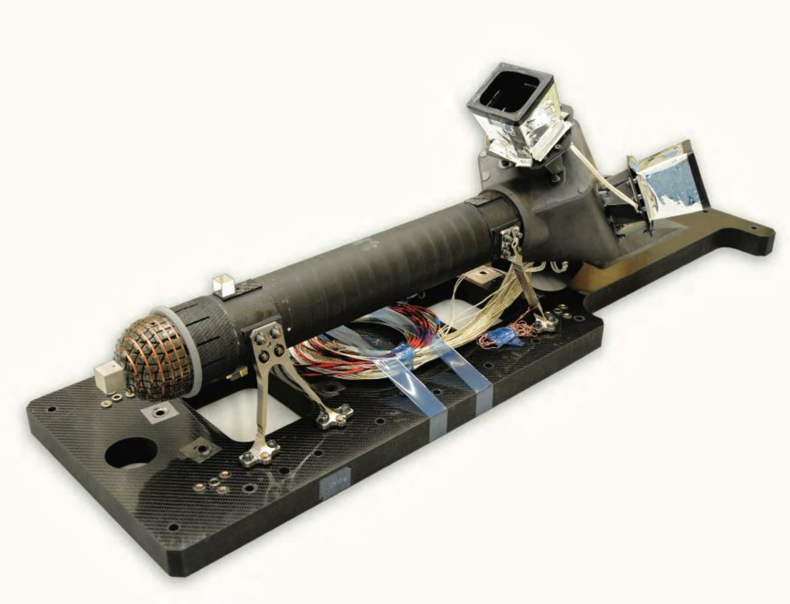
A decade of high quality magnetic observations

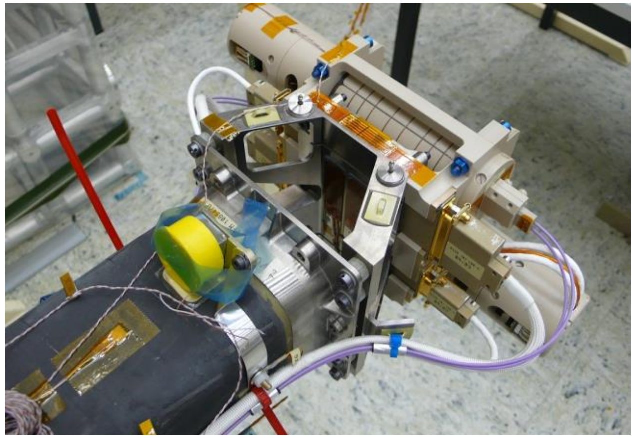
- 3 satellites: Lower pair (A, C) & B at different LT
- Gradients along track and EW btw A,C pair
- Almost complete data availability
  (< 1 day per year per satellite missing)
- Excellent coverage allows us to use strict criteria for geomagnetically quiet conditions



[Produced using VirES for Swarm]

A decade of high quality magnetic observations





- Excellent vector magnetometers
  [CSC pioneered by F. Primdahl, P. Bauer, J. Merayo et al.]
- Non-magnetic star-trackers
  [J. Jørgensen et al.]
- Absolute scalar magnetometers
  [J.M. Leger et al.]
- In-flight calibration
  [N. Olsen, L. Tøffner-Clausen et al.]
- Empirical and physical corrections for spacecraft disturbances
  [P. Brauer, L. Tøffner-Clausen , V. Lesur]

Modelling the time-dependent core field

- **Time-dependent potential field modelling**

$$\mathbf{B} = -\nabla V \qquad \text{where} \quad V = V^{int} + V^{ext}$$

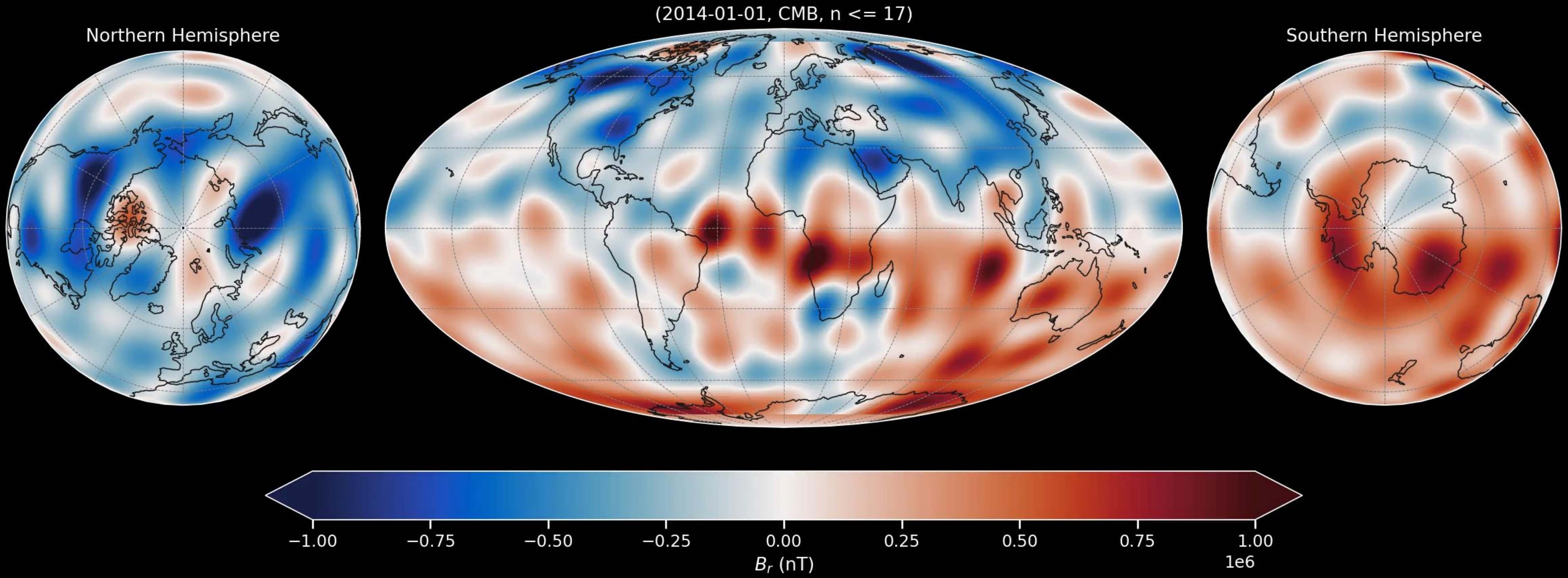
$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m \cos m\phi + h_n^m \sin m\phi \right) \left(\frac{a}{r} \right)^{n+1} P_n^m (\cos\theta) \quad \text{and} \quad g_n^m(t) = \sum_{k=1}^{K} g_{n,k}^m B_k(t)$$

- **CHAOS-type** field modelling approach [Olsen et al. 2006, 2014]:
  - Satellite magnetic measurements in instrument frame
  - Use data from night-side & geomagnetically quiet times
  - Magnetospheric field model (SM/GSM parts + Earth induced counterparts)
  - Robust estimation with temporal regularization (3rd time deriv, 2nd time deriv at ends)

- Estimate separate models for core and lithospheric fields [Otzen et al. 2024]
- Vector, scalar & gradient data: **Swarm A,B,C 2014 - 2024**, 15s sampling + Ground Obs

- **8,074,818** data in all; **27,874** model params
- Huber-weighted RMS misfits at mid/low lats: ΔB_r =**1.47nT**, ΔB_θ= **2.54nT**, ΔB_ϕ= **2.20 nT**

Radial field evolution at Core-Mantle Boundary



Core field morphology and evolution

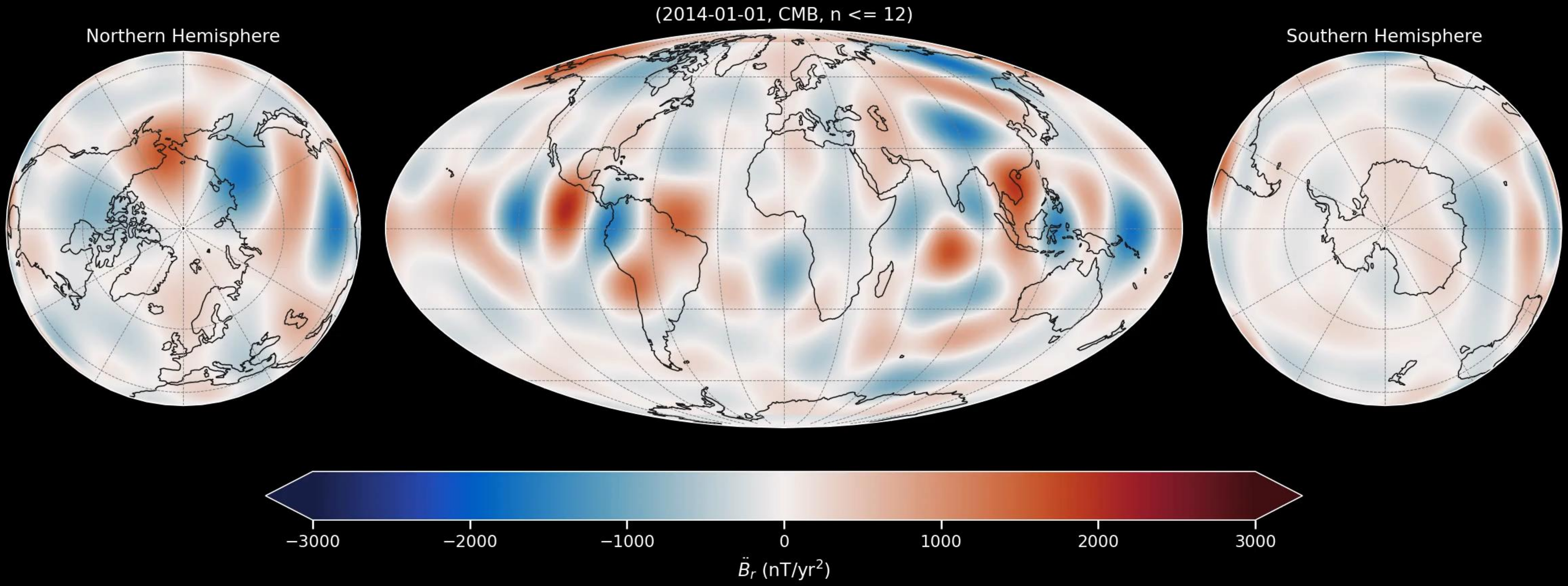
- **At low latitudes: intense westward drifting features occur in oppositely signed pairs**
- Similar features in simulations occur through expulsion of intense azimuthal field close to CMB [Aubert et al., 2013]

- **In north and south polar regions: field evolution is surprisingly rapid and asymmetric**
- May indicate intense convection in northern polar region [e.g. Schaeffer et al., 2017]

- **South Atlantic weak field region associated with CMB reversed flux patches** [Gubbins et al. 1987, Finlay et al. 2020]
- Origin remains unclear but may be somehow connected to large-scale gyres?

- To learn about underlying flow dynamics need to look at field derivatives…..

Radial field secular acceleration at CMB

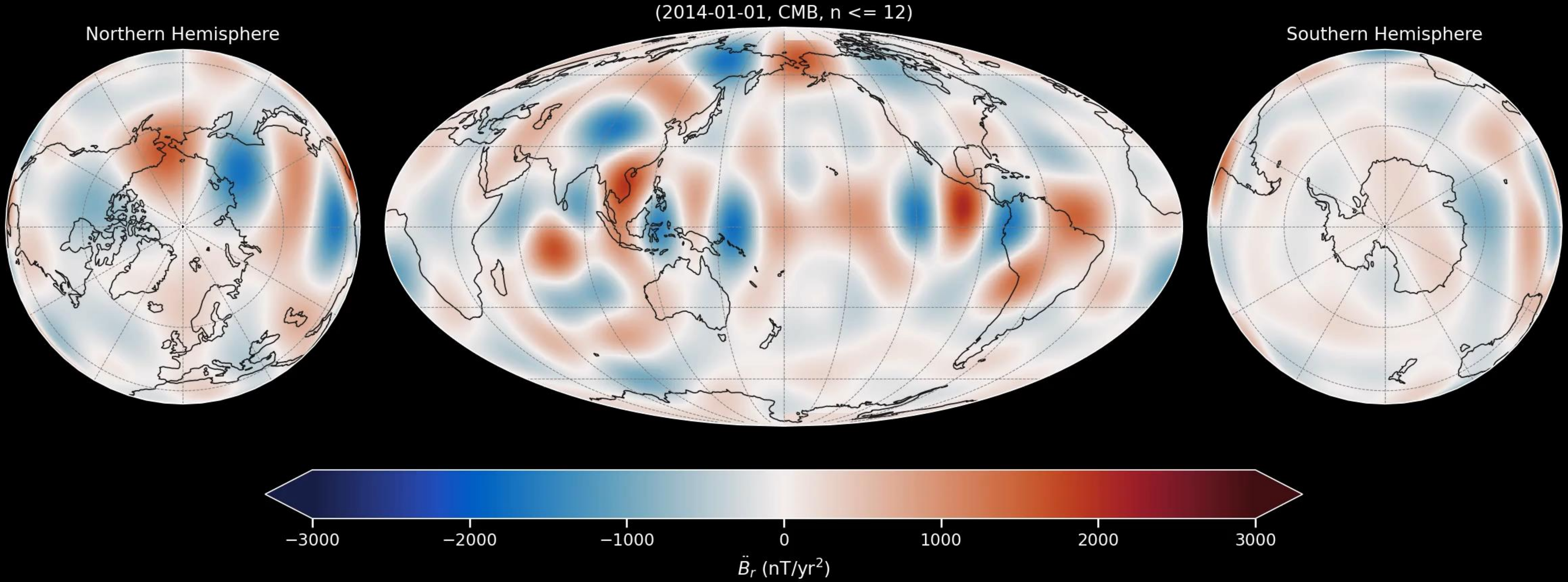


(2014-01-01, CMB, n <= 12)

Northern Hemisphere

Southern Hemisphere

Radial field secular acceleration at CMB



Insights into rapid core dynamics & waves

- **North and South polar regions show very different dynamics**
- Strong activity in the Northern polar region now appears to be weakening
- Acceleration of intense flows (jet) under Canada and Siberia slowing? [e.g. Livermore et al. 2017]

- **Significant field variability in the low latitude Pacific region**
- Clear evidence for **wave propagation** in this region [Gillet et al., 2022, Lesur et al. 2023]

- Understanding such waves is necessary to better predict future field evolution.
  But how are they driven, what is role of underlying core field & mantle conductivity?
  [Talks by F. Gerick, O. Barrois, D. Jault, Poster by J. Min]

Present limitations and possible remedies

- **Length of high quality time series remains short**

  -> Fully utilize MAGSAT, Ørsted, CHAMP + ground obs.

  -> Huge benefits from a long mission, esp. *Swarm* B

- **Uncertainties in field models under-estimated**

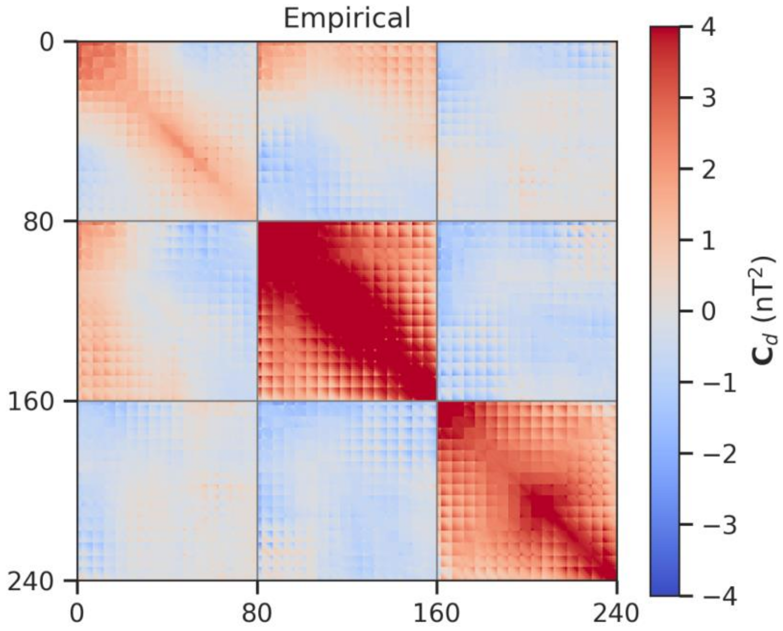
  -> Better account for correlations in unmodelled fields [Poster by C. Kloss]

- **Separation of higher frequency core signals**

-> Better modelling and separation of LT dependent ionospheric and magnetospheric fields

-> Use of more realistic temporal priors in field models

-> Next generation missions: MSS-1+ [K. Zhang et al.], NanoMagSat [G. Hulot et al.]



Summary

- Swarm satellites provide us with 10 years+ of high quality data to study the evolution of Earth’s core magnetic field

- Insights include:
  - **Continued growth of SAA and links to reversed flux at CMB**
  - **North and South polar regions have very different dynamics**
  - **Waves at low latitudes, including under the Pacific**

- Improved understanding relies on advances in geodynamo simulations and theory

- Still much to be understood; many opportunties as time series lengthens and with complementary data arriving from new missions