Swarm Satellite Constellation Application and Research Facility: Status and Plans

Alan W P Thomson[3]

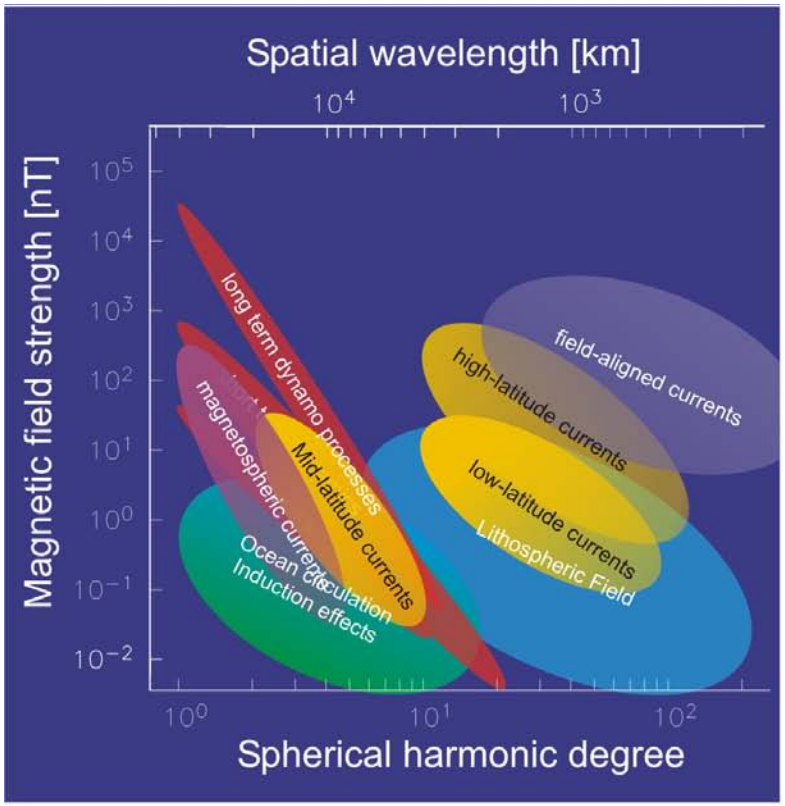
and

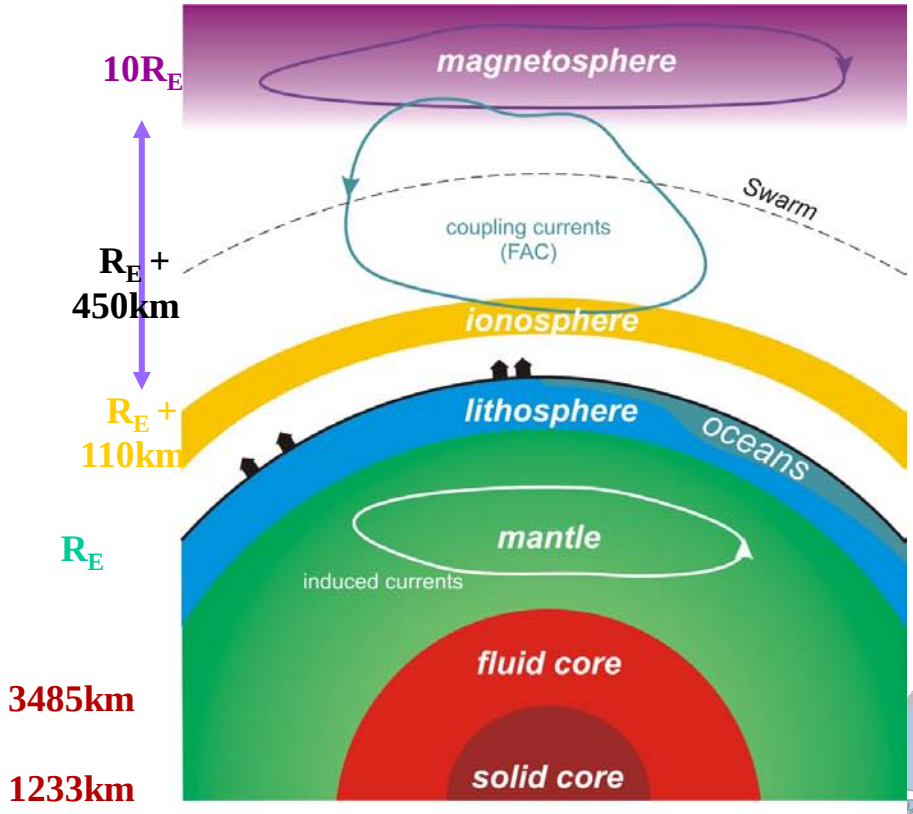
Patrick Alken[2,8], Ciaran Beggan[3], Arnaud Chulliat[2], Eelco Doornbos[4], Rune Floberghagen[5], Eigil A Friis-Christensen[1], Brian Hamilton[3], Gauthier Hulot[2], Jose van den IJssel[4], Alexei V Kuvshinov[6], Vincent Lesur[7], Hermann Luhr[7], Susan Macmillan[3], Stefan Maus[8], Nils Olsen[1], Poul Erik H Olsen[1], Jaeheung Park[7], Gernot Plank[9], Patricia Ritter[7], Martin Rother[7], Terence J Sabaka[10], Claudia Stolle[1], Erwan Thebault[2], Lars Tøffner-Clausen[1], Jakub Velimsky[11], Pieter N Visser[4]

[1]**DTU Space**, Technical University of Denmark, Copenhagen, Denmark.

[2]**IPGP**, Paris, France. [3]**BGS**, Edinburgh, United Kingdom. [4]**DEOS**, Delft, Netherlands. [5]**ESRIN, ESA**, Frascati, Italy. [6]**ETH**, Zurich, Switzerland. [7]**GFZ**, Potsdam, Germany. [8]**NOAA**, Boulder, CO, United States. [9]**ESTEC, ESA**, Noordwijk, Netherlands. [10]**GSFC**, Greenbelt, MD, United States. [11]**CUP**, Prague, Czech Republic.

Geomagnetic Field Sources





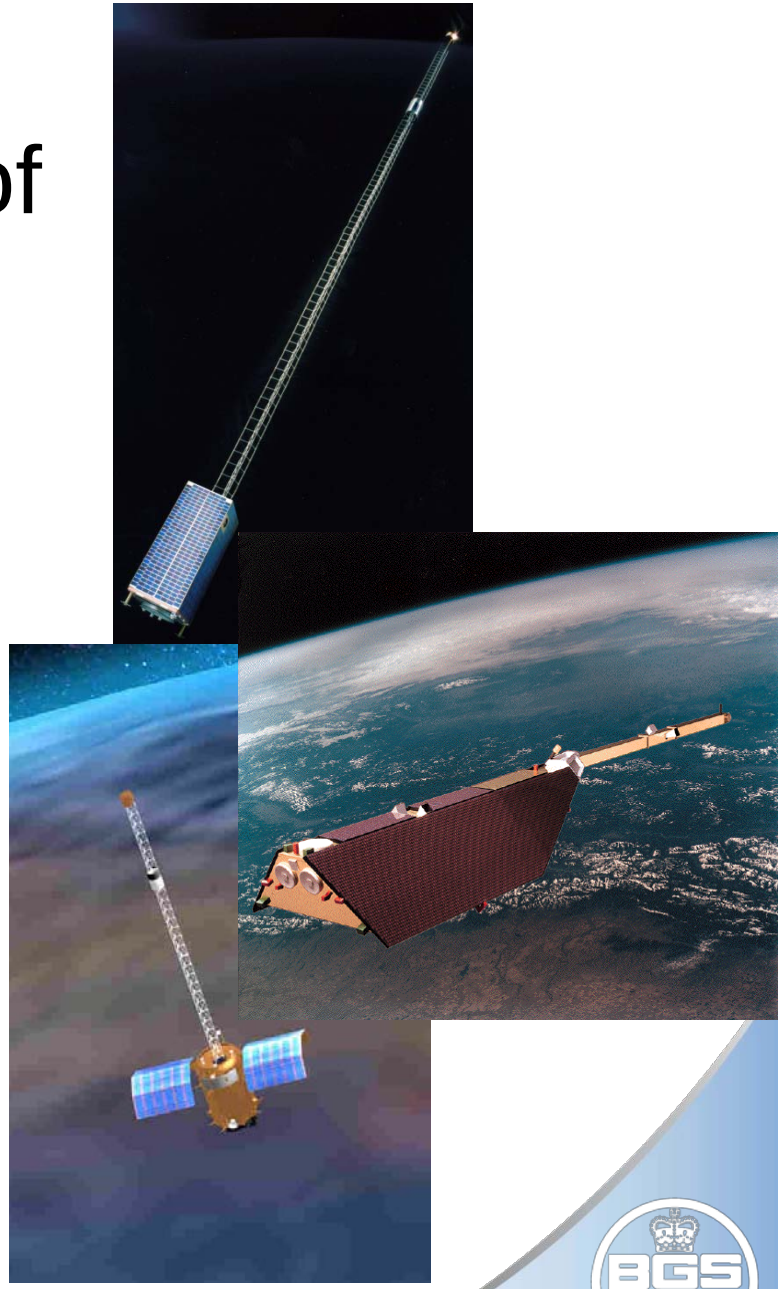
21st Century Satellites Measuring All Sources of Earth's Magnetic Field

- Ørsted
  Launched on 23th February 1999
  Polar orbit, 650-850 km altitude
  all local times within 790 days (2.2 years)
  - Currently only occasional scalar data

- CHAMP
  Launched on 15th July 2000
  low altitude (<300 - 450 km)
  all local times within 130 days
  - De-orbited September 2011

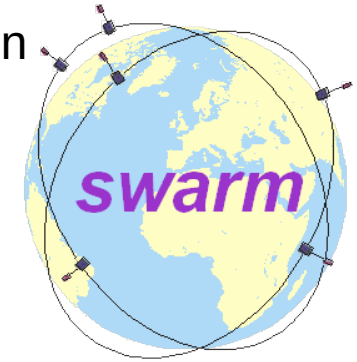
- SAC-C
  Launched on 21th November 2000
  700 km altitude, fixed local time $10^{30}/22^{30}$
  (no vector data due to payload failure)

single-satellite missions,
no explicit advantage of multi-point observations in space

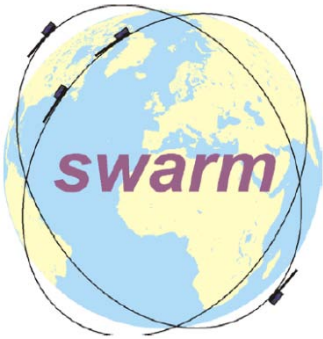


Swarm History

- 1998: First Proposal for ESA Earth Explorer Opportunity Mission
  - Consortium of 16 European institutes led by DTU Space
  - Consists of 6 “Ørsted-type” satellites in two orbital planes
  - Proposal ranked no 4 out of 27



- 2002: Second proposal
  - 4 “CHAMP-type” satellites



- 2002-2004: Phase A
  - End-to-End Mission simulation
  - Reduction to 3 satellites: 2 lower flying side-by-side plus one at higher altitude

“mature …

… and innovative”

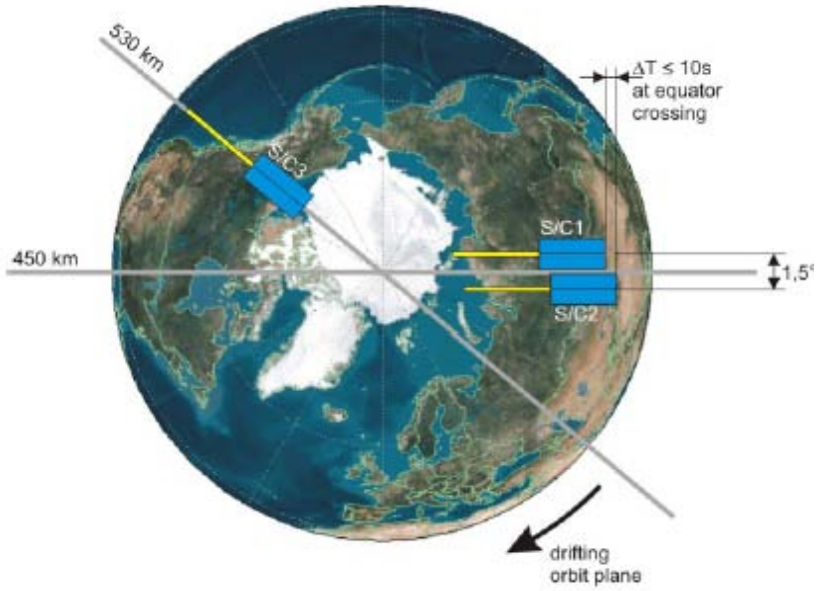
technology and payload (Ørsted and CHAMP)

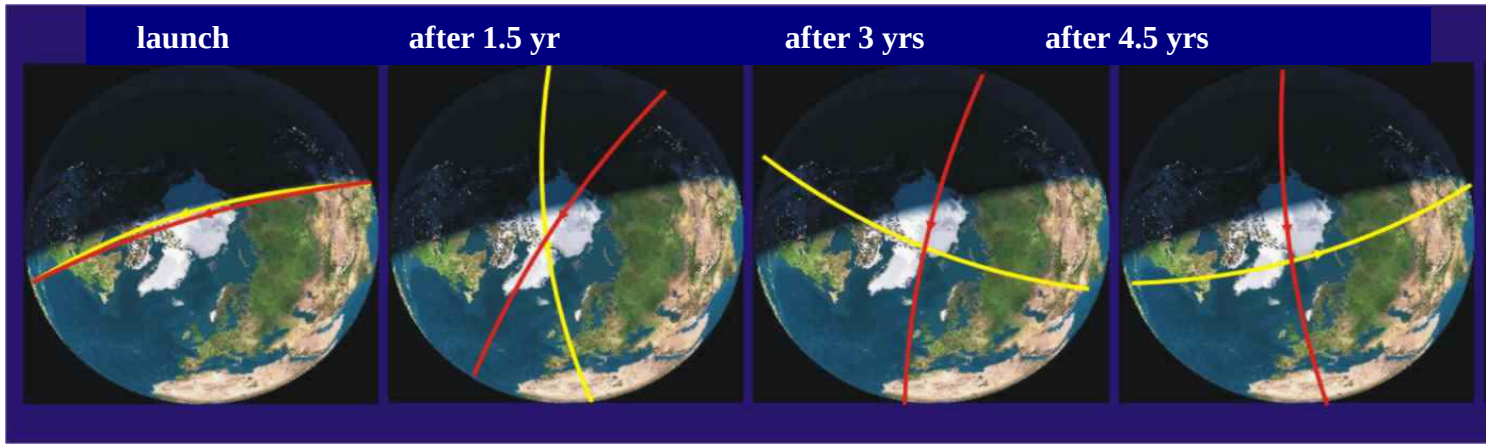
constellation aspect and science

- May 2004: selection by ESA for full implementation
- **Launch: 17th July 2012**

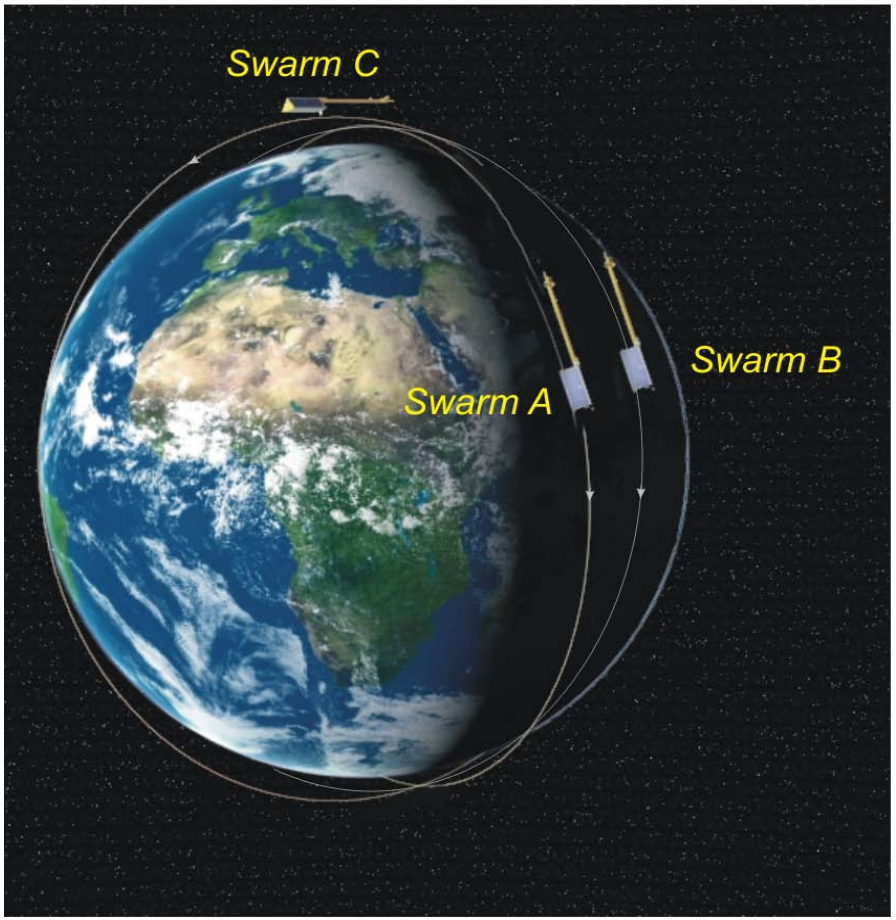
Constellation of Three Satellites

- >4 years operational phase
- Altitude of lower pair down to 300 km (or lower) for “zoom” on crustal signal
- Altitude of 3rd satellite: 530 km
- 24 hours LT coverage within 7-10 months
- Inclination difference: drift of orbital planes

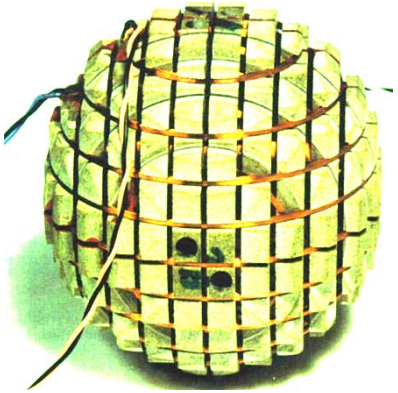


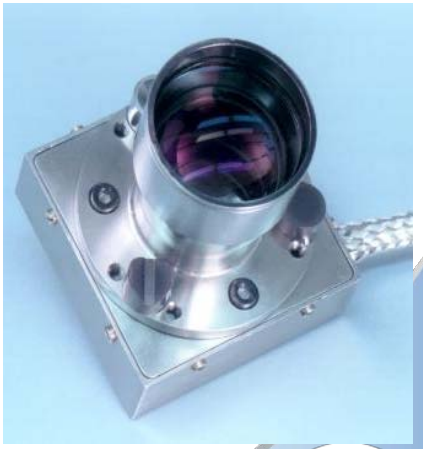


Each *Swarm* Satellite*:* Heritage from Ørsted and CHAMP



- Vector magnetometer
- Scalar magnetometer
- Triple-head star sensor
- Electric field instrument
- Accelerometer
- GPS receiver





Swarm Science Topics

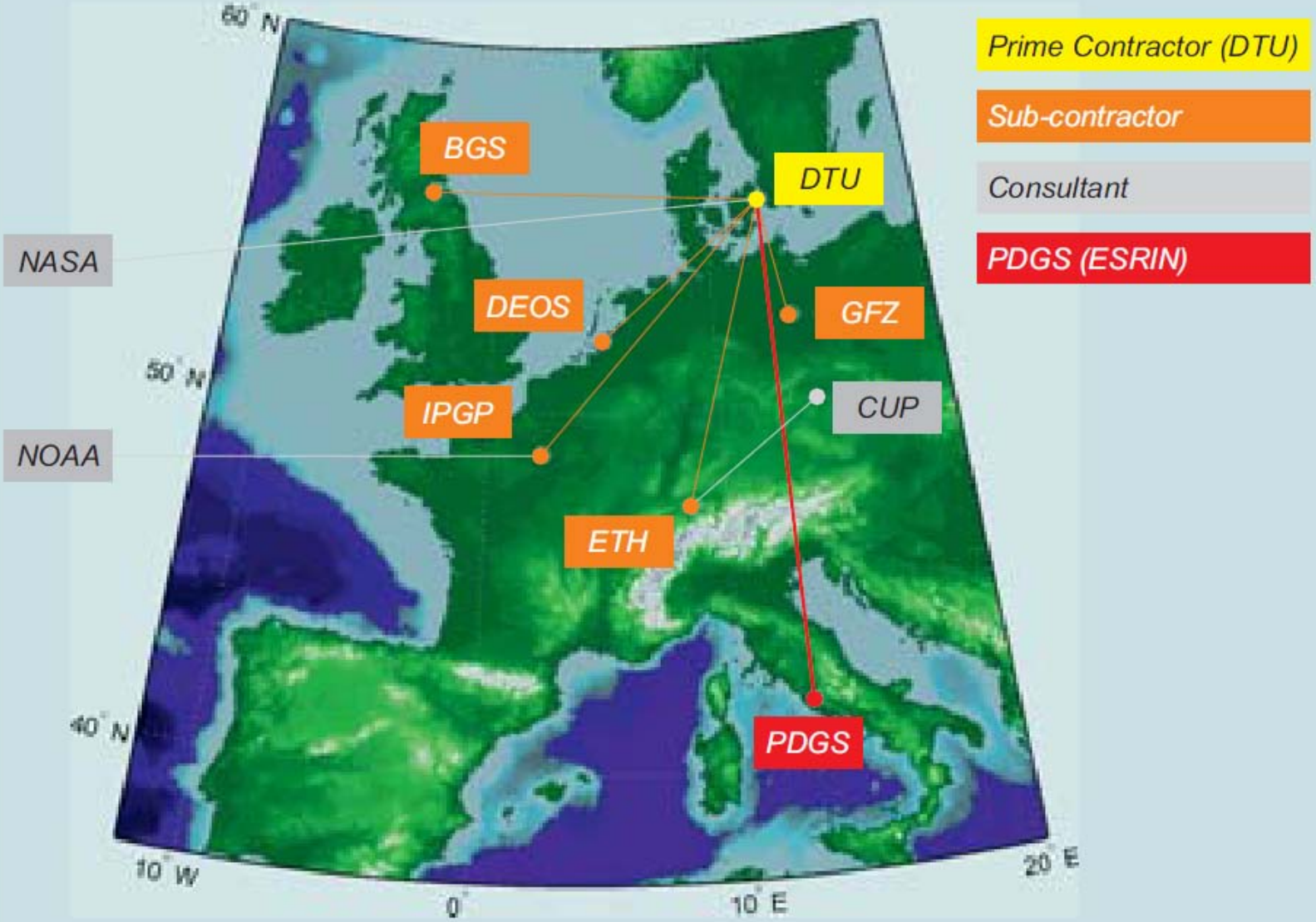
- Core Field and Temporal Variations
  - Determination of space-time structure of core field and its changes
- Lithospheric Magnetisation
  - Determination of the small-scale crustal field
- Electrical Conductivity of the Mantle
  - Global 1D conductivity model
  - Lateral variations of conductivity
- Earth's Electrodynamic Environment
  - Ionospheric, magnetospheric and field-aligned currents
  - *F*-region plasma bubbles, ionospheric profiling (TEC)
- (Space Weather Applications)

SCARF – Structure & Purpose

- ESA has established a “Satellite Constellation Application and Research Facility” (SCARF), as a consortium of several research institutions to produce high quality science (‘Level-2’) products
  - To aid exploitation of Swarm data stream
  - To help scientific community exploit Swarm during the mission by providing reference field models and products

- Level-2 products, delivered through the Level-2 Processing System (L2PS) will include
  - models of the core, lithospheric, ionospheric and magnetospheric fields
  - derived parameters such as mantle conductivity, thermospheric mass density and winds, field-aligned currents, an ionospheric plasma bubble index, the ionospheric total electron content and the dayside equatorial zonal electrical field
  - CAT-1 (SCARF: scientist-in-the-loop) and CAT-2 (ESRIN: automated)

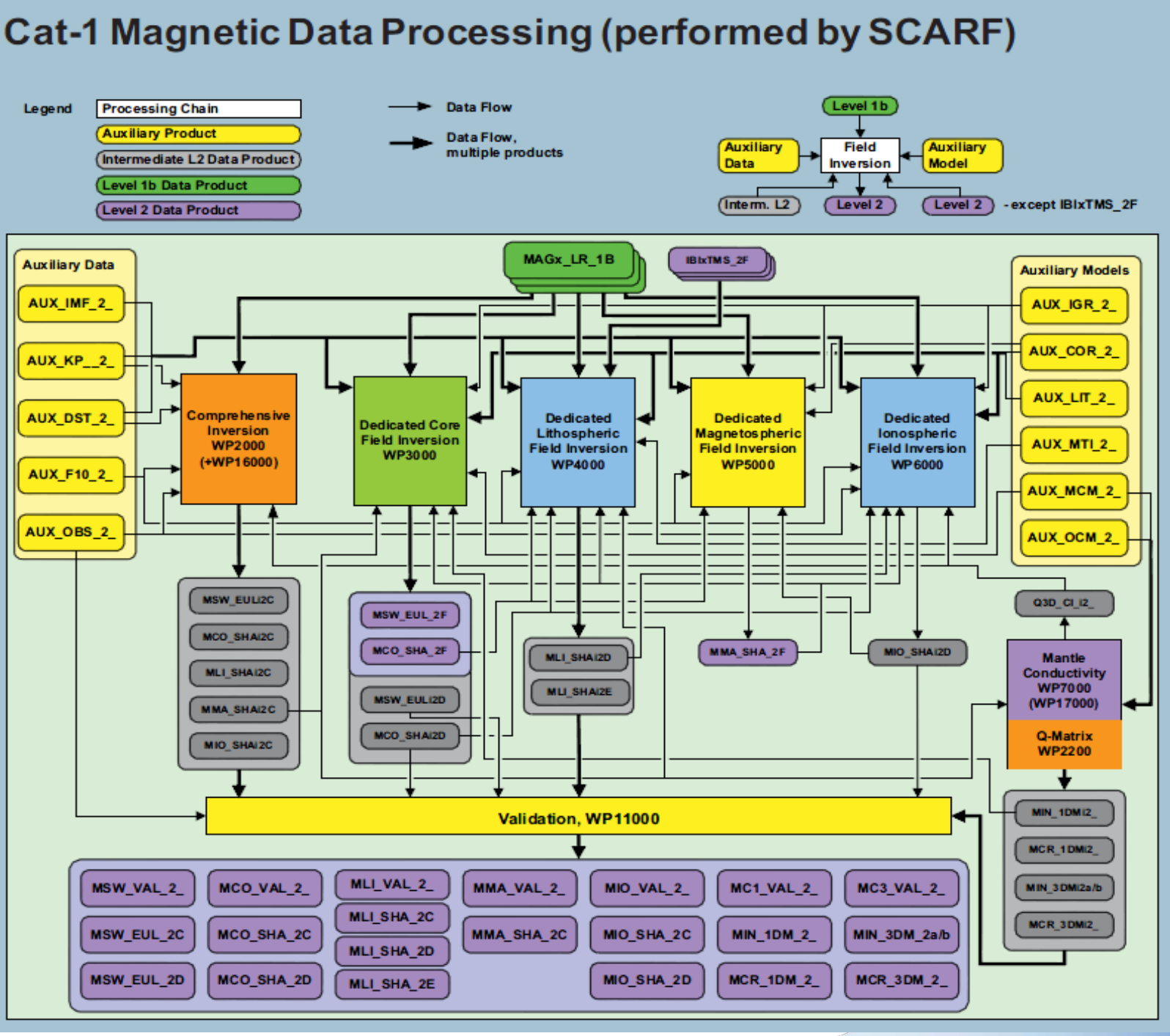
The Partners of SCARF



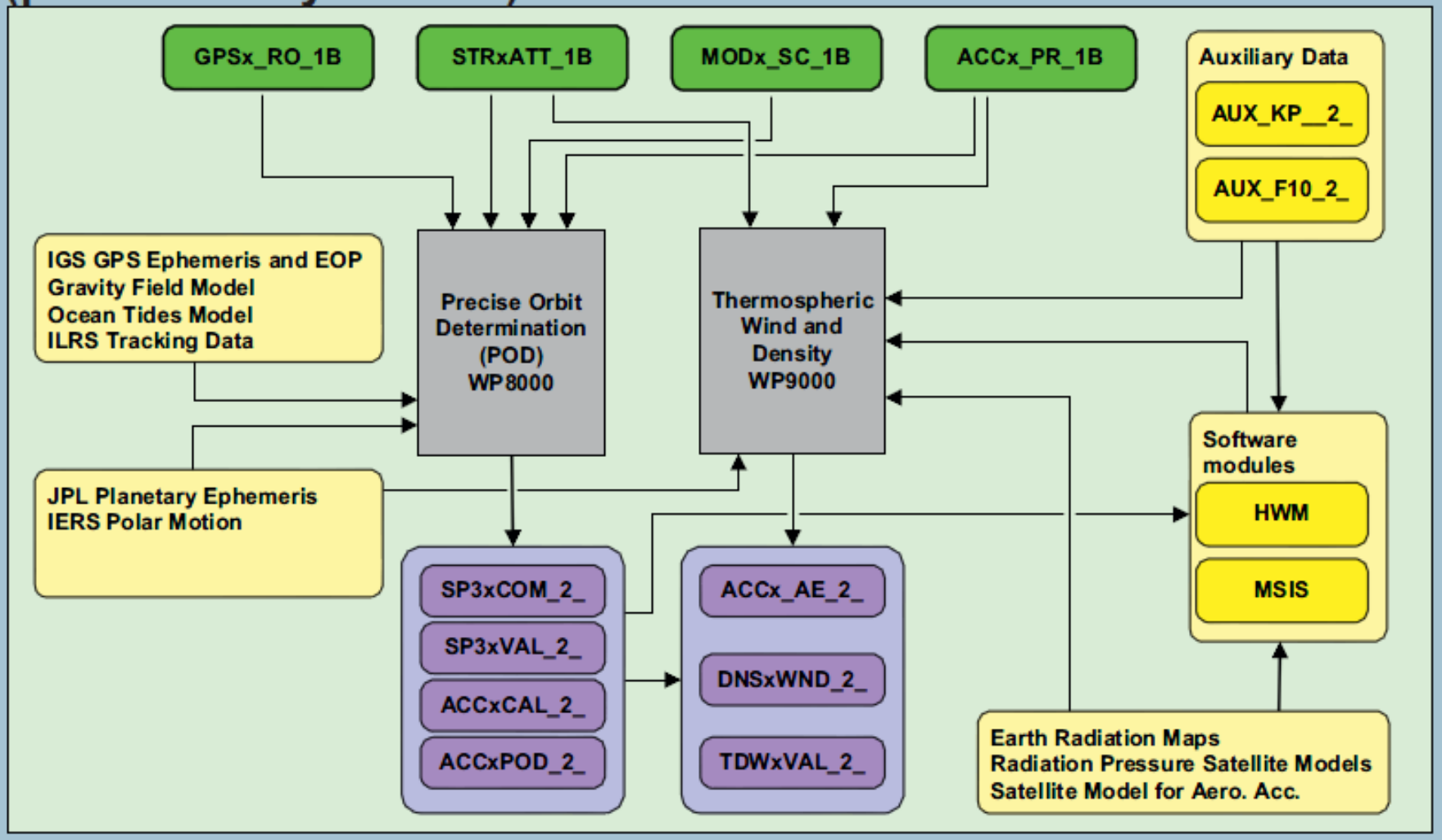
Swarm Constellation Application and Research Facility

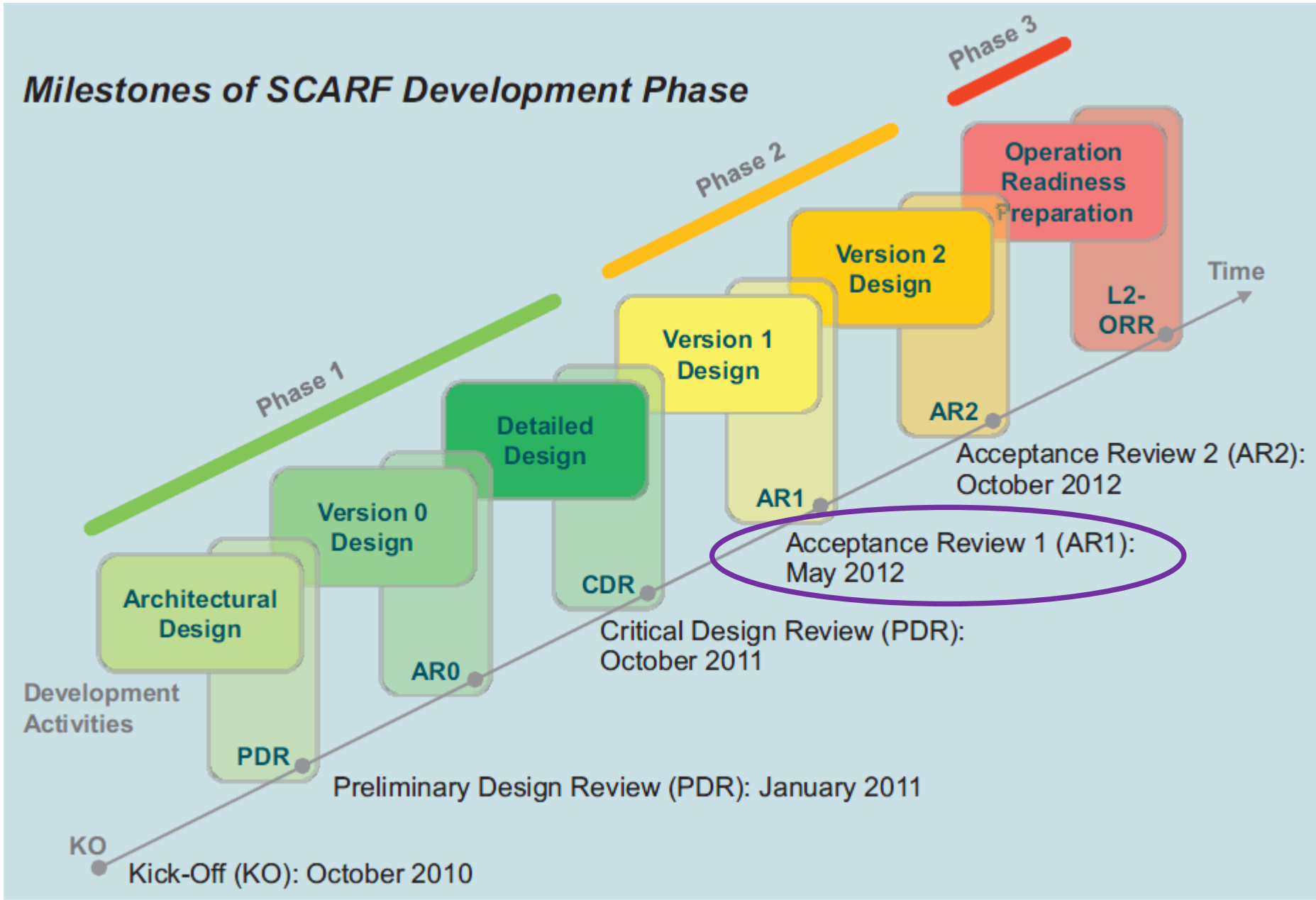
SCARF Development Phase: October 2010 - March 2013
SCARF Exploitation Phase: 2013 - 2018 (5 years)

L2PS Architec-ture



Cat-1 Processing of POD and Thermospheric Winds (performed by SCARF)

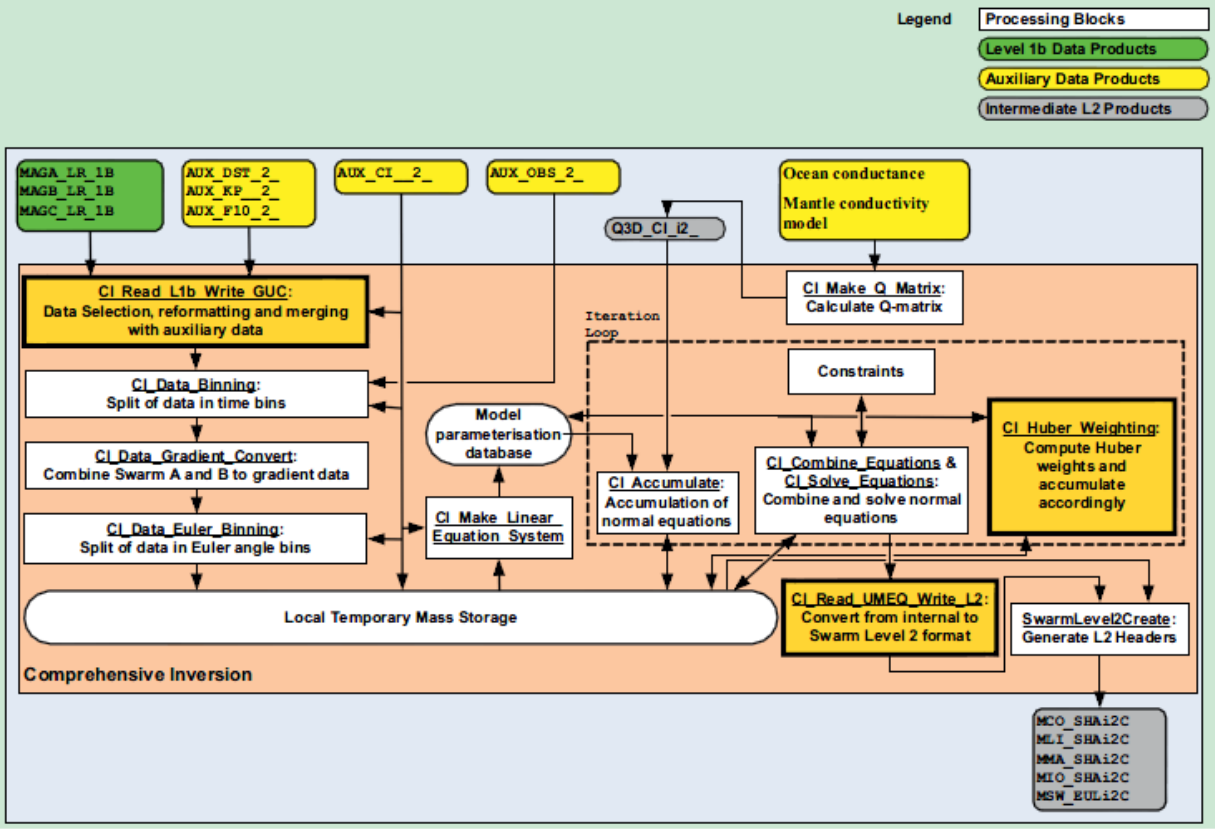



Milestones of SCARF Development Phase
Phase 3
Phase 2
Phase 1
Operation Readiness Preparation
Version 2 Design
Version 1 Design
Detailed Design
Version 0 Design
Architectural Design
Time
L2-ORR
AR2
AR1
AR0
CDR
PDR
KO
Development Activities
Acceptance Review 2 (AR2): October 2012
Acceptance Review 1 (AR1): May 2012
Critical Design Review (PDR): October 2011
Preliminary Design Review (PDR): January 2011
Kick-Off (KO): October 2010

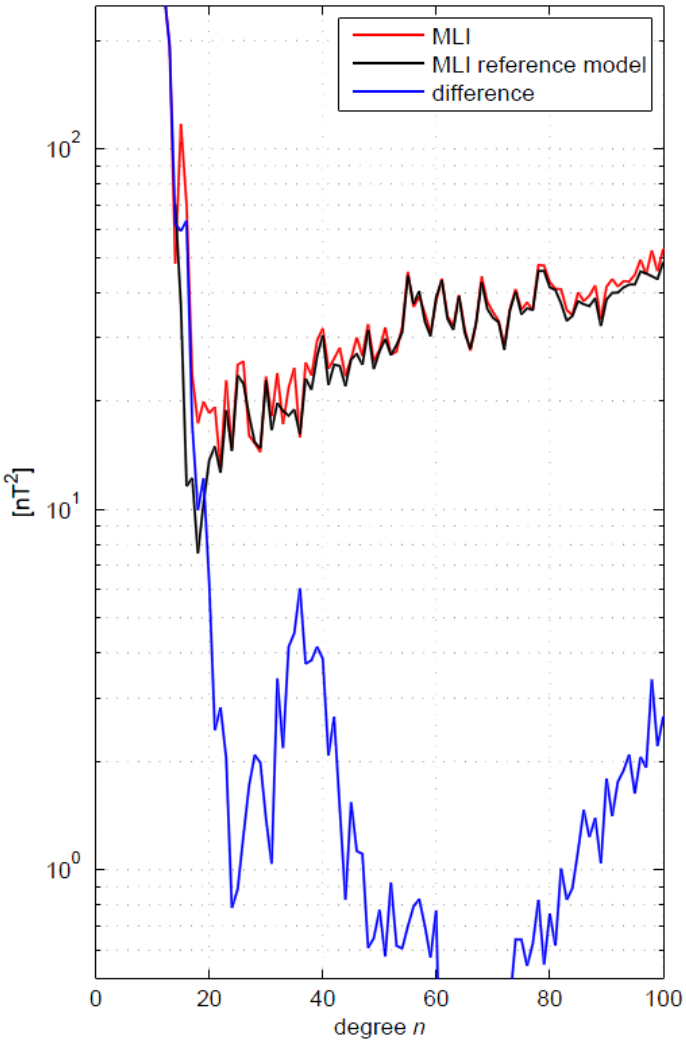
The Comprehensive Inversion Chain

The Comprehensive Inversion takes Level-1b data (time series of magnetic field measurements) and estimates simultaneosly the following L2 products:

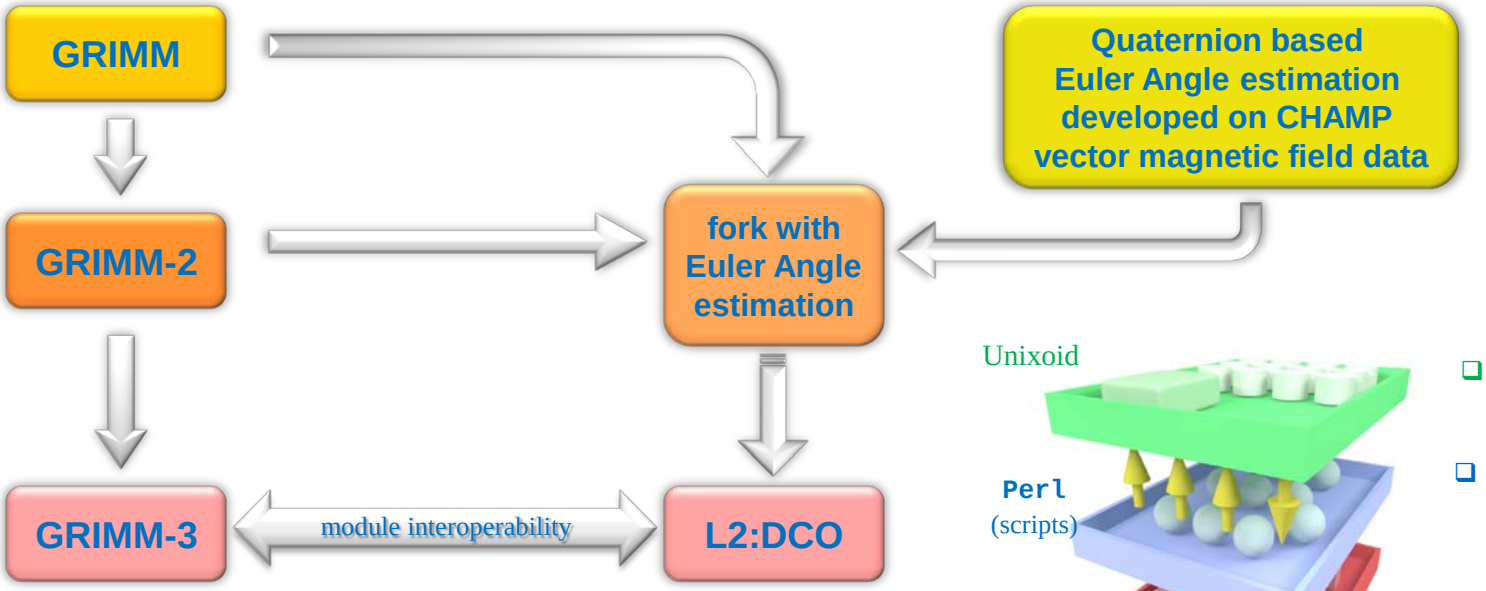
- **MCO**: Core field up to degree $n = 20$, temporal resolution order-5 splines, 6 months knot separation
- **MLI**: Lithospheric field up to $n = 150$
- **MMI**: Ionospheric field in quasi-dipole frame, up to $n = 60$; $m = 12$, semi-annual and quarter-daily periodicity; induced contributions accounted for by pre-defined conductivity of 3D mantle + oceans
- **MMA**: Magnetospheric field up to $n = 3$; $m = 1$, 1 hour bins; induced field up to $n,m = 6$, 6 hour bins
- **MSW**: Instrument alignment parameters (Euler angles), 30 days bins



Comprehensive Model: DTU Space



Dedicated Core: GFZ Potsdam



- Unixoid platform: file system and open source database (PostgreSQL).
- Top level functionality and interfacing by **`perl`** scripts, partly derived from CHAMP utilities.
- Pure computational parts derived from GRIMM inversion family (library module compatibility.)

DCO: Four subtasks:

Fast Core **Fast Euler**

Short, recent period covered (One turn in LT)
Simplified SHA time description (linear)
Lower computational requirements

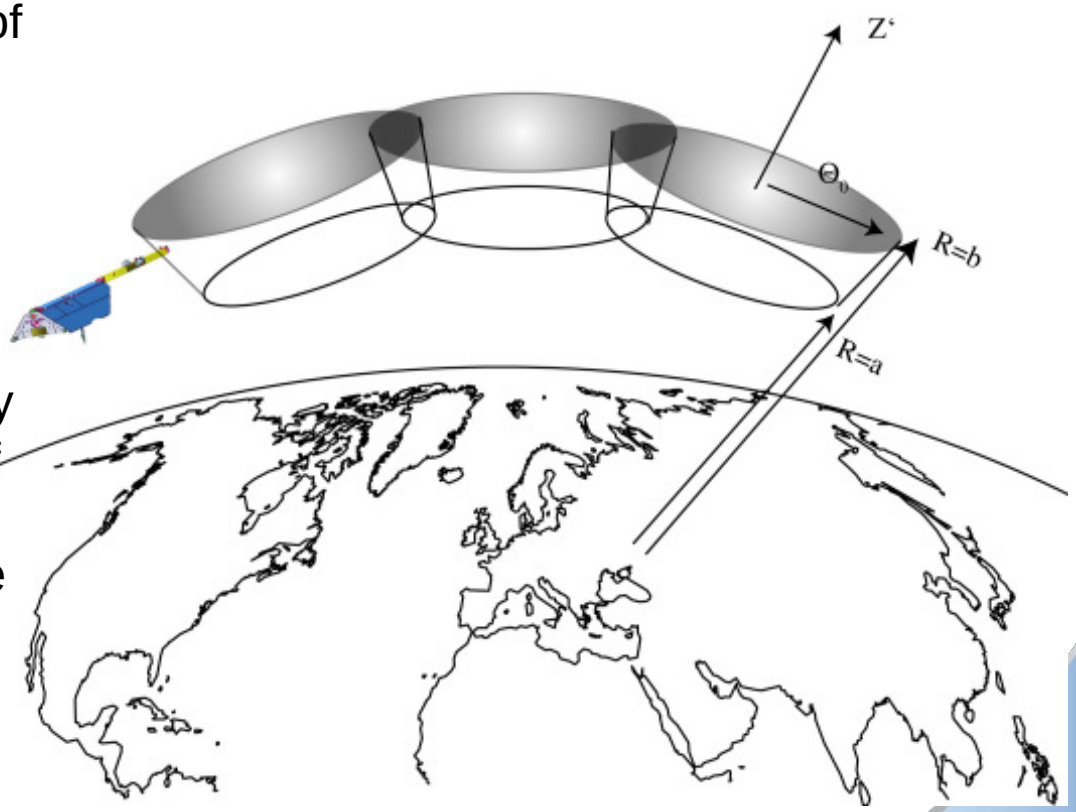
Slow Core **Slow Euler**

All available data period (at least one year)
Full complexity (order 6 splines for time description)
High computational requirements

Lithosphere: IPGP, Paris

The chain relies on regional basis functions to solve for the inverse problem

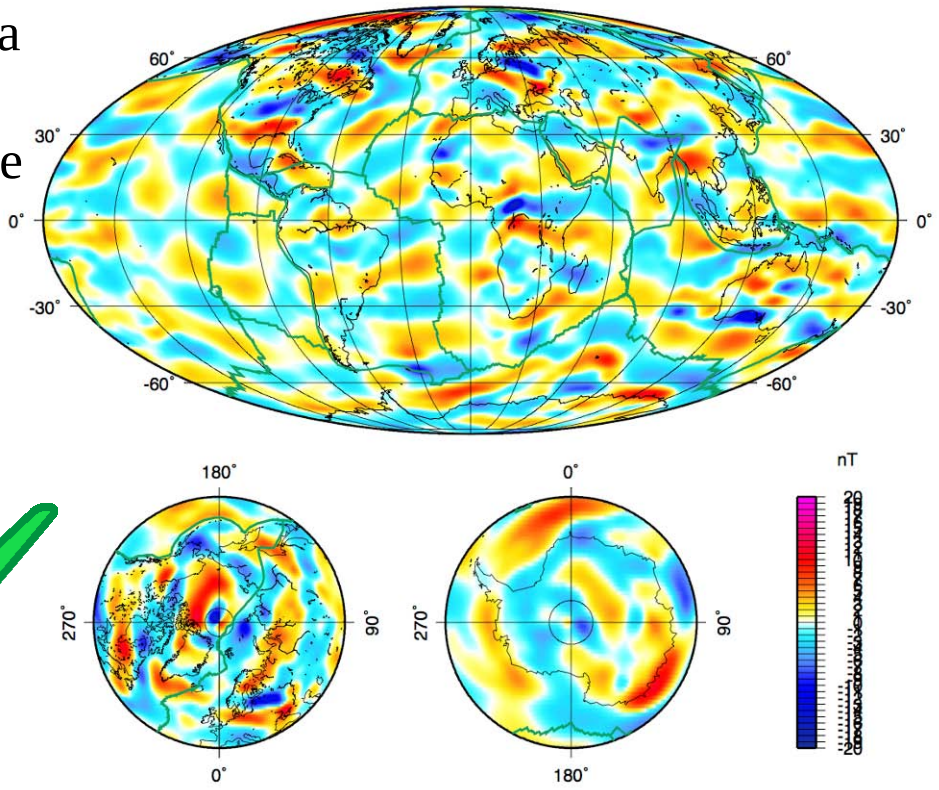
- Models iteratively and piecewise the magnetic field of the lithosphere
- Focuses on small structures using a moving window of regional functions
- Treats the noise regionally
- Represents the field regionally with a manageable number of parameters: the chain is comparatively fast to compute
- Subtract main and magnetospheric field and carefully select quiet-time magnetic data to isolate lithospheric field



IPGP test: check iterative modelling on global scale

Verify that the piecewise modelling of the data produces the correct global map showing lithospheric field structures.

Input data: Four years of decimated data contining lithospheric field only falling within a set of spherical caps covering the Earth

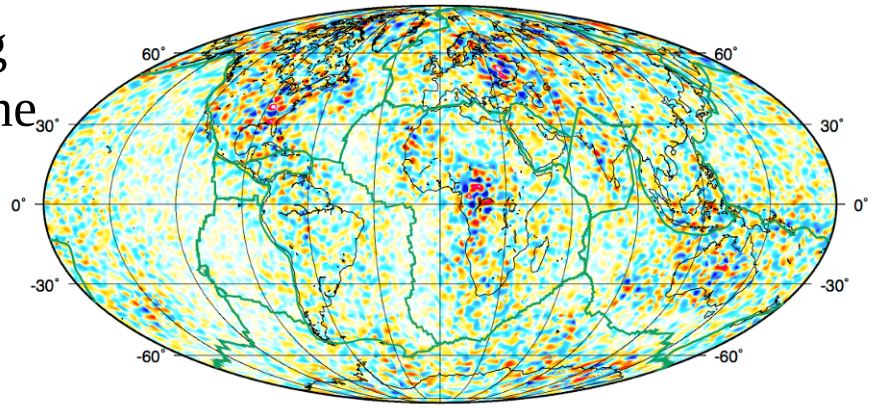


Visual inspection of the output local models estimated on a regular grid is consistent with the input global lithospheric field model.

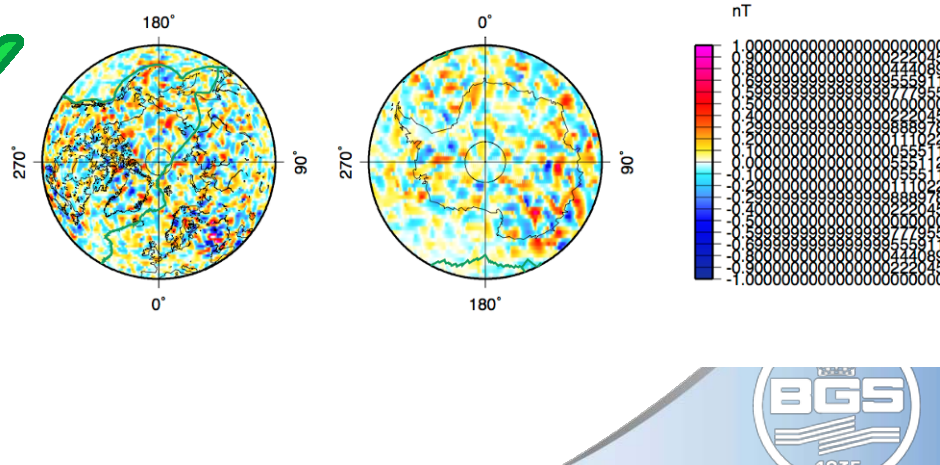
IPGP test: check iterative modelling on global scale

Verify that the piecewise modelling of the data produces the correct global map showing lithospheric field structures.

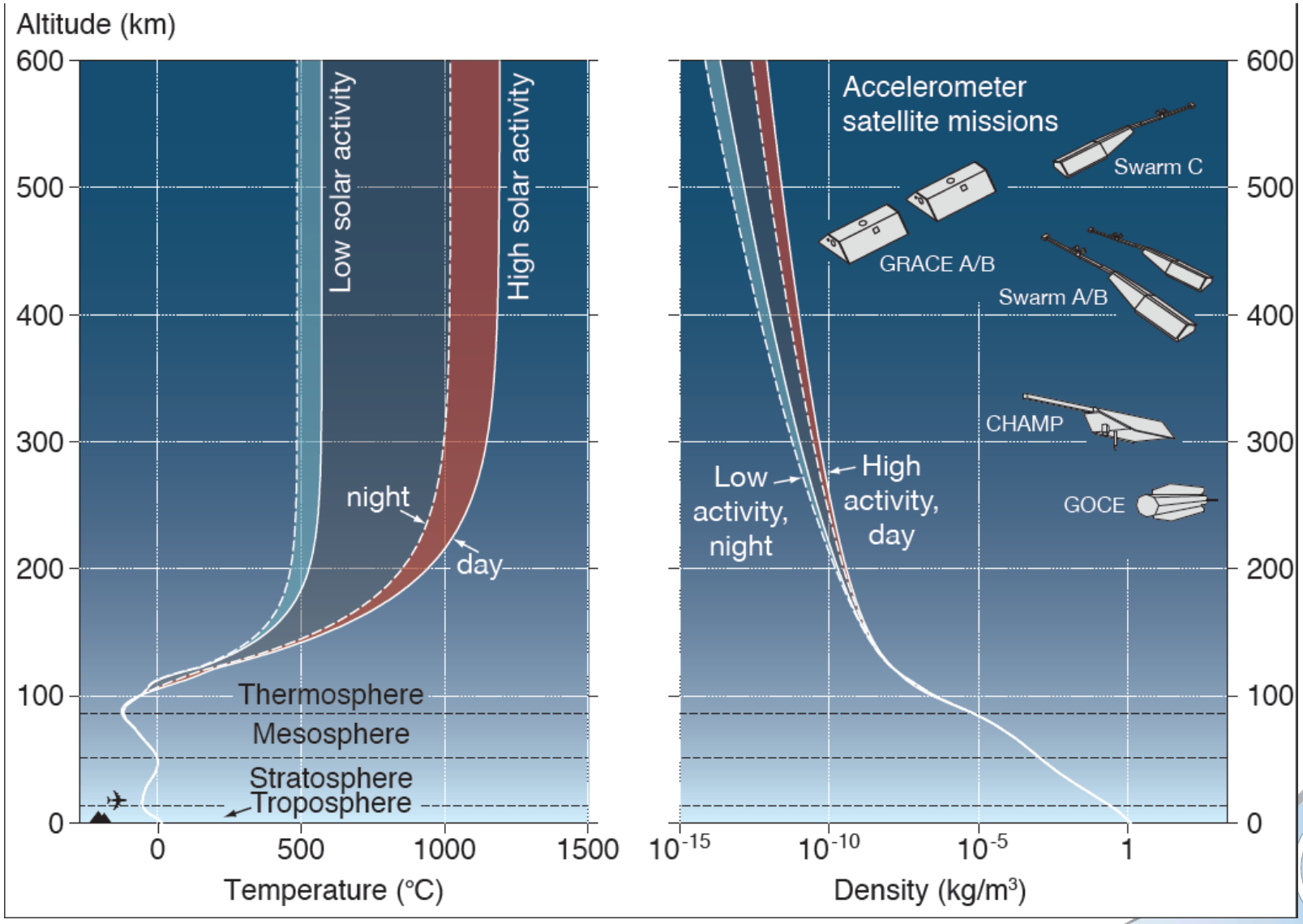
Input data: Four years of decimated data contining lithospheric field only falling within a set of spherical caps covering the Earth



Residuals between input data and estimated model show a standard deviation of about 0.15 nT (level of noise of TDS-1 data)

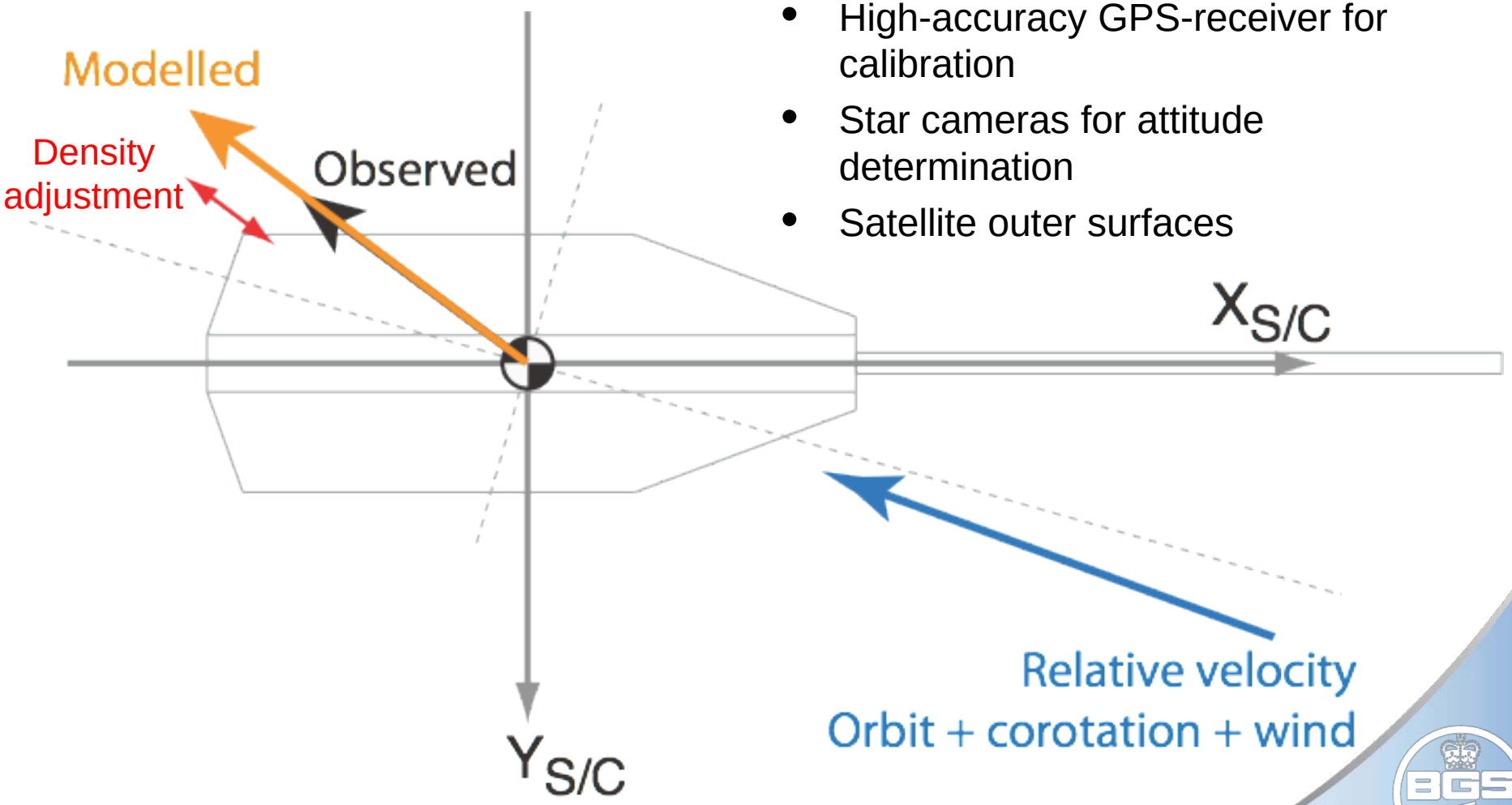


Neutral Atmosphere – DEOS, Delft

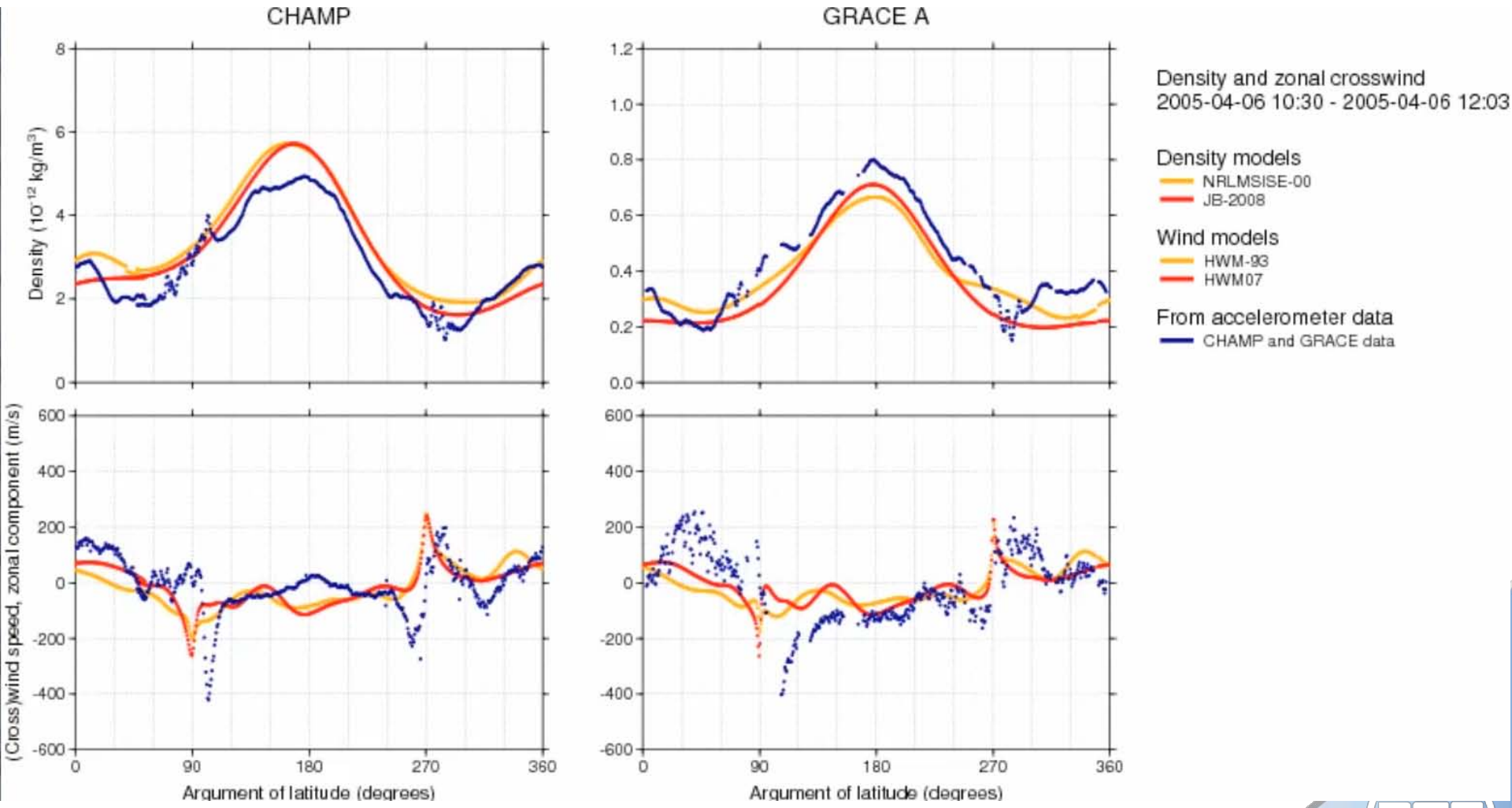


Step 2: Density determination

- Accelerometer
- High-accuracy GPS-receiver for calibration
- Star cameras for attitude determination
- Satellite outer surfaces

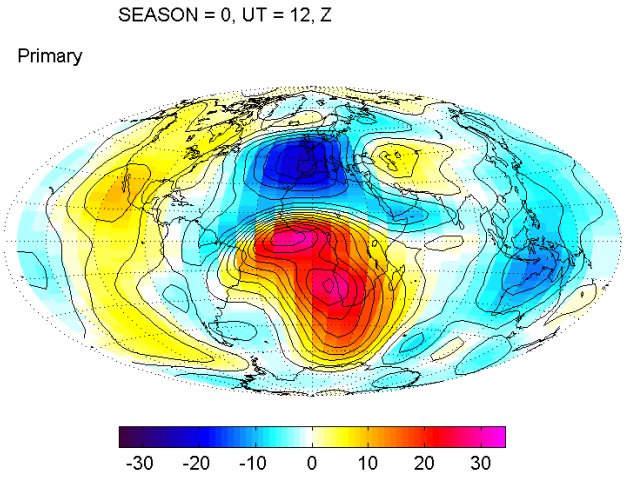


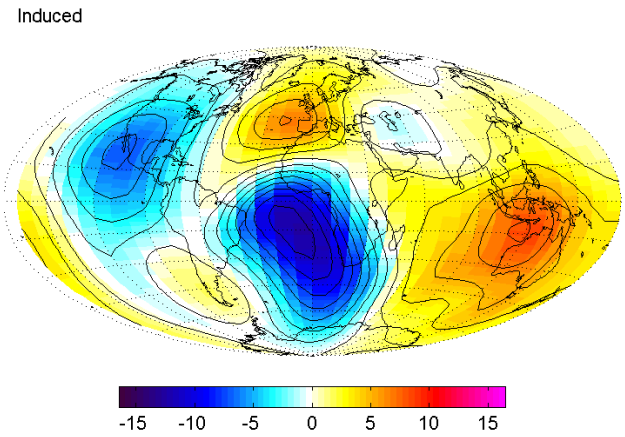
Step 2: Density determination

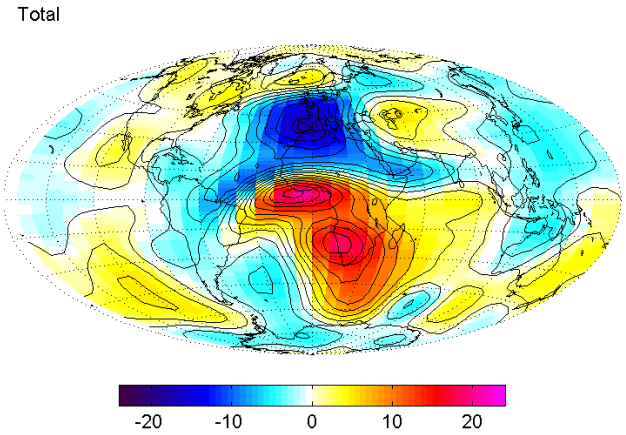


Ionosphere: IPGP, Paris

- Spherical harmonic models of the ionospheric magnetic field at ground and satellite altitudes, for all UT and seasons of a given year, up to degree 45 in quasi-dipole coordinates
- The models account for the F10.7 variability
- Primary (ionospheric) and induced fields are separated using the 3D mantle conductivity model calculated during the mission

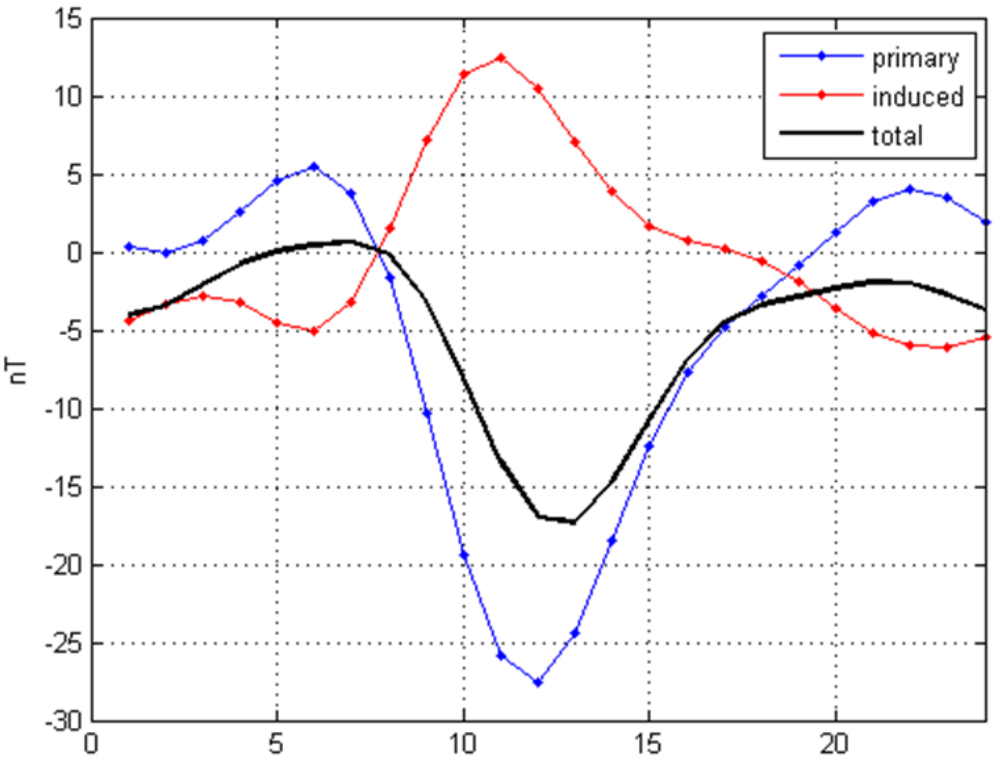






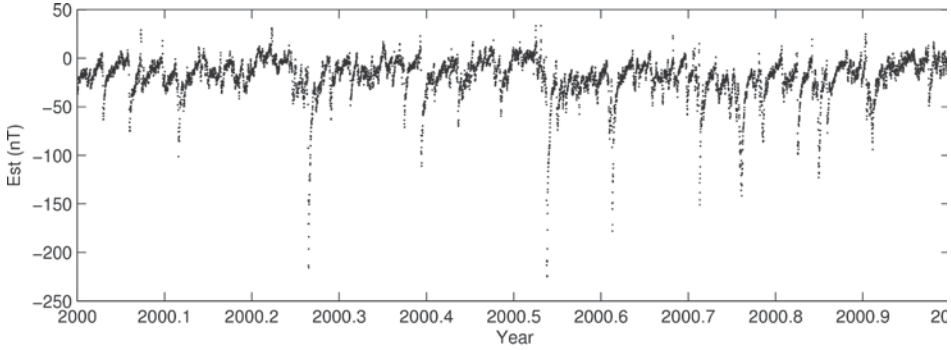
Applications of DIFI models

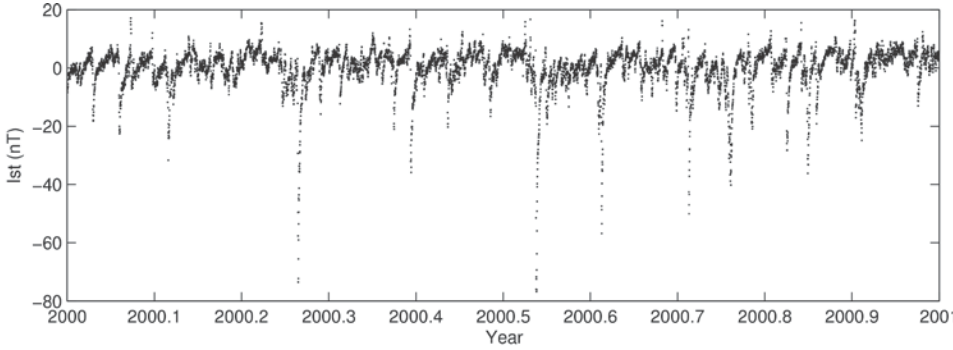
- Investigation of the ionospheric dynamics (time variability of ionospheric currents at mid- to low latitudes, relationships with other parameters such as winds and electric fields)
- Removal of ionospheric fields in magnetic satellite data (in order to investigate other sources)
- Remove of the geomagnetic daily variation in ground data (observatories, repeat stations, magnetic surveys)

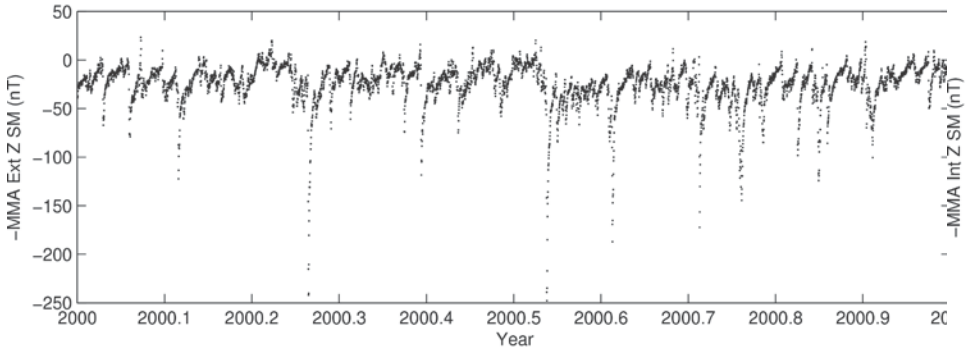


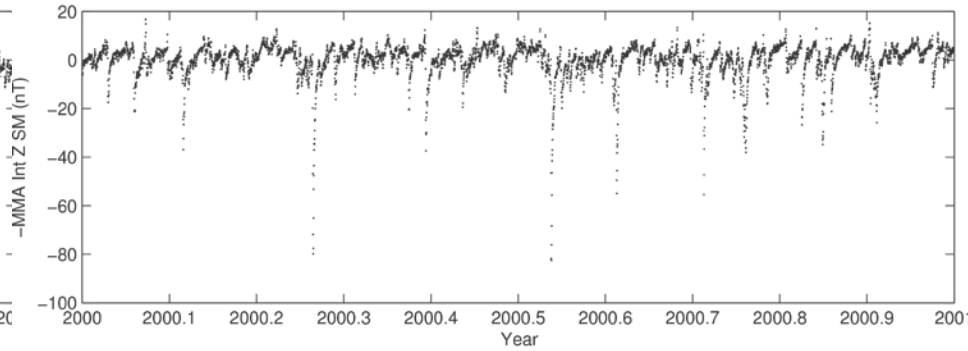
Rapid Magnetospheric Model: BGS, Edinburgh

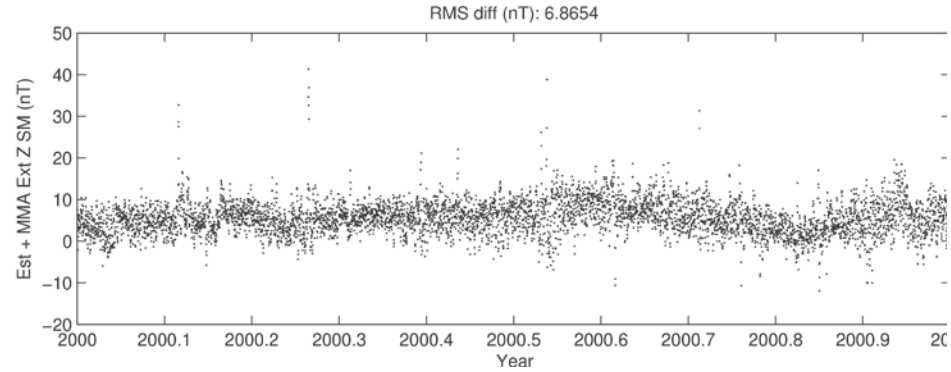
- External dipole model, where component on dipole axis mimics *Dst*
- Here test data are sub-sampled every 20s but the lithospheric model is evaluated to degree 175

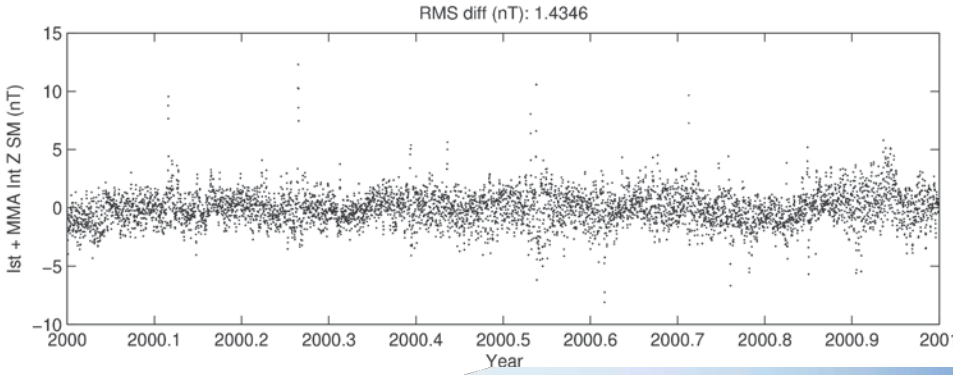




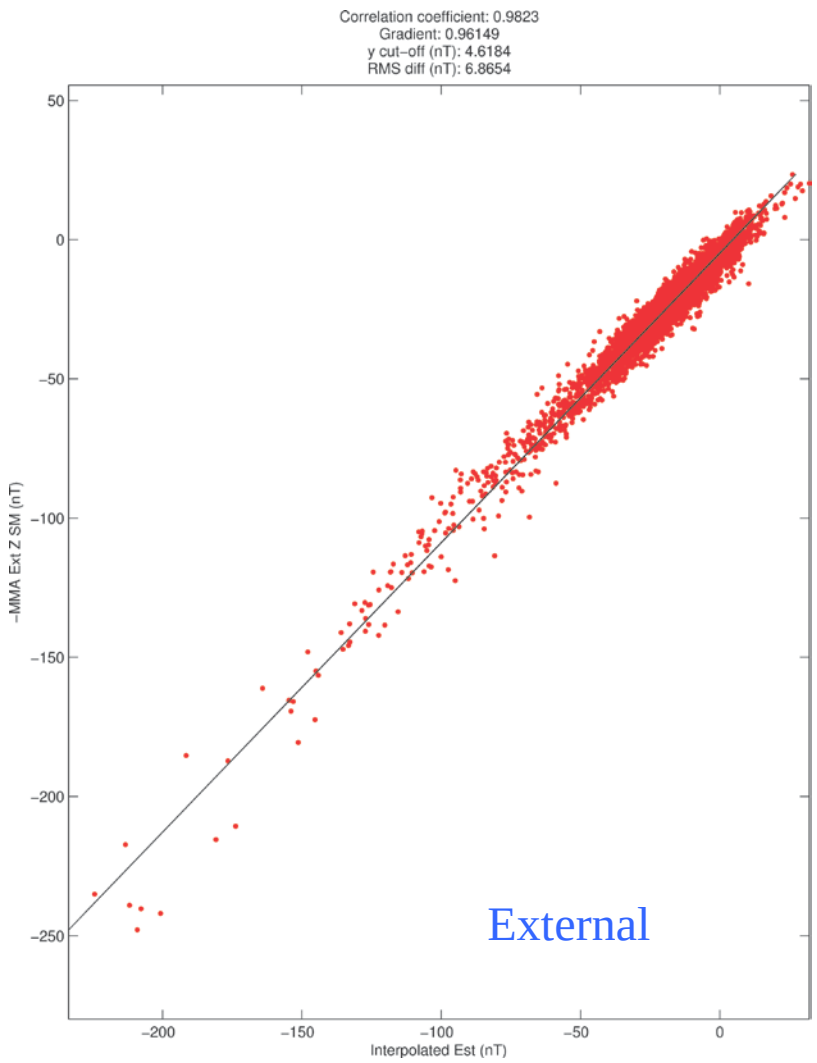






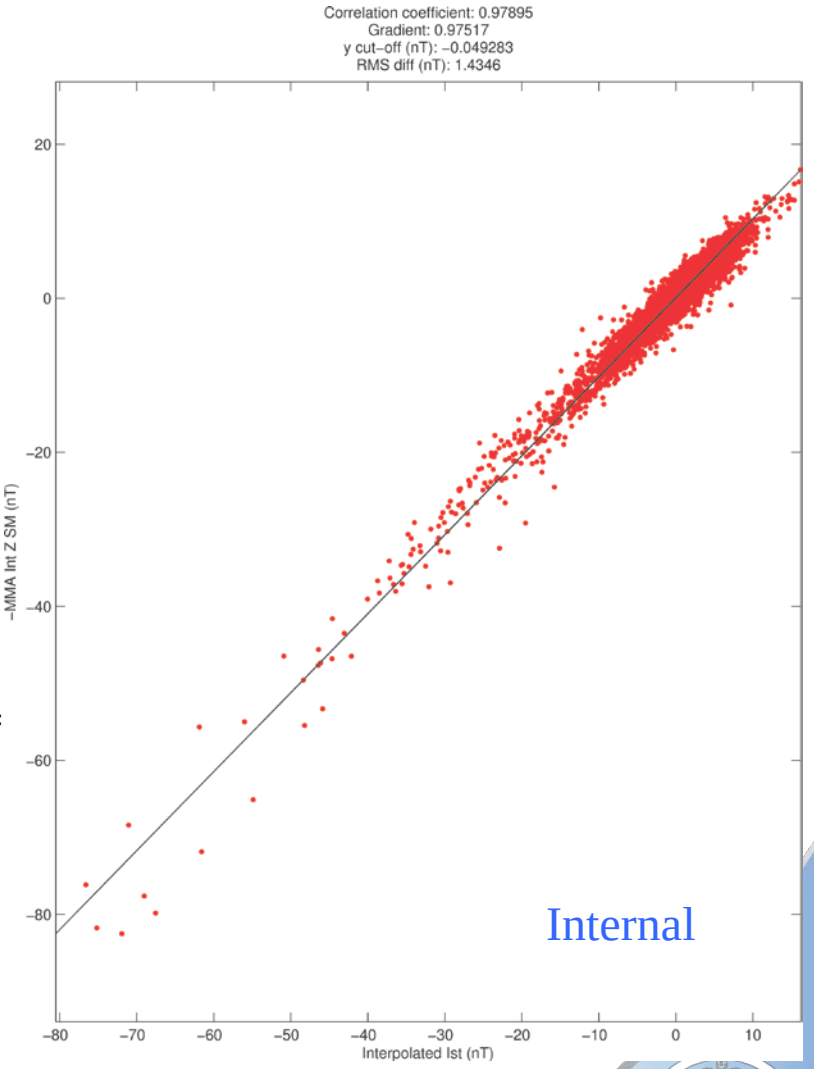


Rapid Magnetospheric Model: BGS, Edinburgh



Linear Correlation: *Est*/*Ist* and MMA in SM coordinates

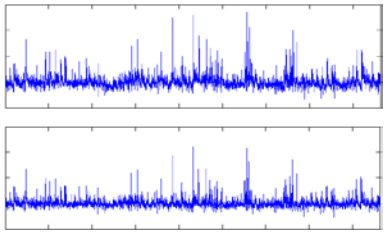
One year of data (2000)



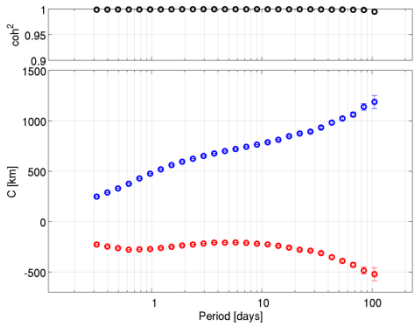
Dst = *Est* + *Ist* , assuming a given conductivity structure

Mantle Conductivity Products (1-D): ETH and CUP

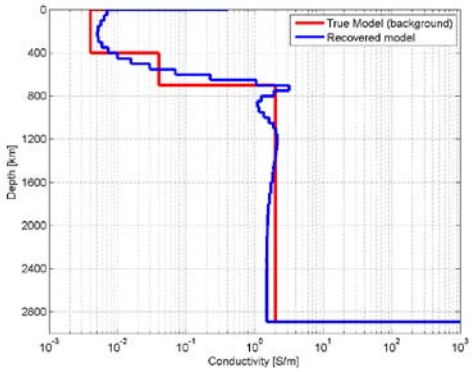
- Global C-responses (in period range between a few hours and a few months)
- Global 1-D electrical conductivity model of the Earth's mantle



Time series of dominant inducing (q10) and induced (g10) coefficients



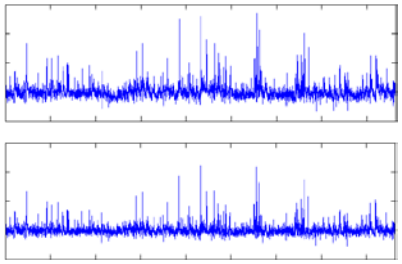
C-responses



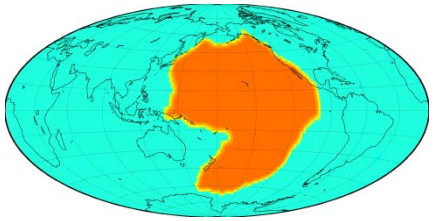
1-D Conductivity

Mantle Conductivity Products (3-D): ETH and CUP

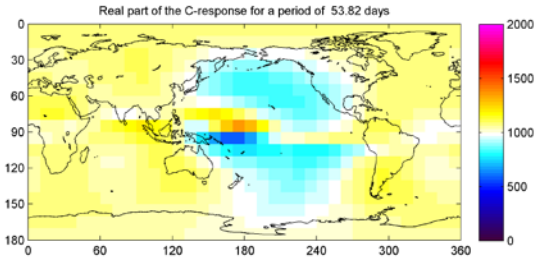
- Maps of C-responses
- 3-D model of the Earth's mantle recovered by frequency domain (FD) approach
- 3-D model of the Earth's mantle recovered by time domain (TD) approach



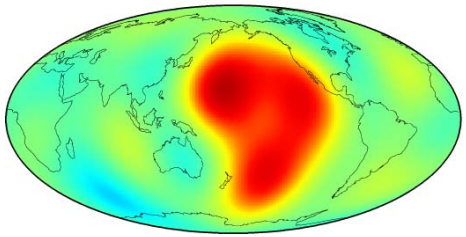
Time series of ALL inducing and induced coefficients



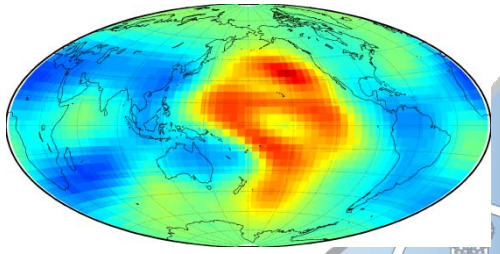
True model



Map of Re C-responses



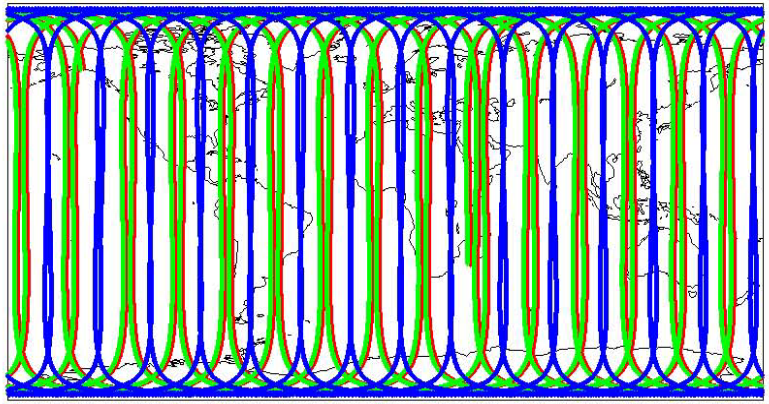
Recovered by TD



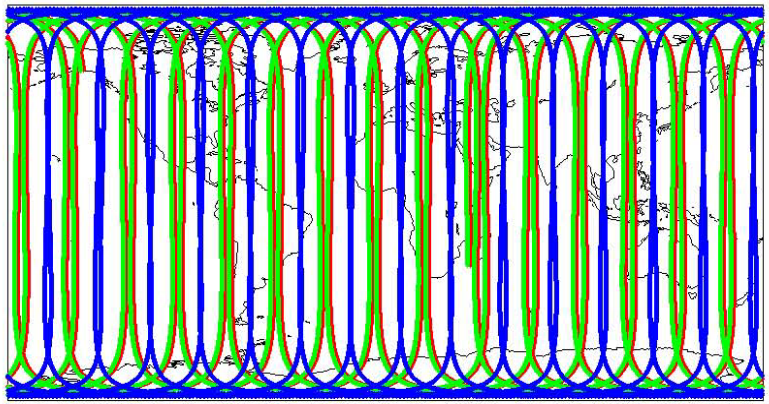
Recovered by FD

Quick Look of Level 1b Data: BGS, Edinburgh

TDS-1 satellite F magnetic data locations for 30-Jul-1998

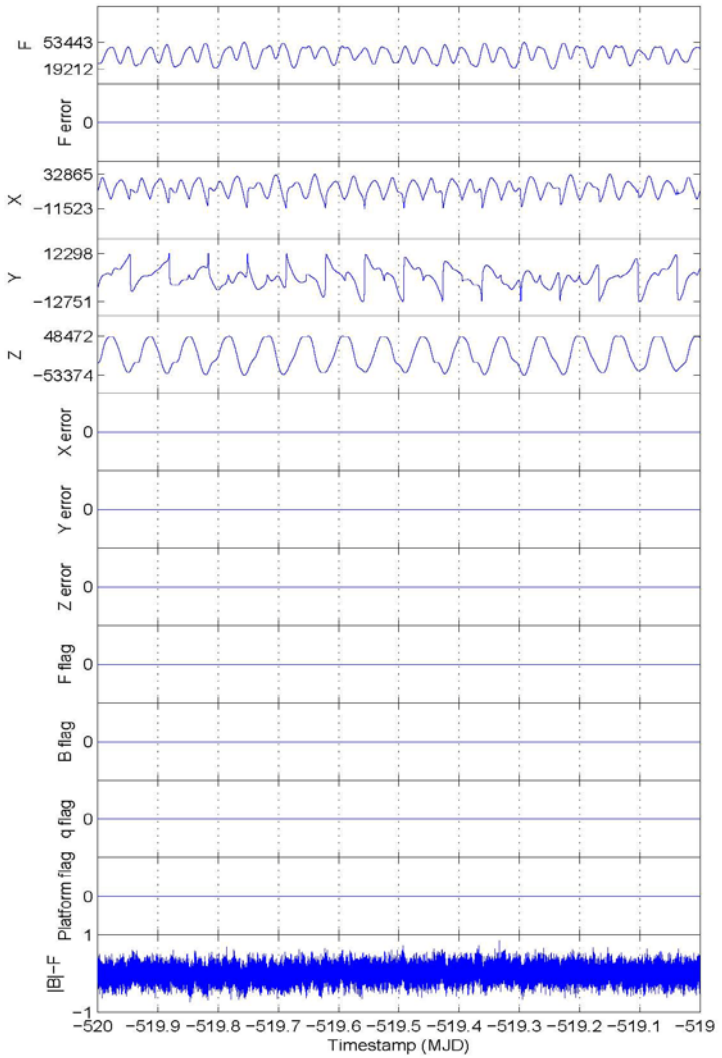


TDS-1 satellite B_{NEC} magnetic data locations for 30-Jul-1998

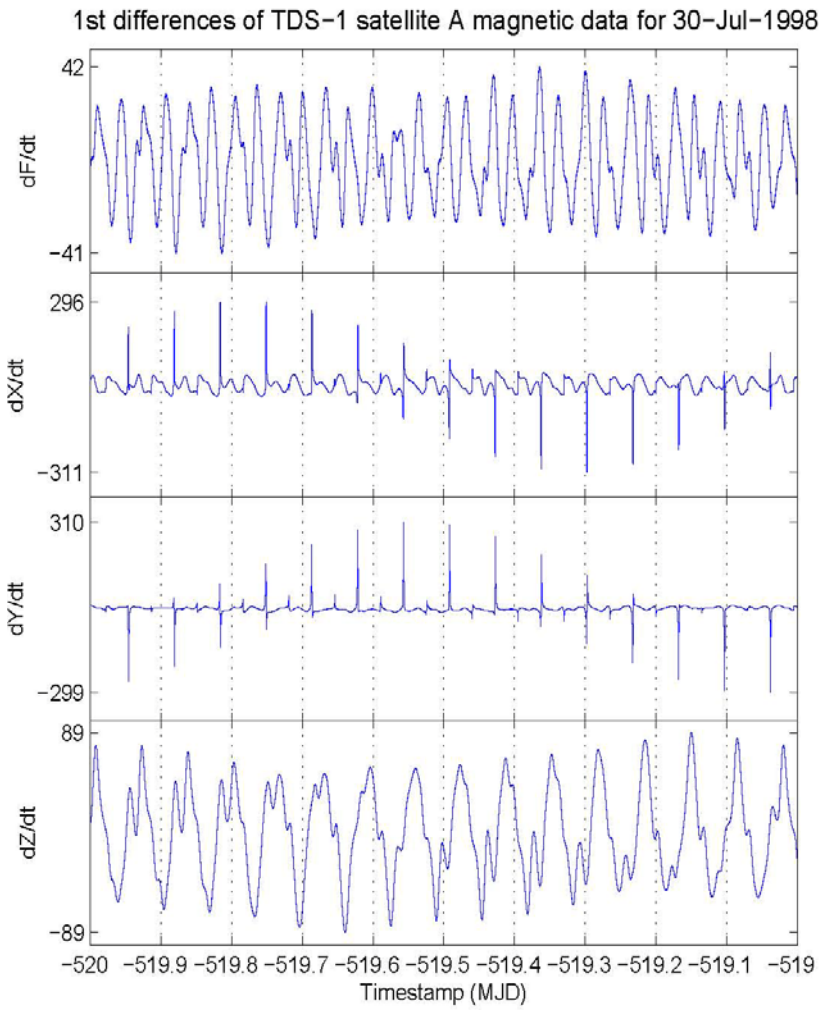


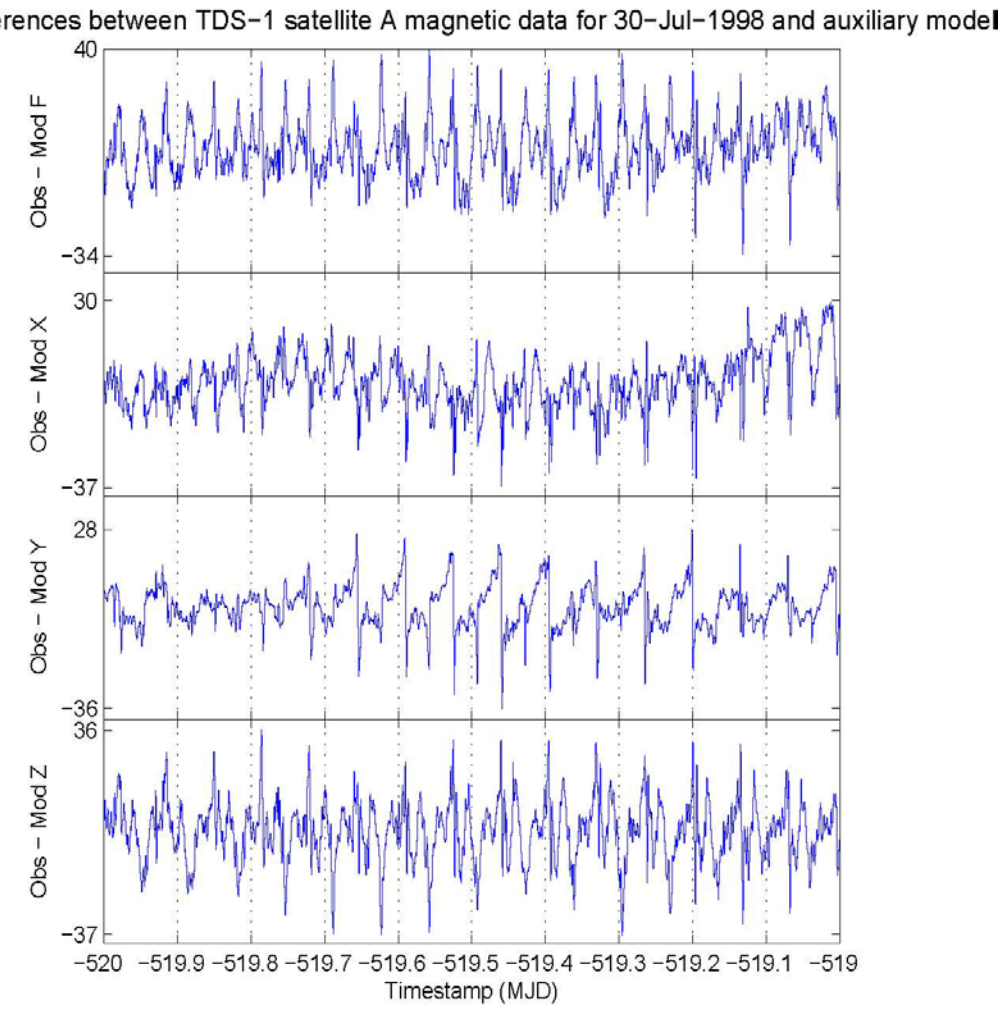
Satellite A Satellite B Satellite C

TDS-1 satellite A magnetic data for 30-Jul-1998



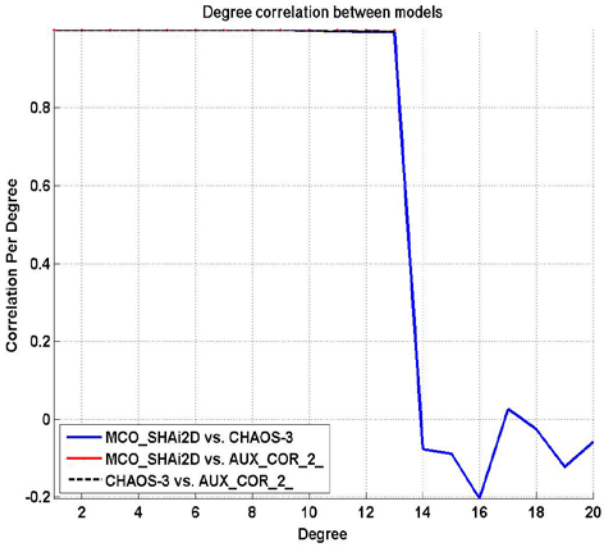
Quick Look of Level 1b Data: BGS, Edinburgh

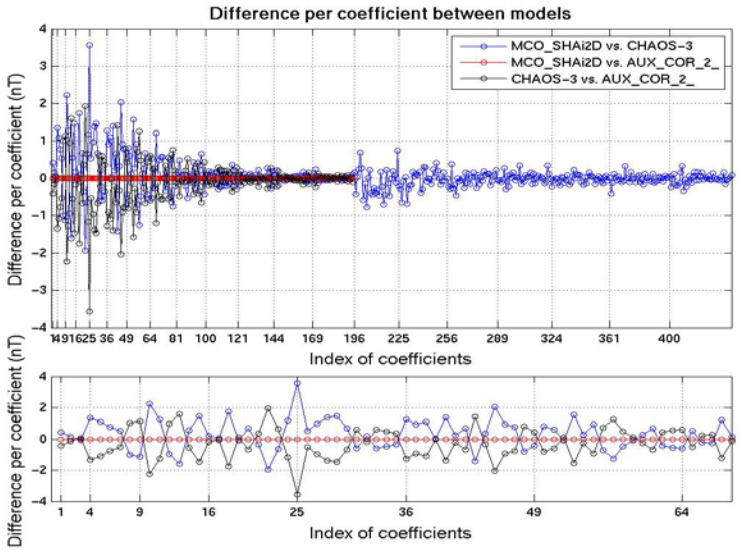


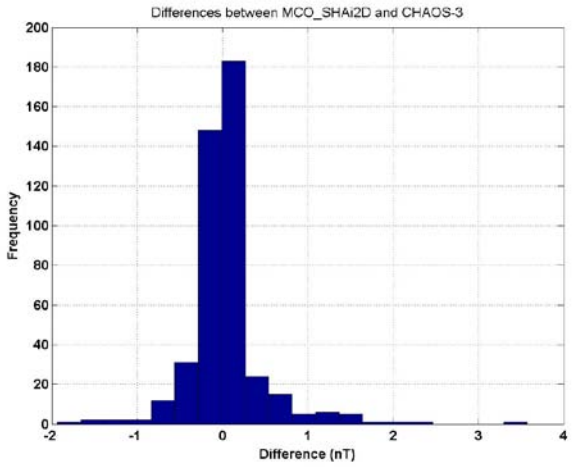


Validation of Level 2 Products: BGS

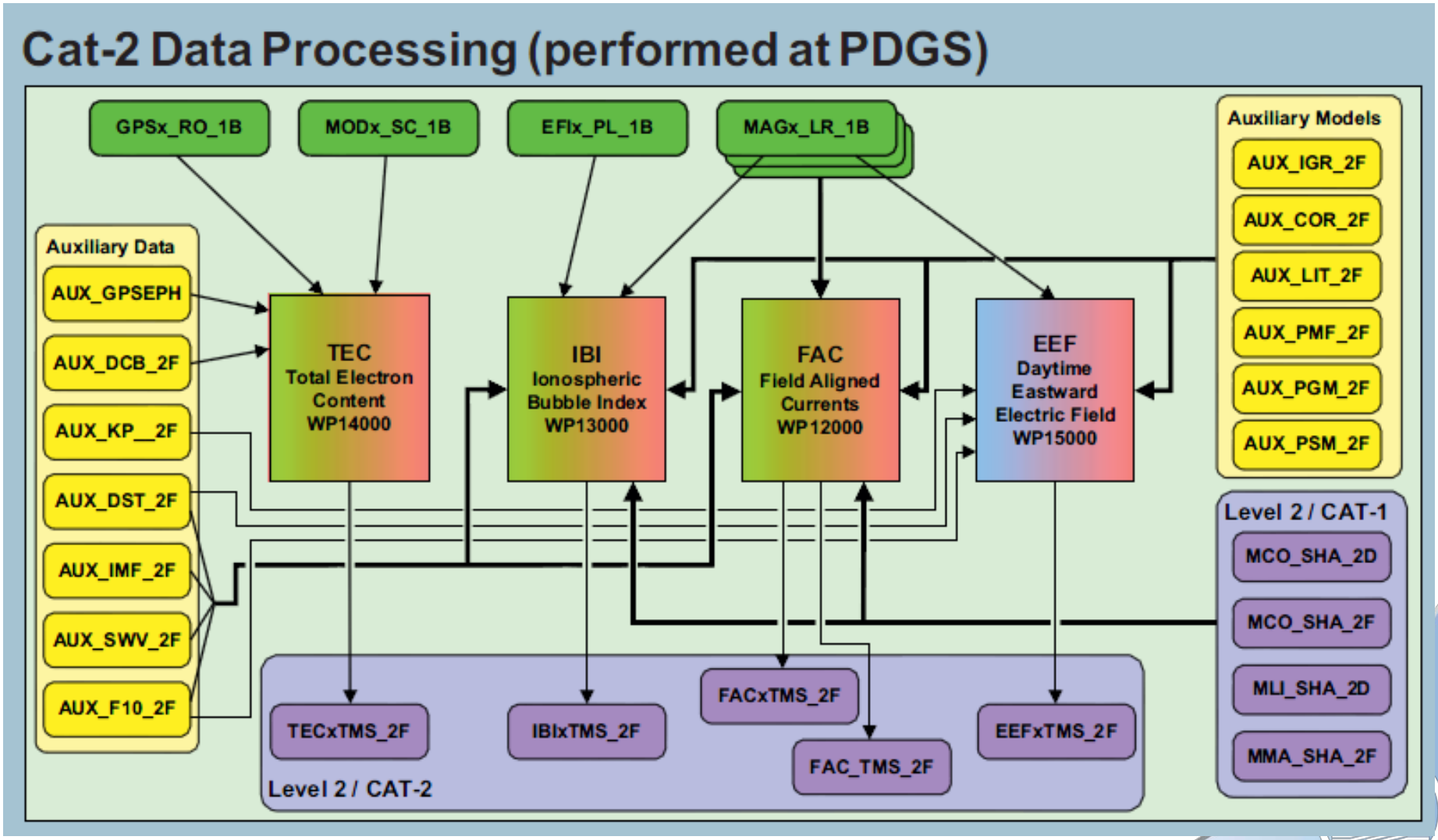
- **MCO**: Eight different figures are produced
  - Spectra; degree correlation; MS diff per degree; spatial plots; diff per degree ...
- Some examples here



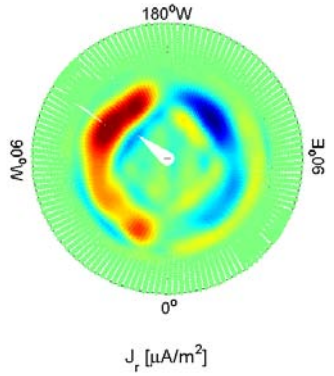




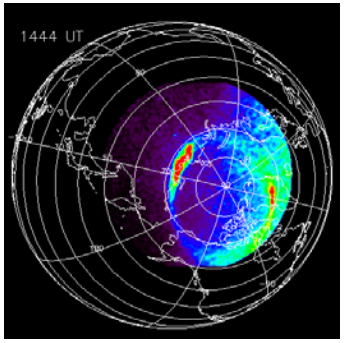
Cat-2 Products Suite: PDGS, ESRIN



Oval of intense field-aligned currents



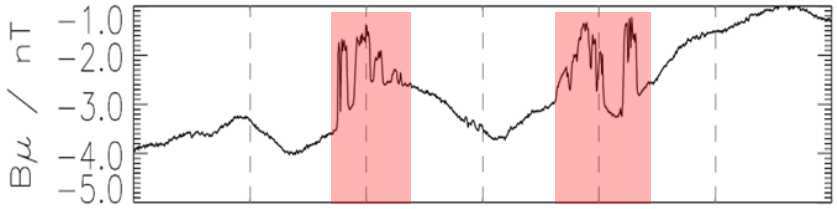
Optical auroral oval



http://spacescience.spaceref.com/newhome/headlines/ssl_report/uvi.gif

Field-Aligned Currents

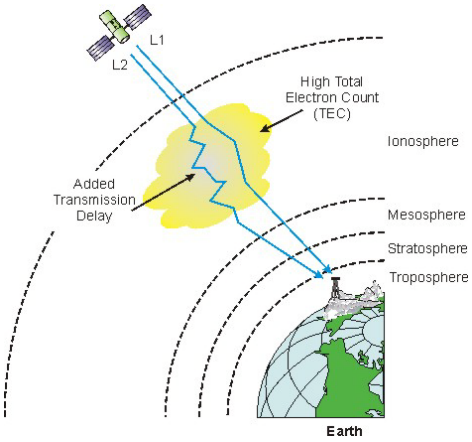
-determines radial and field-aligned currents at the polar region, which are closely related with the aurora.



[*Stolle et al.*, JGR 2006]

Ionospheric Bubble Index

-determines magnetic field fluctuations associated with plasma irregularities in the nighttime equatorial ionosphere.
- confirmed with electron density measurements of EFI instrument



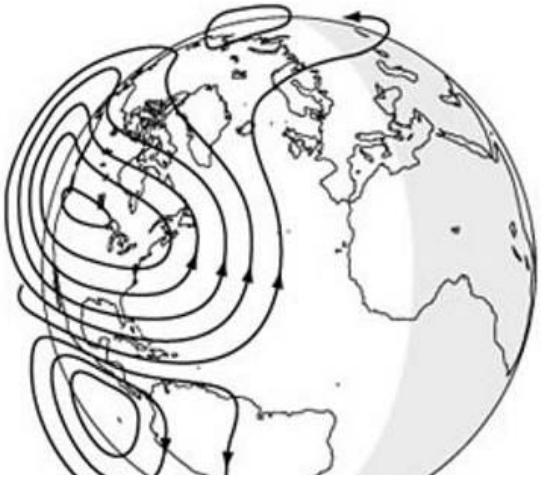
http://www.althos.com/Sample_Diagrams/ag_GPS_Satellite_Ionospheric_Delay_low_res.jpg

Total Electron Content

- determines total ionospheric electron content that delays GPS signals.

Dayside Eastward Electric Field: IPGP

- Drives strong currents in the ionosphere
- Causes plasma to be lifted hundreds of kilometers to the upper ionosphere
- Important ionospheric parameter for modeling/prediction of space weather
- Difficult to measure directly on a global scale
- This Level 2 product estimates the equatorial electric field (EEF) from Swarm magnetometer measurements for each orbit



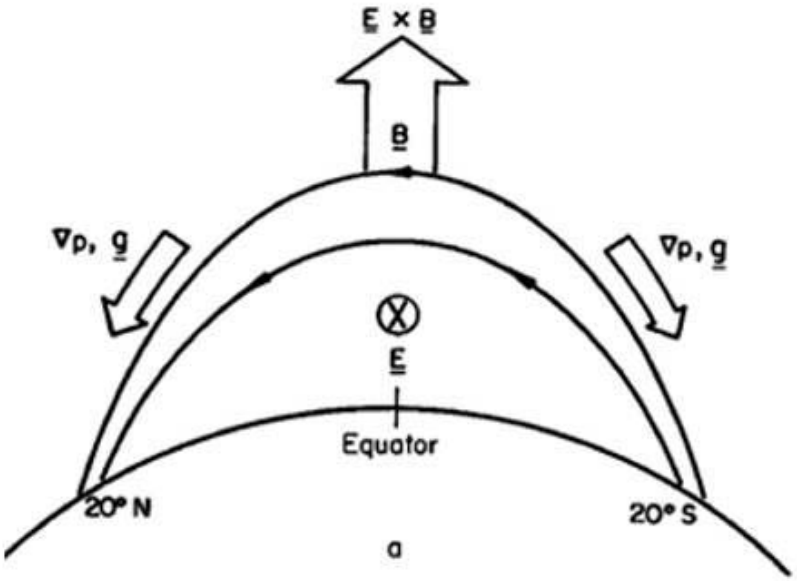


Figure 3 – Appleton Anomaly scheme.

Conclusions

- The Swarm Constellation Application and Research Facility (SCARF), is a consortium of European research institutions with international support
- Level-2 products from SCARF (CAT-1) and the L2PS (CAT-2) will include
  - core, lithospheric, ionospheric and magnetospheric fields
  - derived parameters: mantle conductivity, thermospheric mass density & winds, field-aligned currents, ionospheric plasma bubble index, ionospheric total electron content and dayside equatorial zonal electrical field
- The facility is expected to be operational for a period of 5 years after the launch of Swarm, scheduled for 17th July 2012
- All products will be available through the Swarm Payload Data Ground Segment (PDGS), located at ESA Centre for Earth Observation in Frascati
- Products will aid the scientific community, e.g. by isolating ‘unwanted’ magnetic and other signals to improve modelling and physical interpretation of ‘wanted’ signals