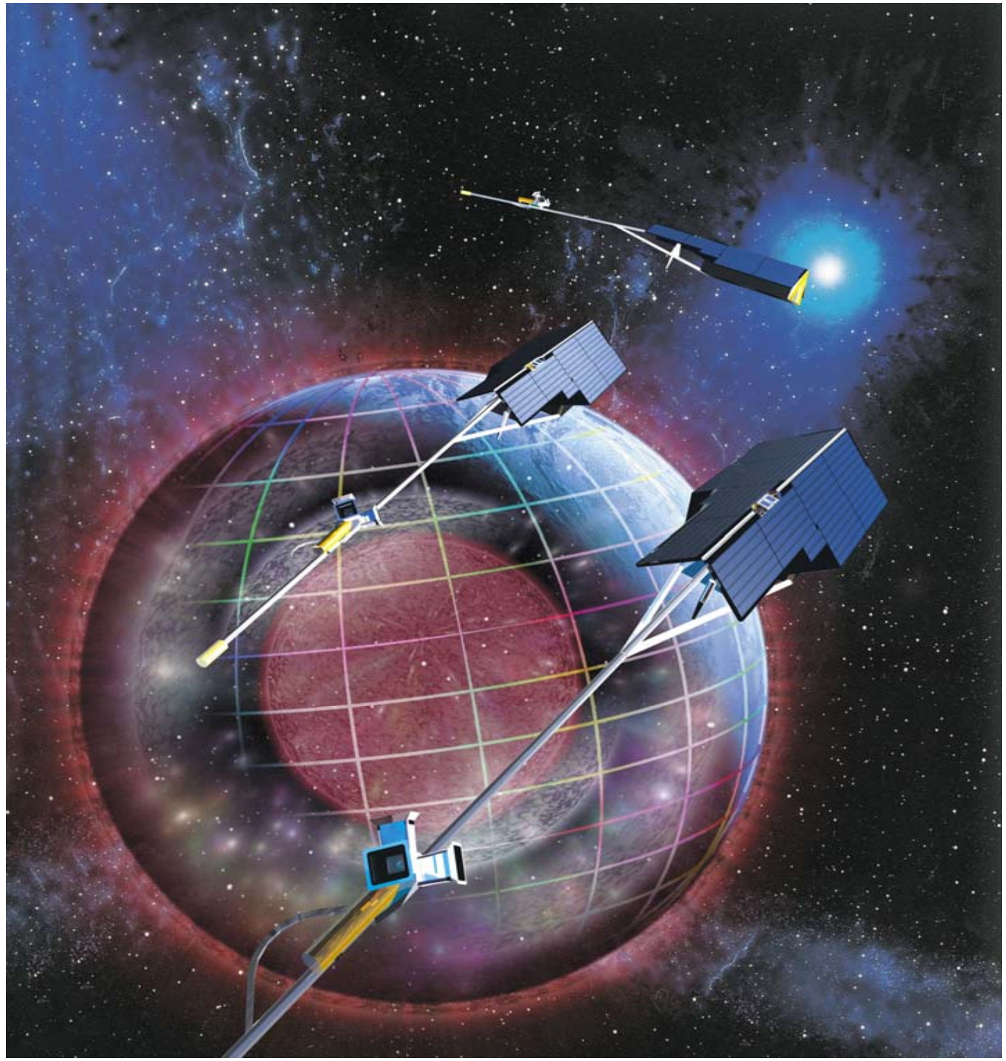
Swarm
Mission Concept

Yvon Menard, Ralf Bock,
Emanuele Neri and
Roger Haagmans

European Space Agency,
the Netherlands

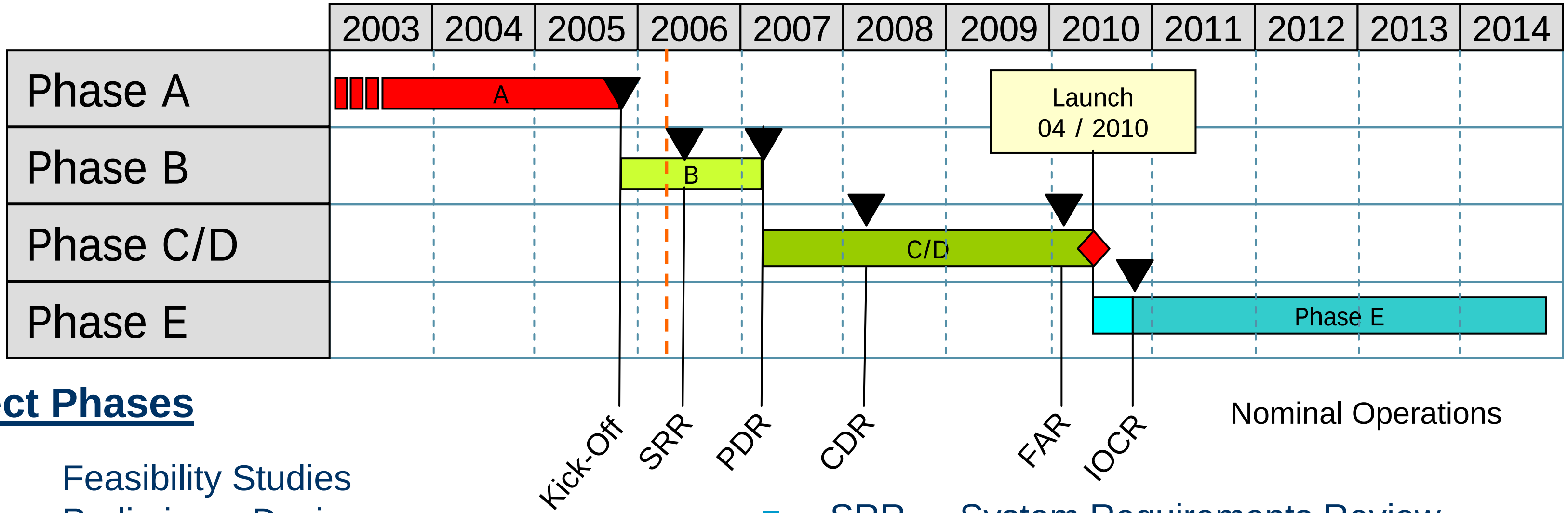


Courtesy EADS, Astrium

- Project Phases & Milestones
- The Swarm System
  - System Elements
  - The Space Segment: Satellite Design and Instruments
  - Mission Analysis
  - Launcher

- Constellation concept and performance
- Studies and scientific interaction

Project Phases and Milestones



Project Phases

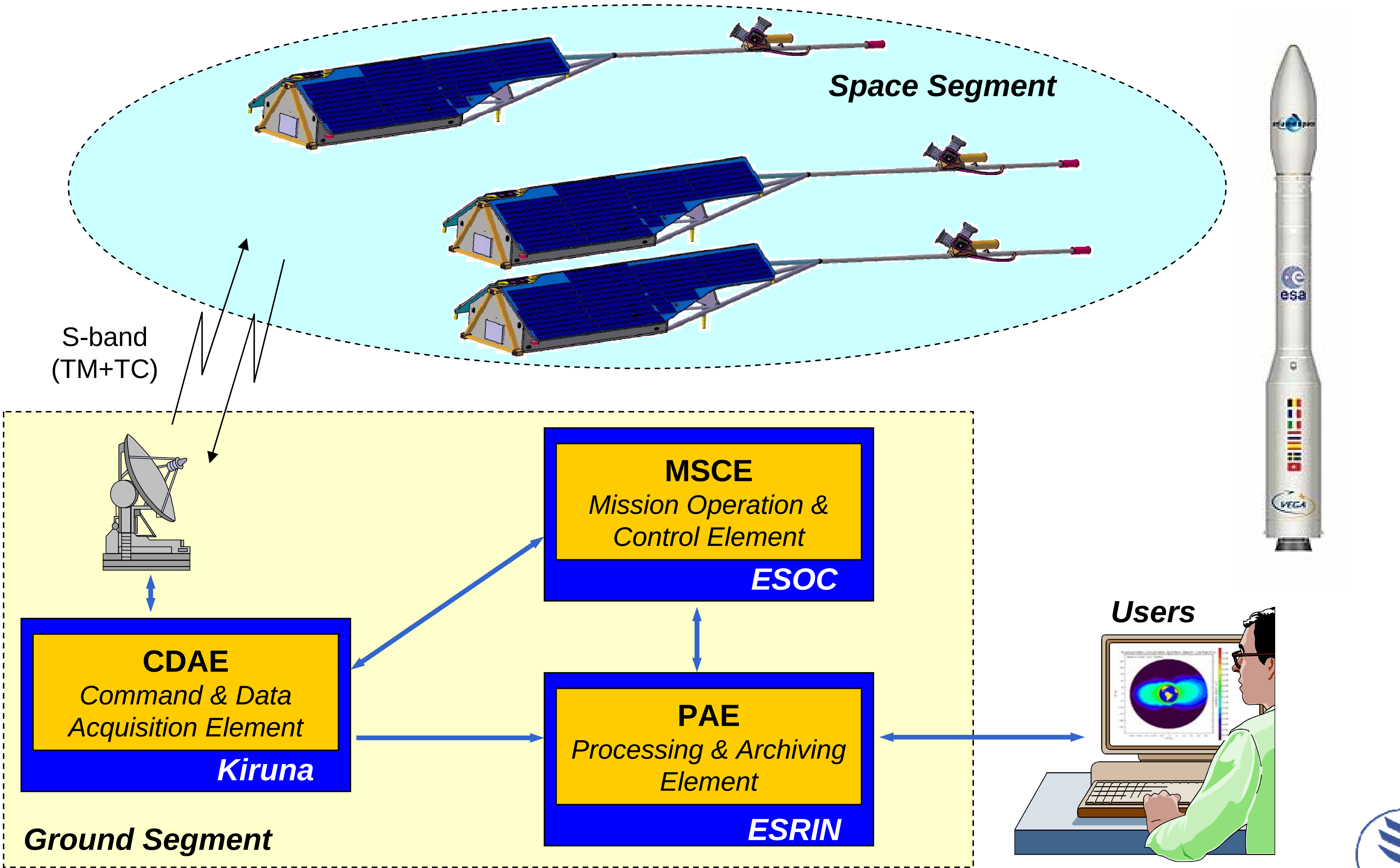
- A Feasibility Studies
- B Preliminary Design
- C Detailed Design
- D Manufacture, Assembly & Test
- E1 LEOP & Commissioning
- E Nominal Operations

- SRR System Requirements Review
- PDR Preliminary Design Review
- CDR Critical Design Review
- FAR Flight Acceptance Review
- Launch
- IOCR In-Orbit Commissioning Review

Industrial Consortium

- Prime Contractor: EADS Astrium GmbH, Germany
  - Project Managemnt & Control, System Engineering, Electrical Engineering, Instruments, Procurement, Product Assurance
- Main Sub-Contractors:
  - EADS Astrium Ltd., UK — Mechanical, Thermal, AIV
  - GFZ Potsdam, Germany — End-to-End System Simulator , Calibration & Validation
  - DNSC, Denmark — Level 1b Processor
  - DTU, Denmark — VFM Instrument

Swarm System Elements



Spacecraft Design Overview

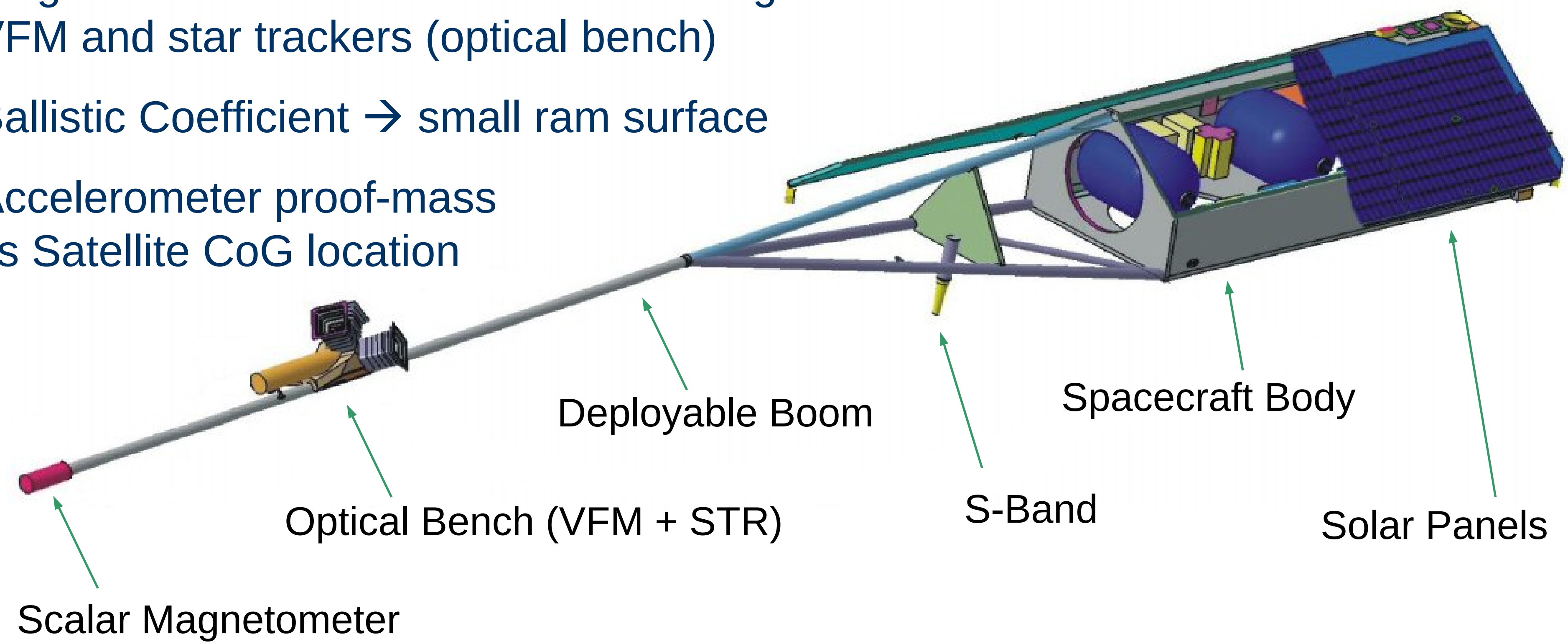
Design Drivers

Magnetic Cleanliness → Magnetometers on deployable boom, non-magnetic materials and caution during handling

Magnetic Field Vector Attitude Knowledge → ultra-stable connection between VFM and star trackers (optical bench)

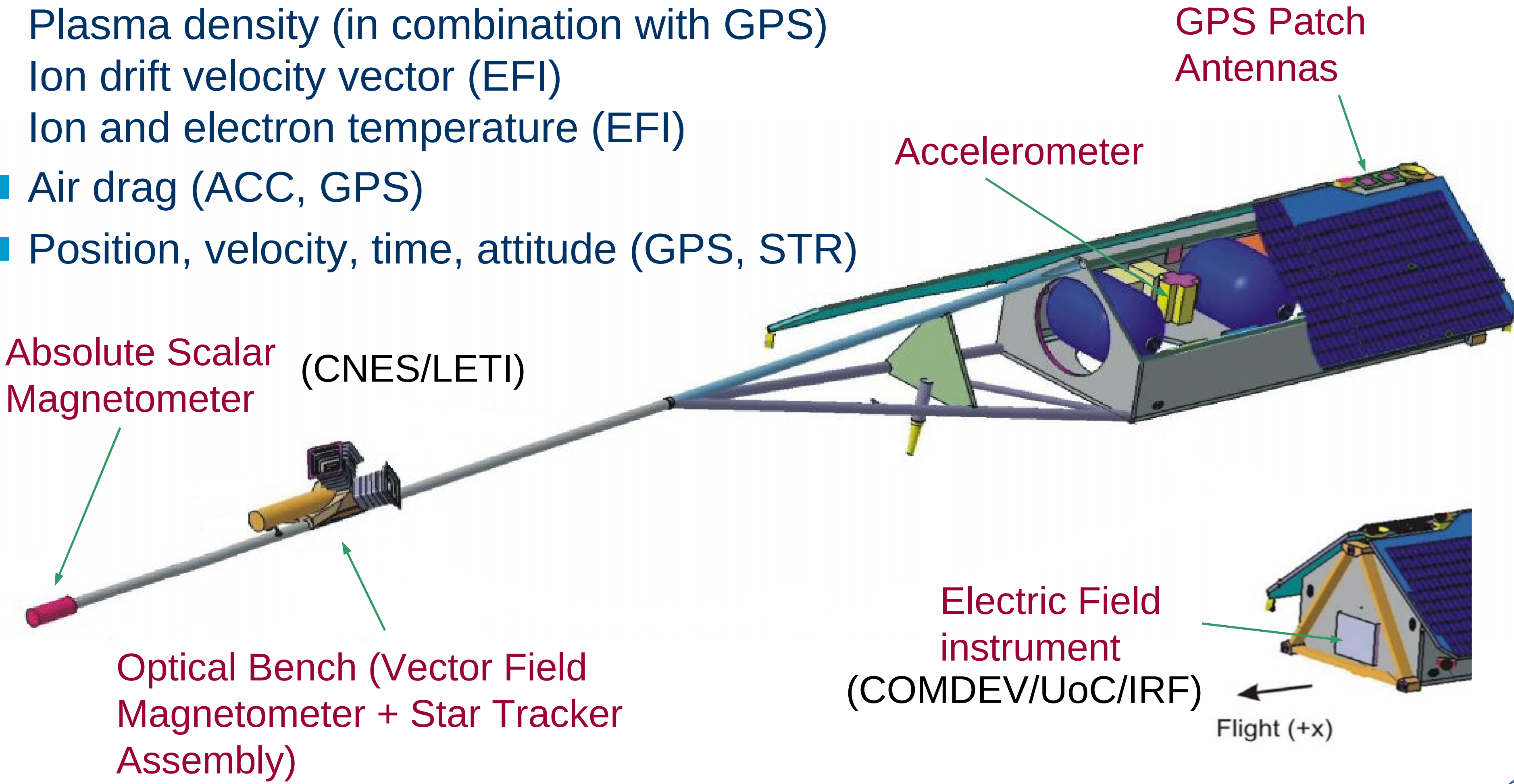
Ballistic Coefficient → small ram surface

Accelerometer proof-mass vs Satellite CoG location

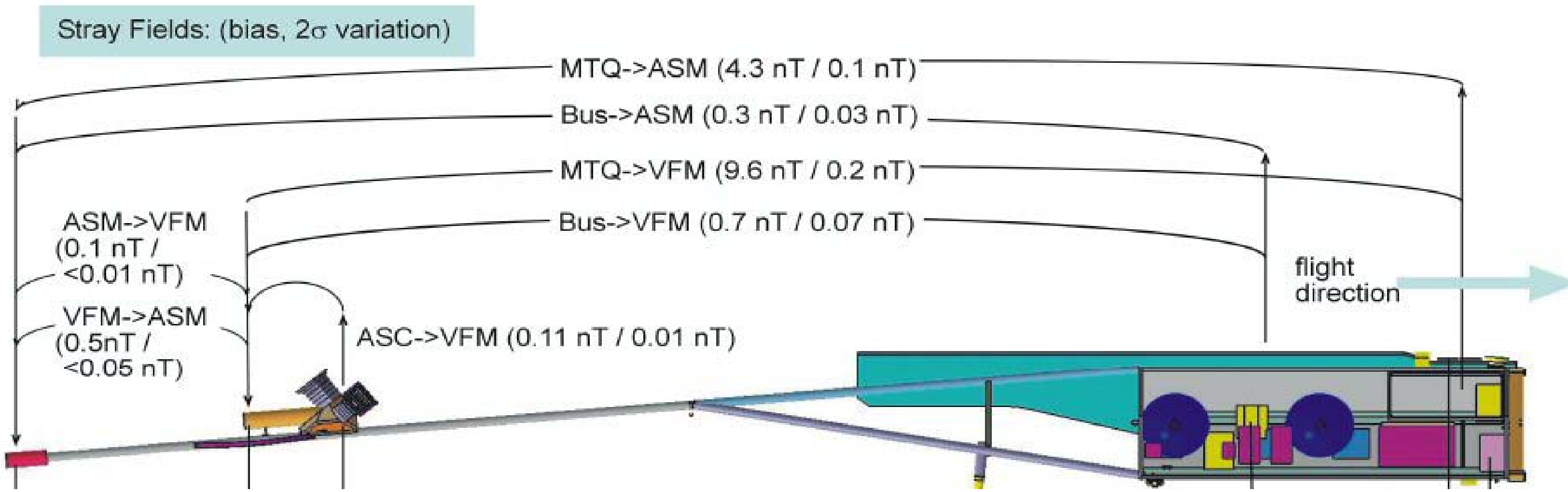


Instruments

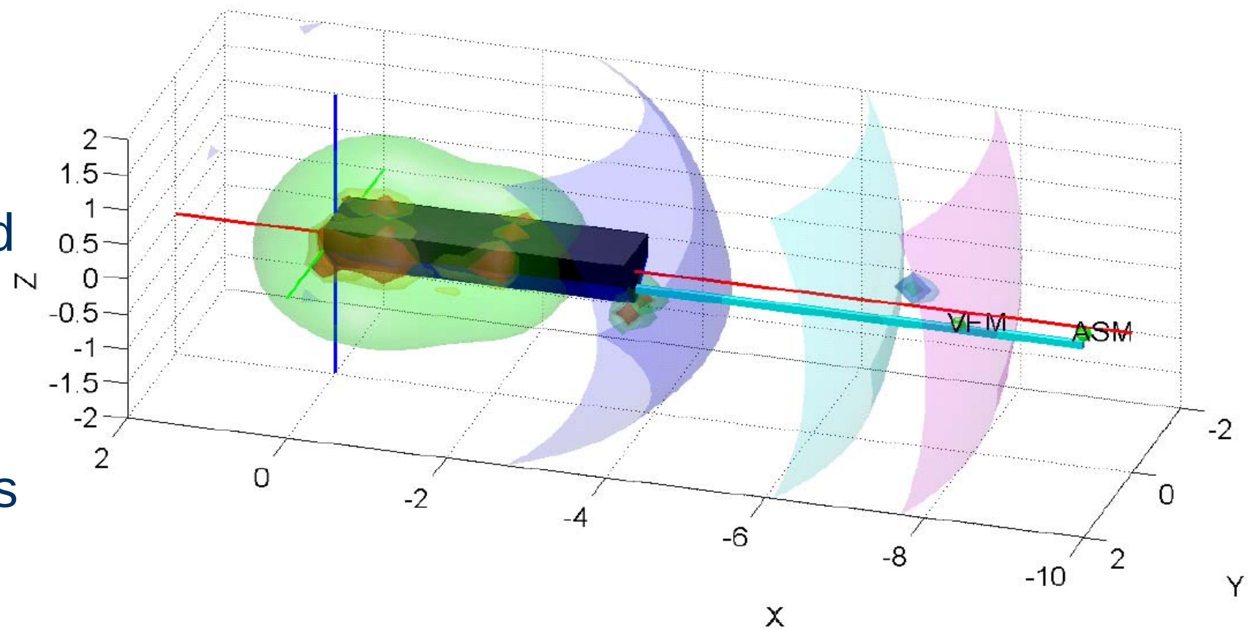
- Magnetic field magnitude (ASM) and vector components (VFM)
- Electric field vector components
  Plasma density (in combination with GPS)
  Ion drift velocity vector (EFI)
  Ion and electron temperature (EFI)
- Air drag (ACC, GPS)
- Position, velocity, time, attitude (GPS, STR)



Magnetic Cleanliness



- Allocate magnetic disturbances
- Setup Magnetic Budgets at ASM and VFM
- Model and Monitor Budgets during all development phases



Spacecraft Data Sheet

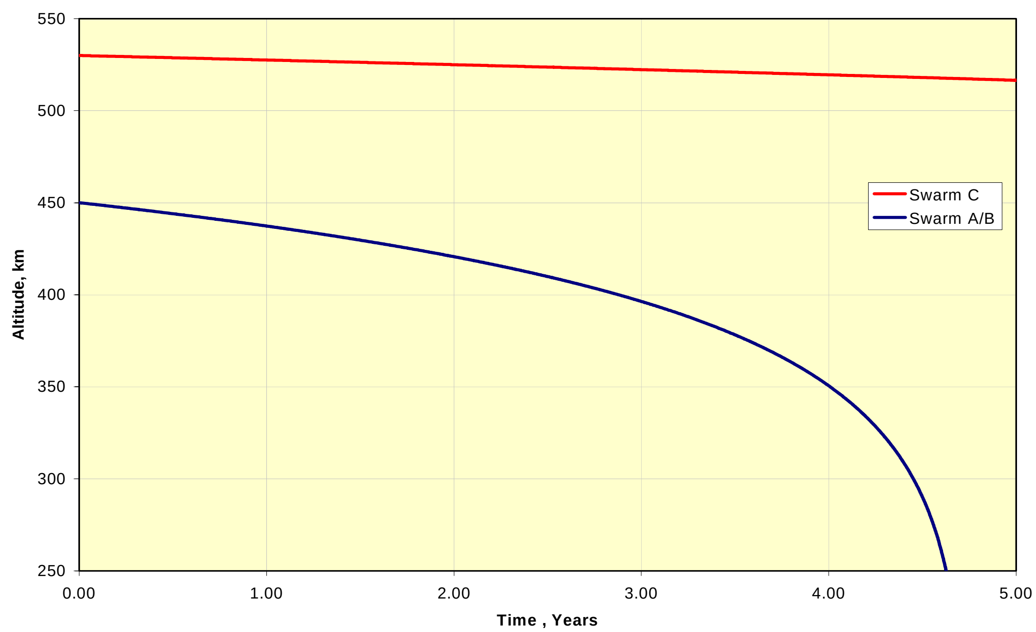
Mass ▪ Dry Mass ~400 kg ▪ Cold Gas Propellant, 40-100kg, N or CF4	**Attitude and Obit Control** ▪ 3-axes stabilised ▪ Thrusters ▪ Magnetorquers (air coil) ▪ Magnetometers ▪ GPS ▪ CESS	**Power** ▪ 240 W total ▪ 95 W Instruments ▪ GaAs TJ Solar Cells ▪ Solar Panel positive grounding ▪ Li-Ion Battery
Dimensions ▪ Length 9.4 m ▪ Width 1m (SC body) ▪ Height 0.85m ▪ Ram surface ~0.7m^2	**Data & Comms** ▪ 1.5 Gbit/day ▪ 1 dump per day ▪ S-band 2 GHz band ▪ 1.3 or 6 Mbps downlink rate	**Launcher Class** ▪ Vega, Rockot, Dnepr (LEO, 1.5 – 2 tons)

Swarm Orbits

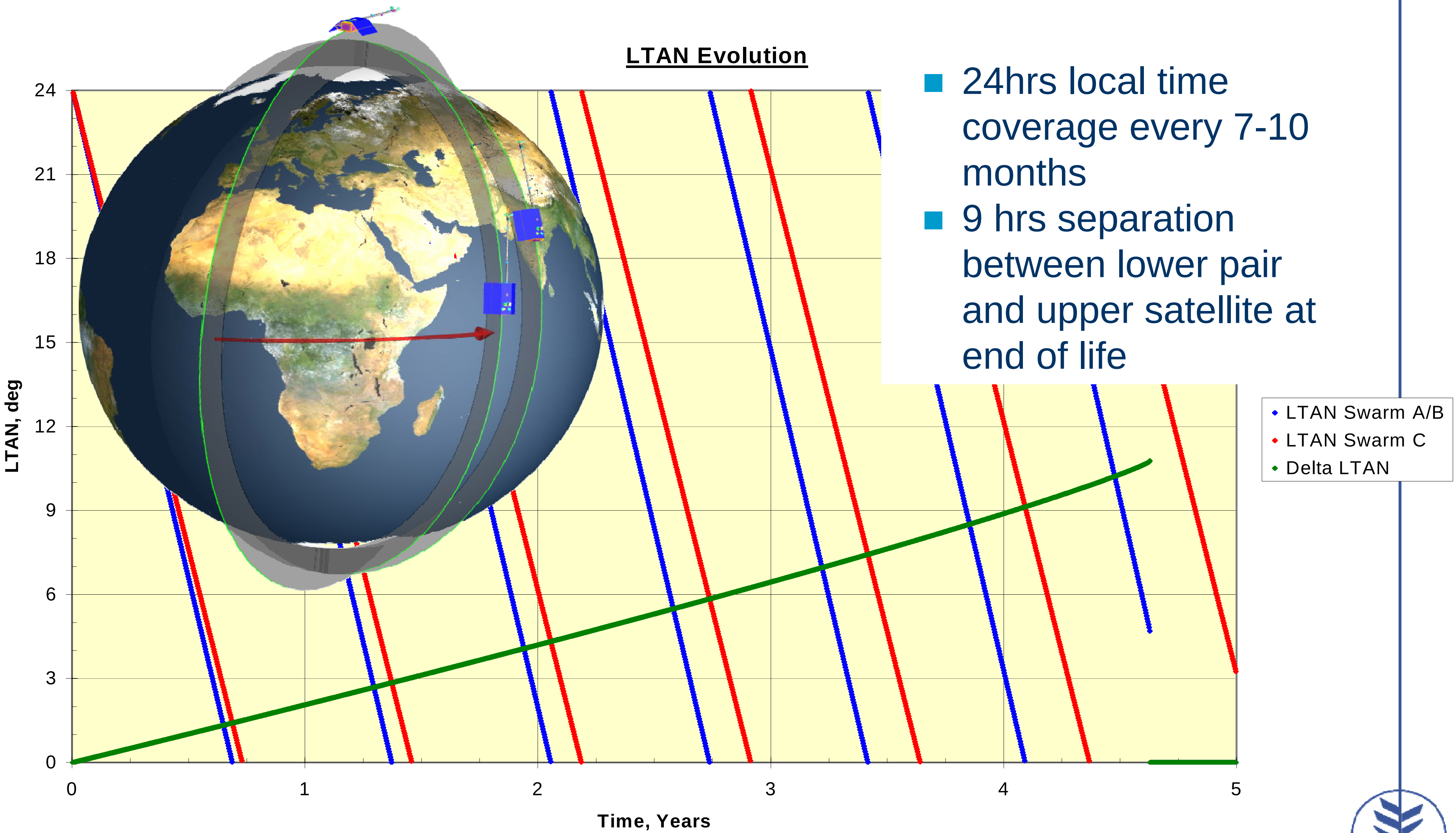
- Polar
- Circular
- Mission Duration
  - 3 months commissioning
  - 4 year nominal operations

	Swarm A	Swarm B	Swarm C
Altitude, (R_E=6378 km)	450	450	530
Inclination	87.4	87.4	88.0
RAAN	X	X+1.4 deg	Y

- Altitude Decay due to Atmospheric Drag
  → Launch into Solar Max
  → Spacecraft Ballistic Coefficient
  → Station Keeping Manoeuvres

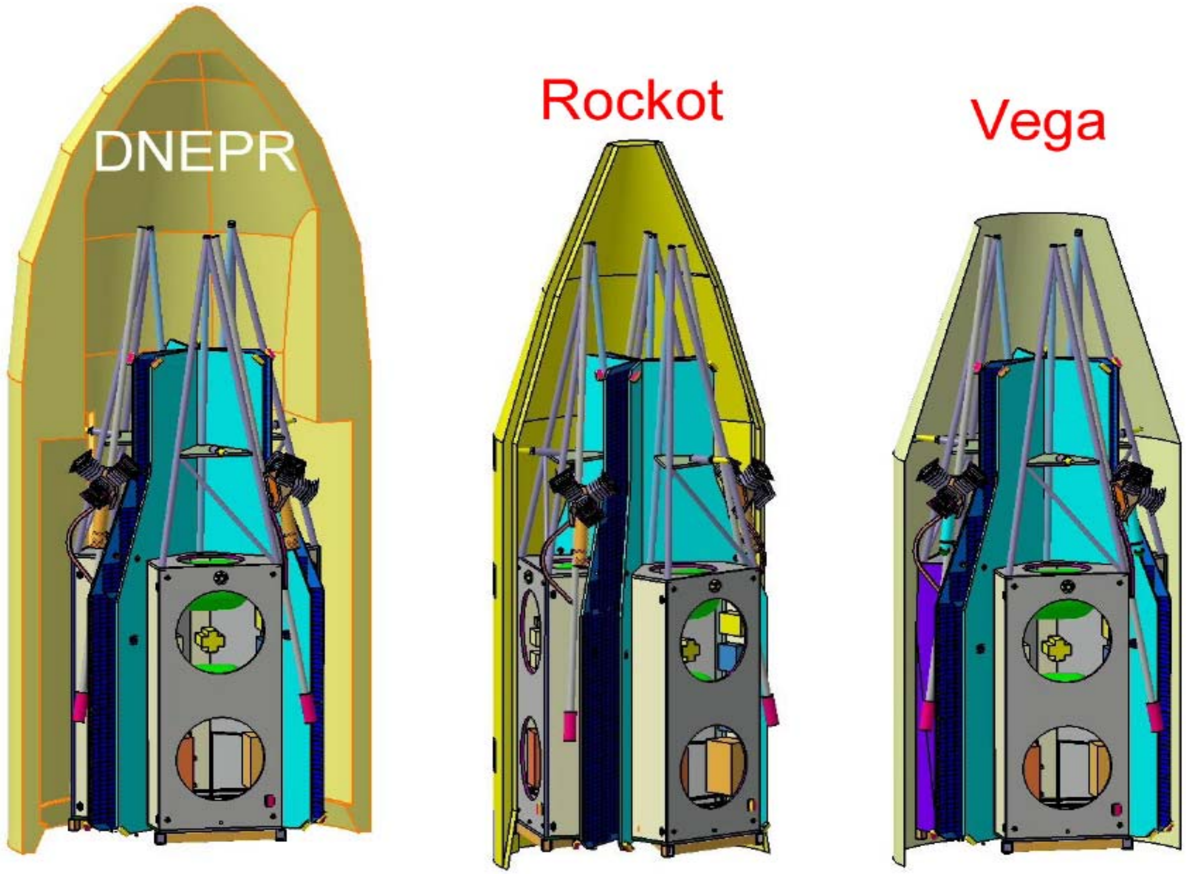


Mission Analysis



- 24hrs local time coverage every 7-10 months
- 9 hrs separation between lower pair and upper satellite at end of life

Launcher & Orbit Injection



Launcher Baseline

- Single Launch
- Compatibility with 3 different Launchers (2 after PDR)
  - → Total Mass
  - → CoG
  - → Accommodation

Injection Scenario Analysis

- Intermediate orbit: embark propellant for final orbit acquisition ; significant number of manoeuvres required
- Direct injection: re-ignitable upper stage; satellite CoG location

The Swarm Mission

Primary Objectives

- core dynamics, geodynamo processes, and core-mantle interaction
- lithospheric magnetisation
- 3-D electrical conductivity of the mantle

Theme: Earth's Interior

Unique view "inside" the Earth from space for core, mantle & crust

correction

- electric currents in magnetosphere and ionosphere

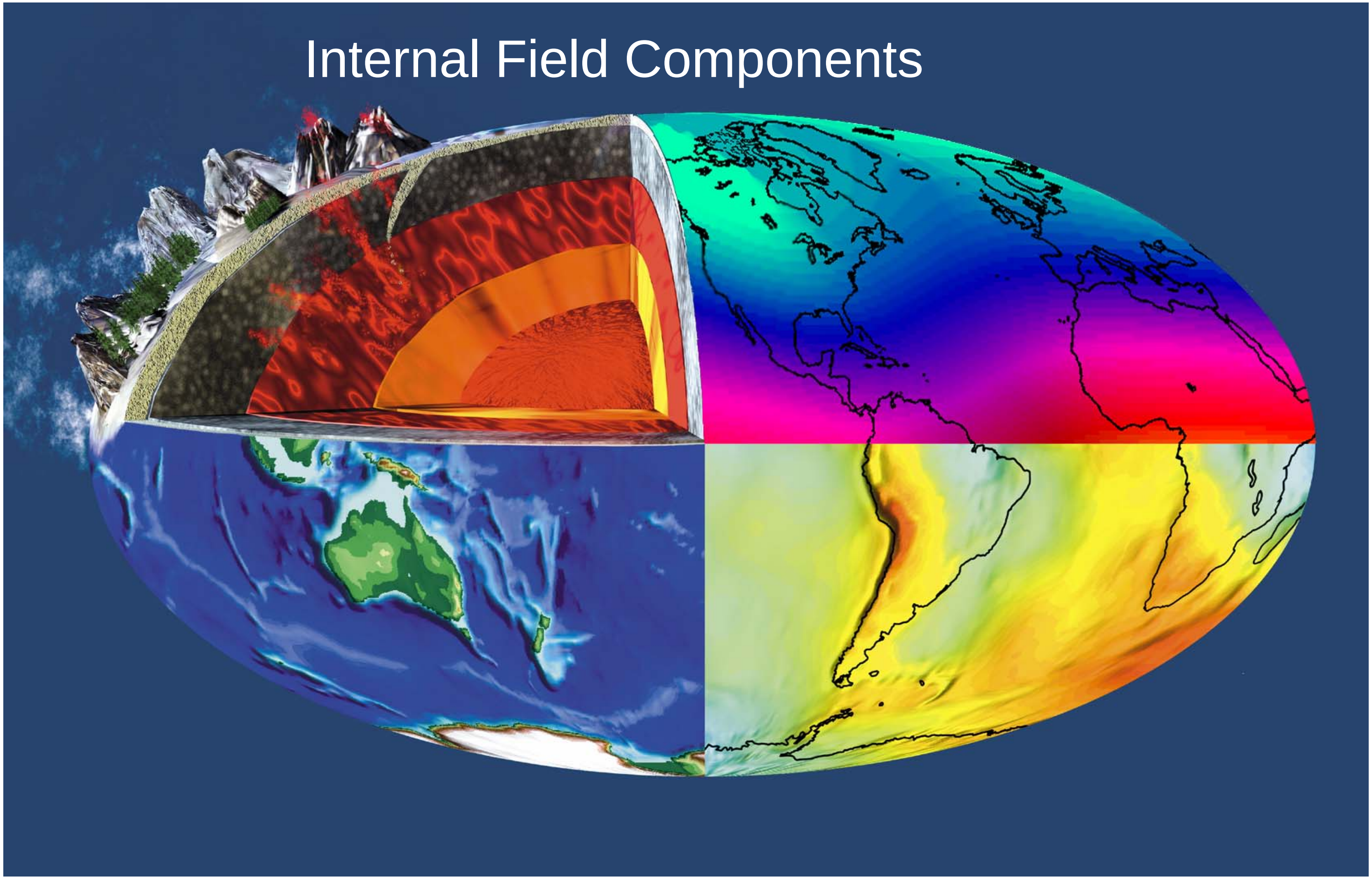
Theme: Physical Climate

Sun's influence within Earth system

Secondary Objectives

- magnetic forcing of the upper atmosphere
- magnetic signature related to ocean circulation

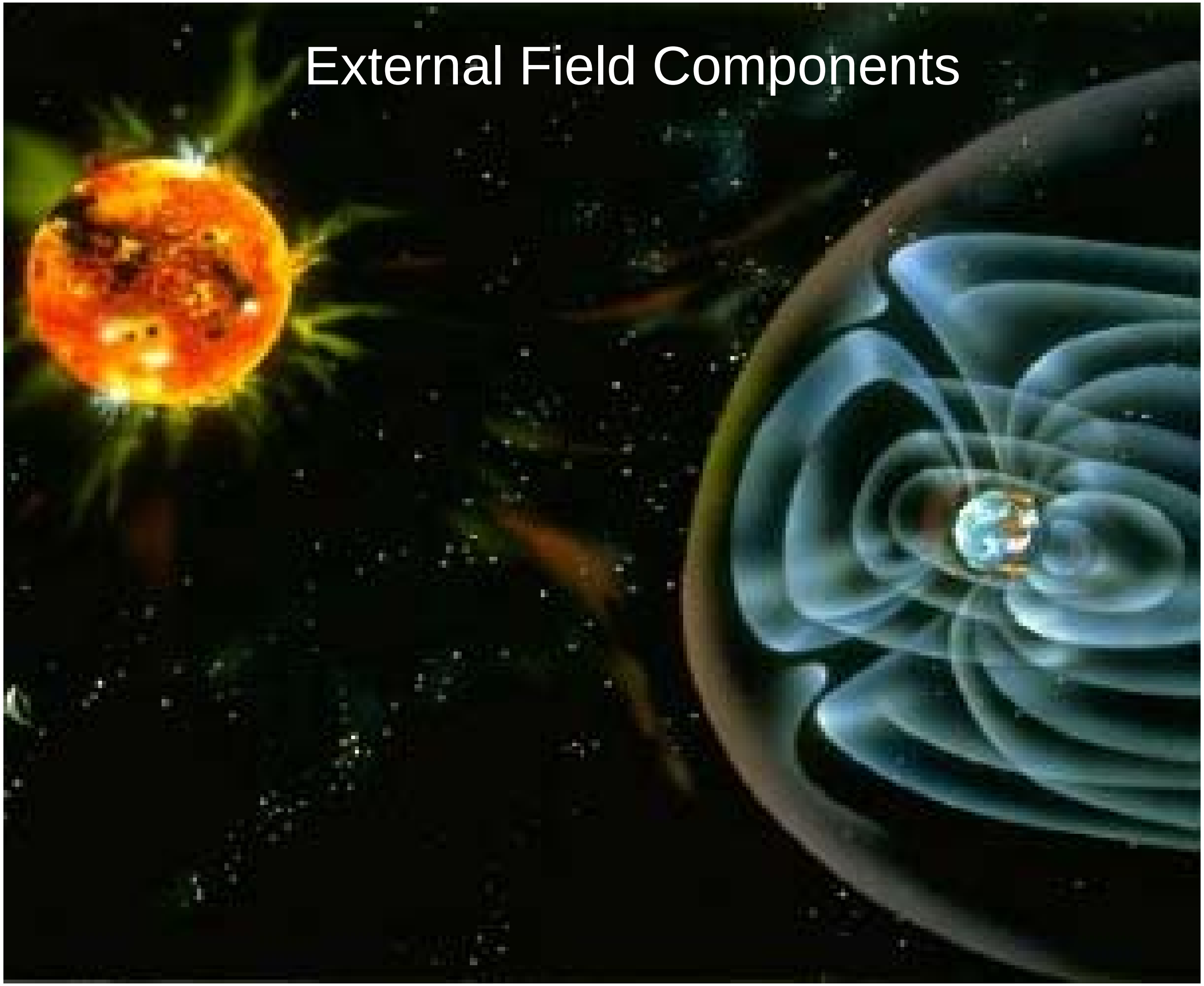
Anticipated Signals at 400km



Anticipated Signals at 400km

Research objectives	Time range	Spatial range	Signal range	Signal at certain wavelength (wl)	Measurement (B = magnetic)
Core dynamics and geodynamo processes	static	3000 km to global	< 65000 nT	2.35 nT @ 3000 km wl	B-field vector, attitude and position
	3 months to decades	2500 km to global	±200 nT/yr	0.025 nT/3 months @ 2850 km wl	
Lithospheric magnetisation	decades to static	300 km to 3000 km	±25 nT	2.35 nT @ 3000 km wl 0.009 nT @ 360 km wl	B-field vector, attitude and position
3-D mantle conductivity	1.5 hours to 11 years	300 km to global	±200 nT	n.a. (modelled as conductivity)	B-field vector, attitude and position
Ocean circulation	12 hours to 2 years	600 km to 10000 km	±5 nT	0.5 nT @ 10000 km wl 0.01 nT @ 600 km wl	B-field vector, attitude and position

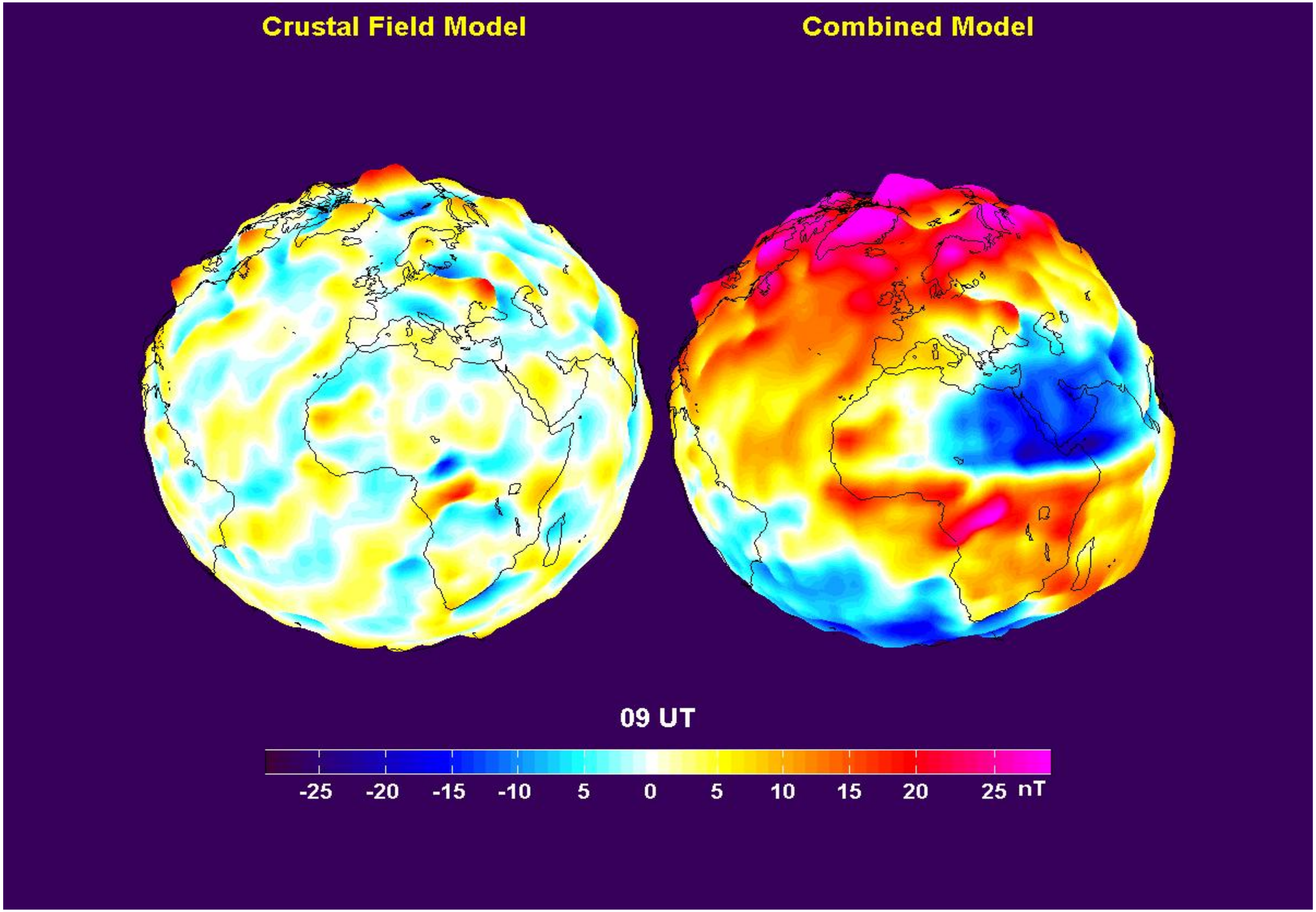
Anticipated Signals at 400km



Anticipated Signals at 400km

Research Objectives	Time Range	Spatial Range	Signal Range	Measurement (B=magnetic E=electric)
Ionosphere-magnetosphere current systems	0.1 sec to 11 years	1 km to global	B-field: ±1000 nT E-field: ±0.2 V/m	B-field, E-field, and ion drift velocity vectors, attitude and position
	10 sec to 3 months	10 km to global	Ion drift velocity: ±4000 m/s	
Magnetic forcing of the upper atmosphere	10 sec to 2 years	20 km to global	Plasma density $1 \cdot 10^{8}$ m^{-3} to $5 \cdot 10^{13}$ m^{-3} Air drag: $1 \cdot 10^{-5}$ m s^{-2}	B-field and E-field vectors, ion and electron temperature and plasma density, acceleration, attitude and position
	10 sec to 3 months	200 km to global	Ion and electron temperature: 1000-100000 K	

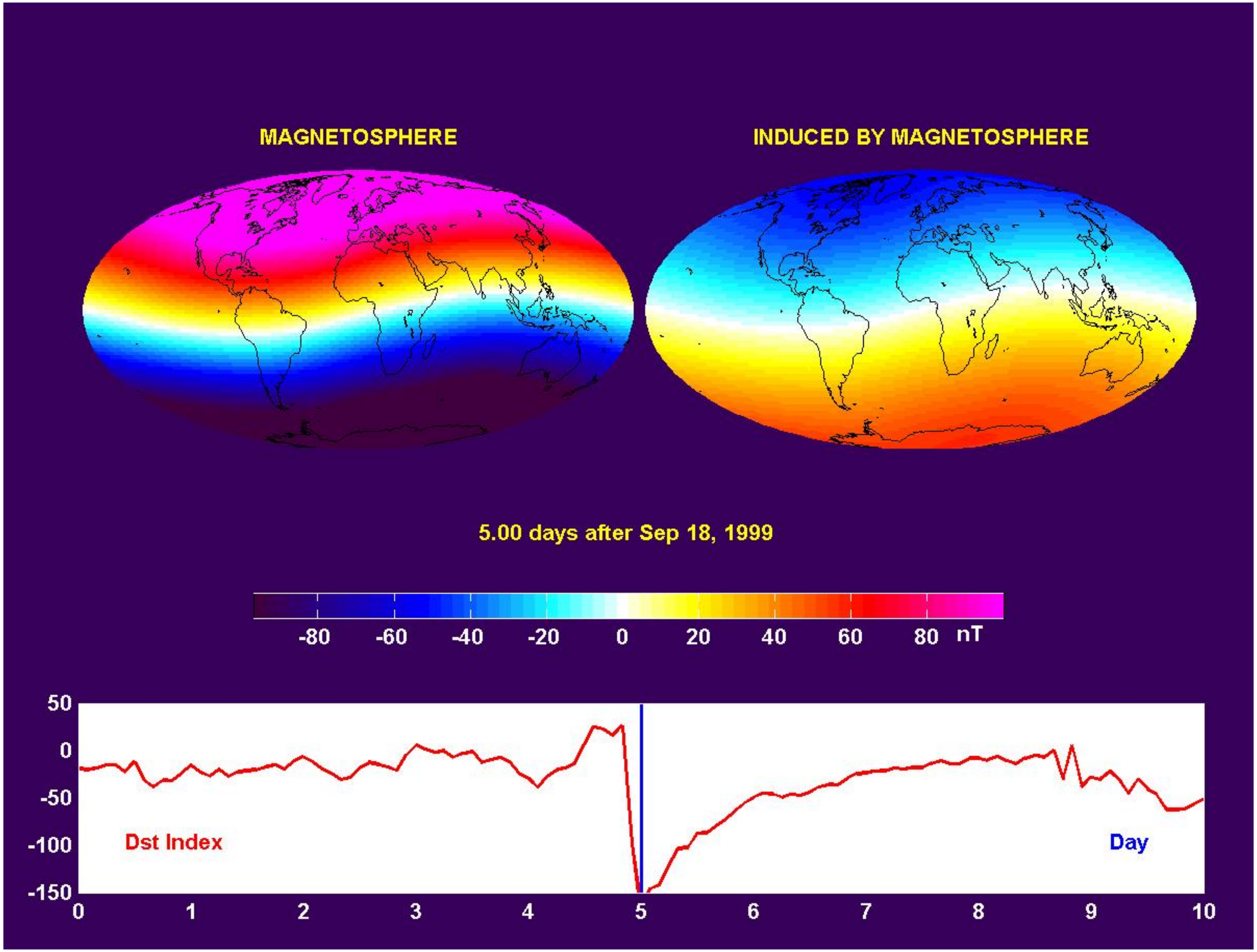
Magnetic Field Variation at 400km



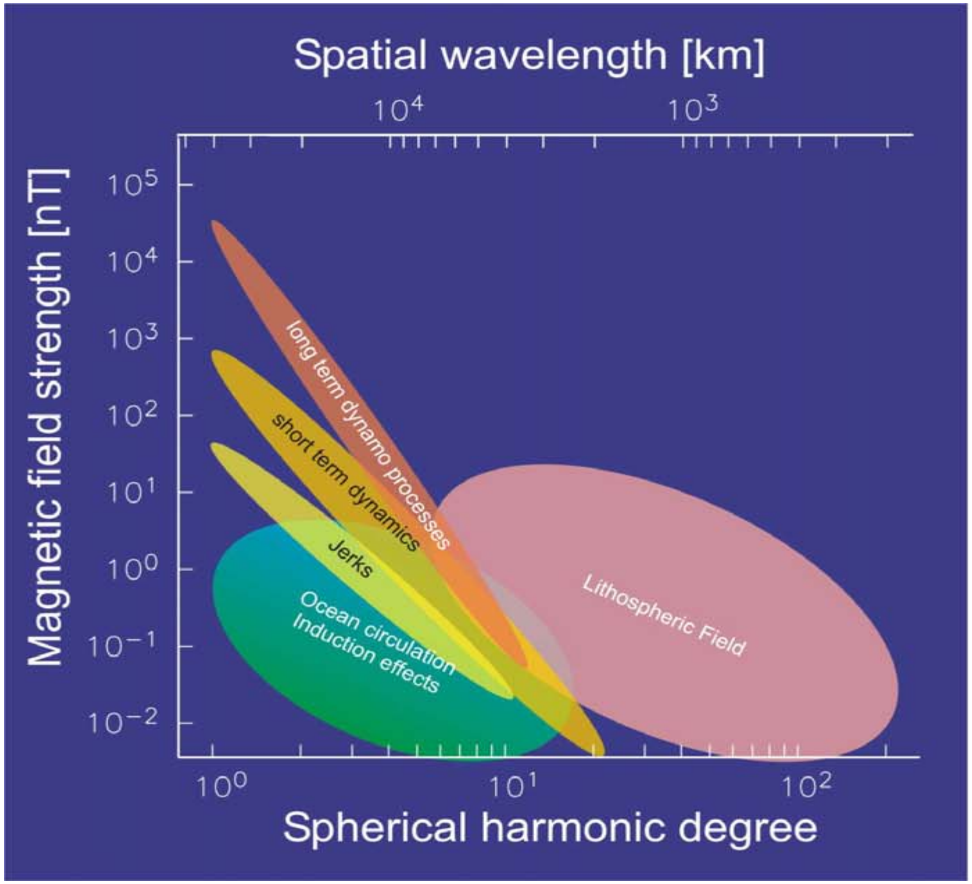
Magnetosphere (*Z*) at 400 km altitude

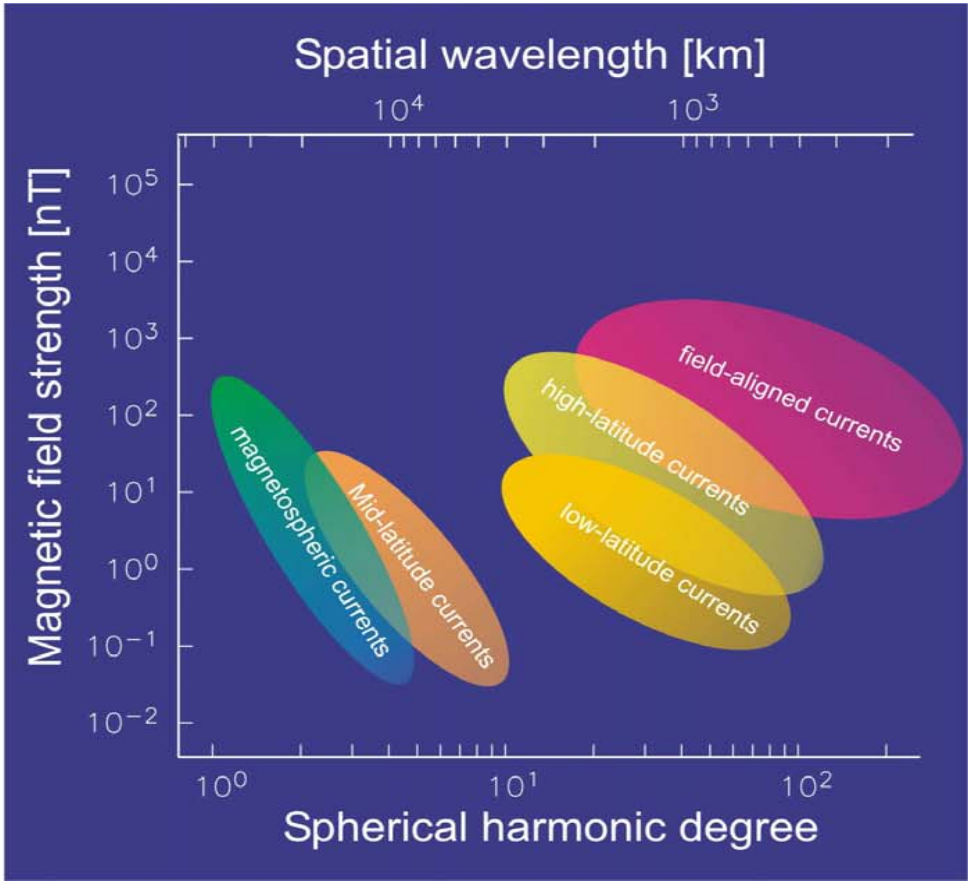
10 days

Changing Dst

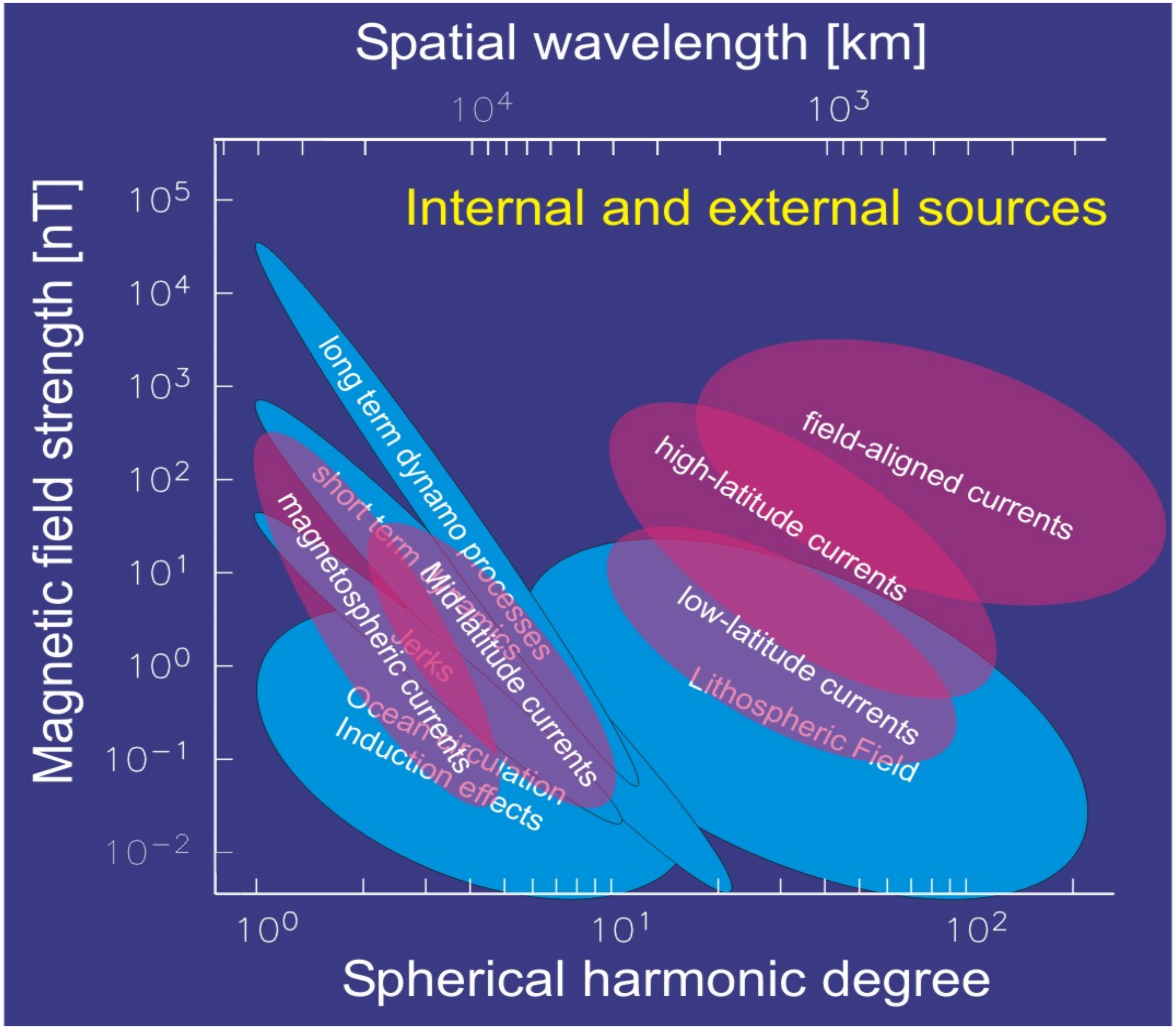


Magnetic Field Variation at 400km



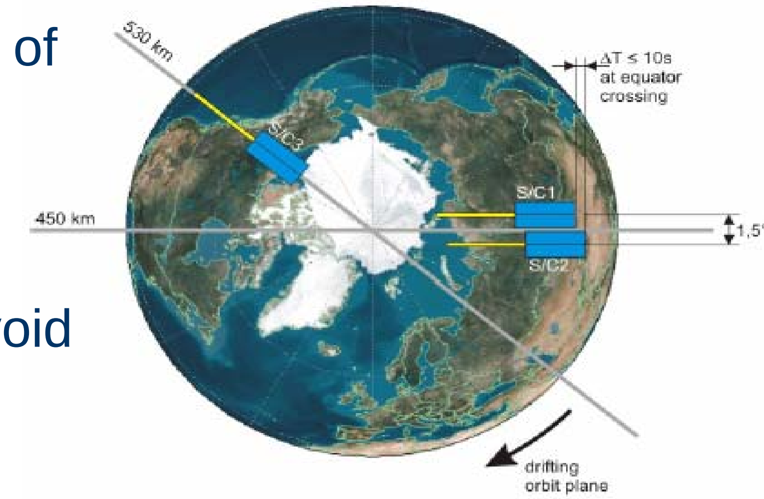


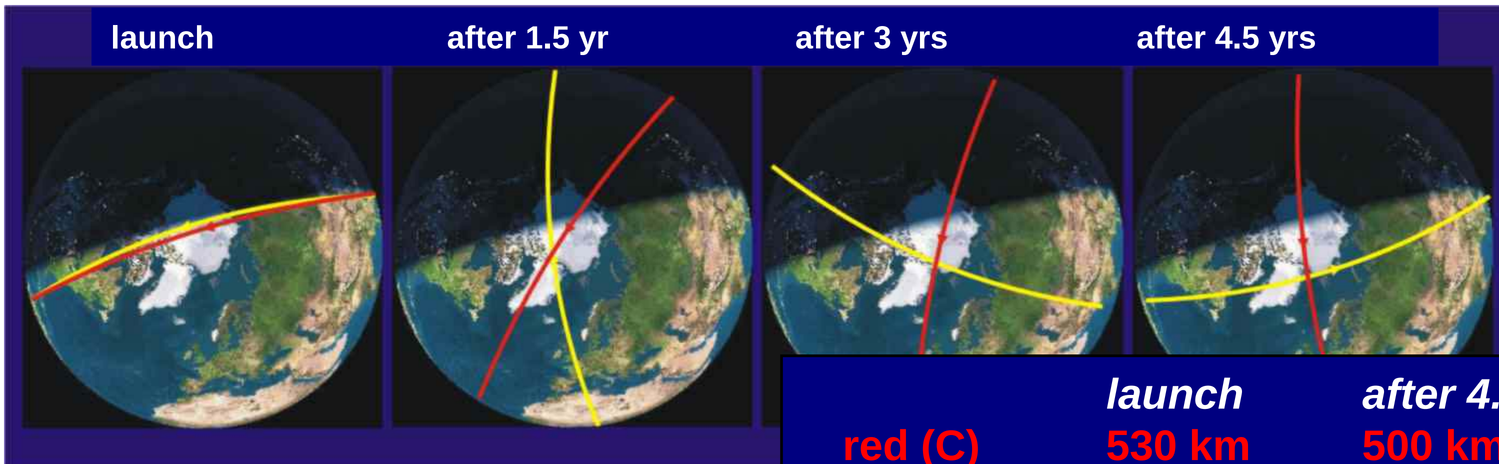
Magnetic Field Variation at 400km



Constellation Requirements

- 4 years operational phase
- Low altitude down to 300km (or lower) and pair of satellites for “zoom” in on crustal signal
- Altitude difference: higher (<530km) & lower satellites (< 450km)
- 24 hours LT coverage within 7-10 months to avoid seasonal or yearly periods ->inclination range between 86°-88°.
- Inclination difference: drift between orbital planes up to 9 hours LT after four years



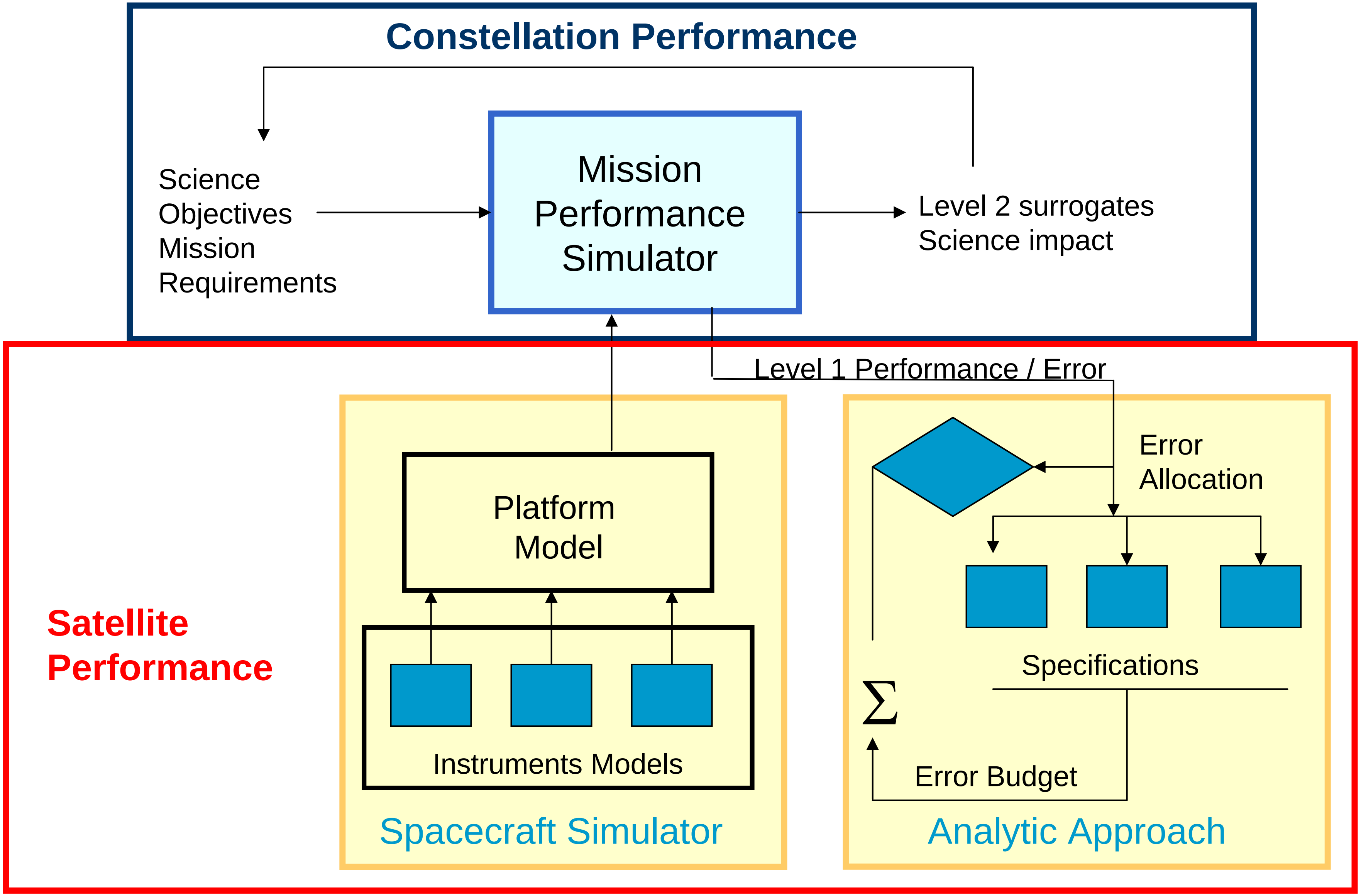


	launch	after 4.5 years
red (C)	530 km	500 km
yellow (A,B)	450 km	300 km

Studies

Issue	Activity	Result	
"Ideal" Constellation and Mission Impact	Closed loop simulation: recovery of models related to primary objectives	3 satellites concept as baseline	✓
Accelerometer necessary for air drag product ?	Air drag from single satellite precise orbit analysis against accelerometer data	Complementary information	✓
Impact of joint use electric and magnetic field data	Coupled model simulation: check different current regimes & develop approaches for analysis	FAC estimation Horizontal currents Activity Indices	✓
Quantify role of ocean circulation on performance	Forward modelling ocean circulation model effects on satellite data	Impact demonstrated	✓
Improved Comprehensive magnetic field Inversion Analysis	Higher data sampling rate in measurement frame, lower pair "gradients", multi-satellite alignment	Data rate Rest ongoing	✓

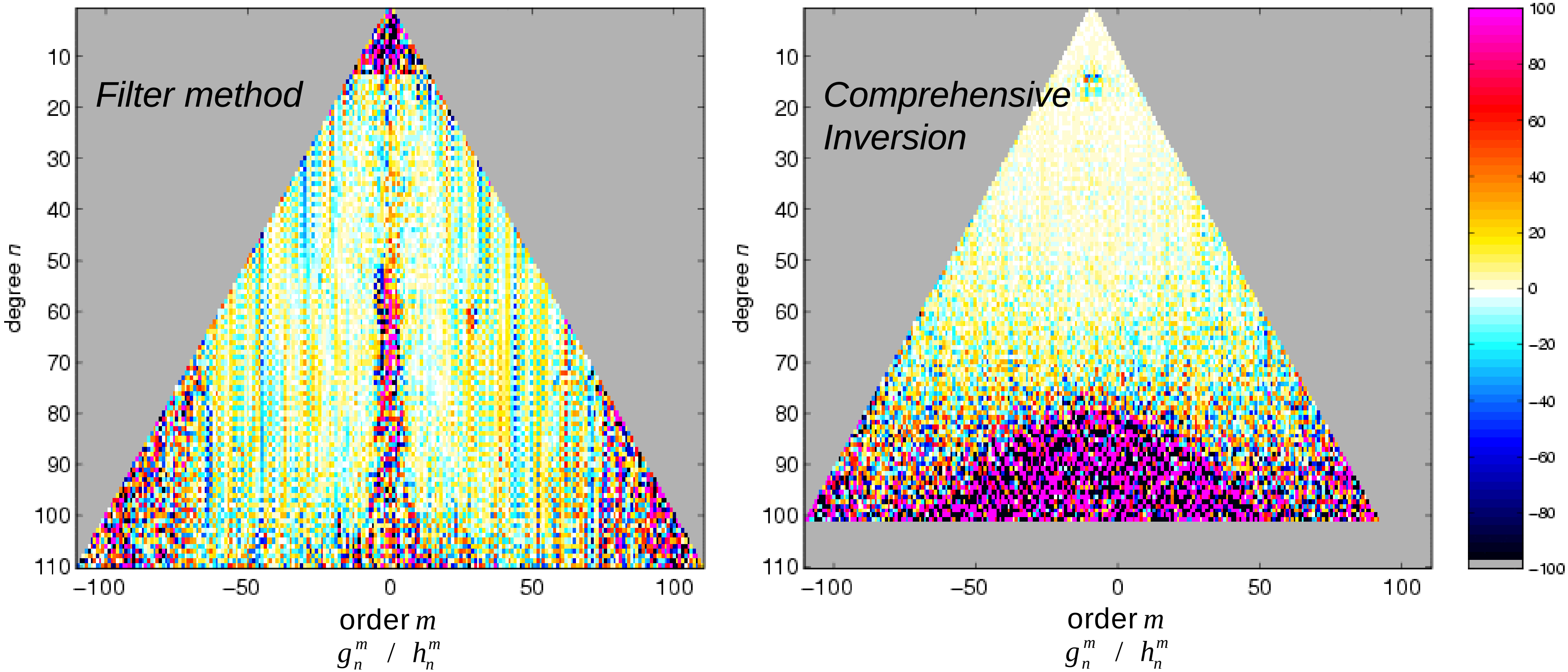
End-to-End Approach



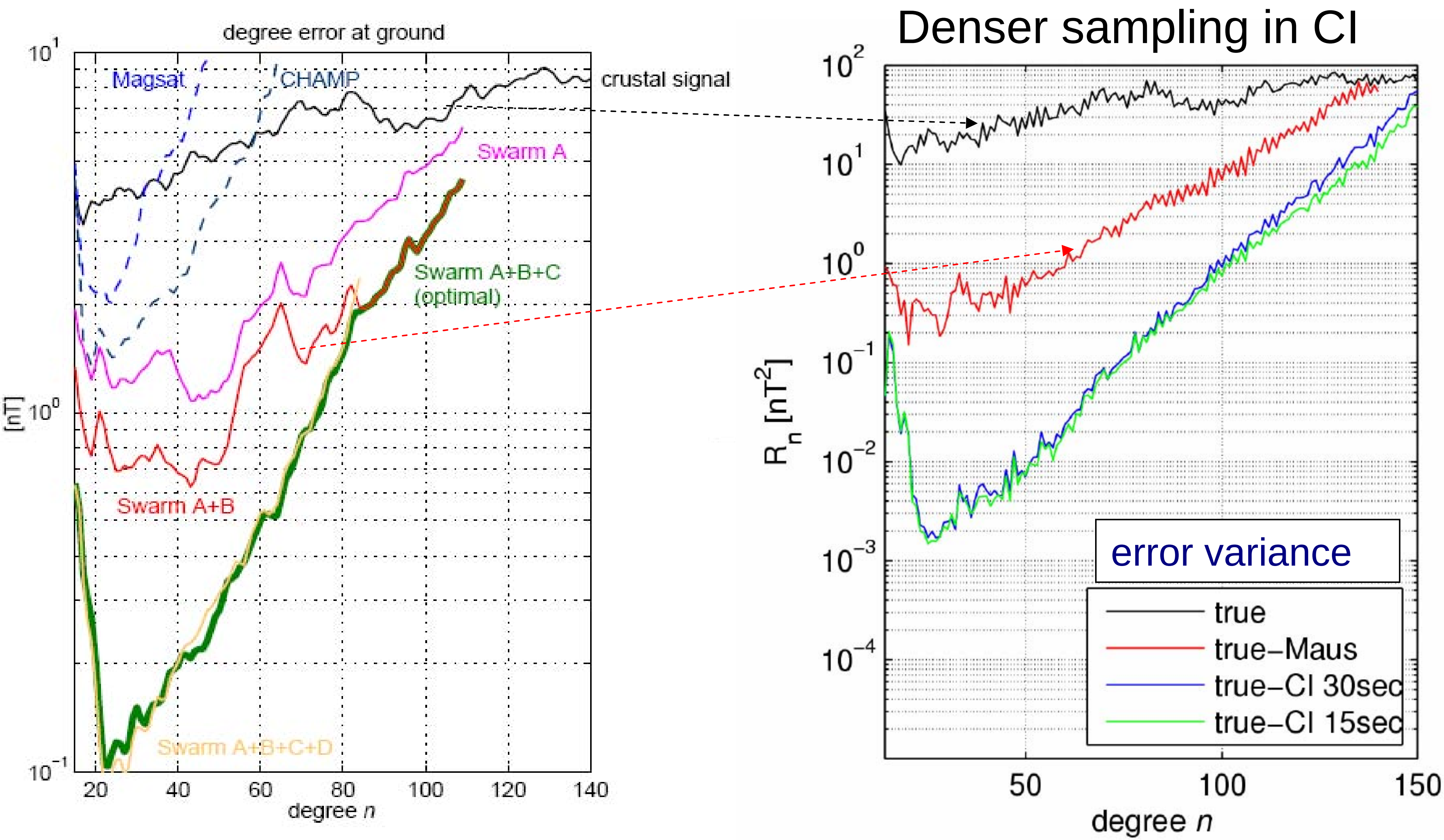
Example: lithosphere model performance

Phase A status

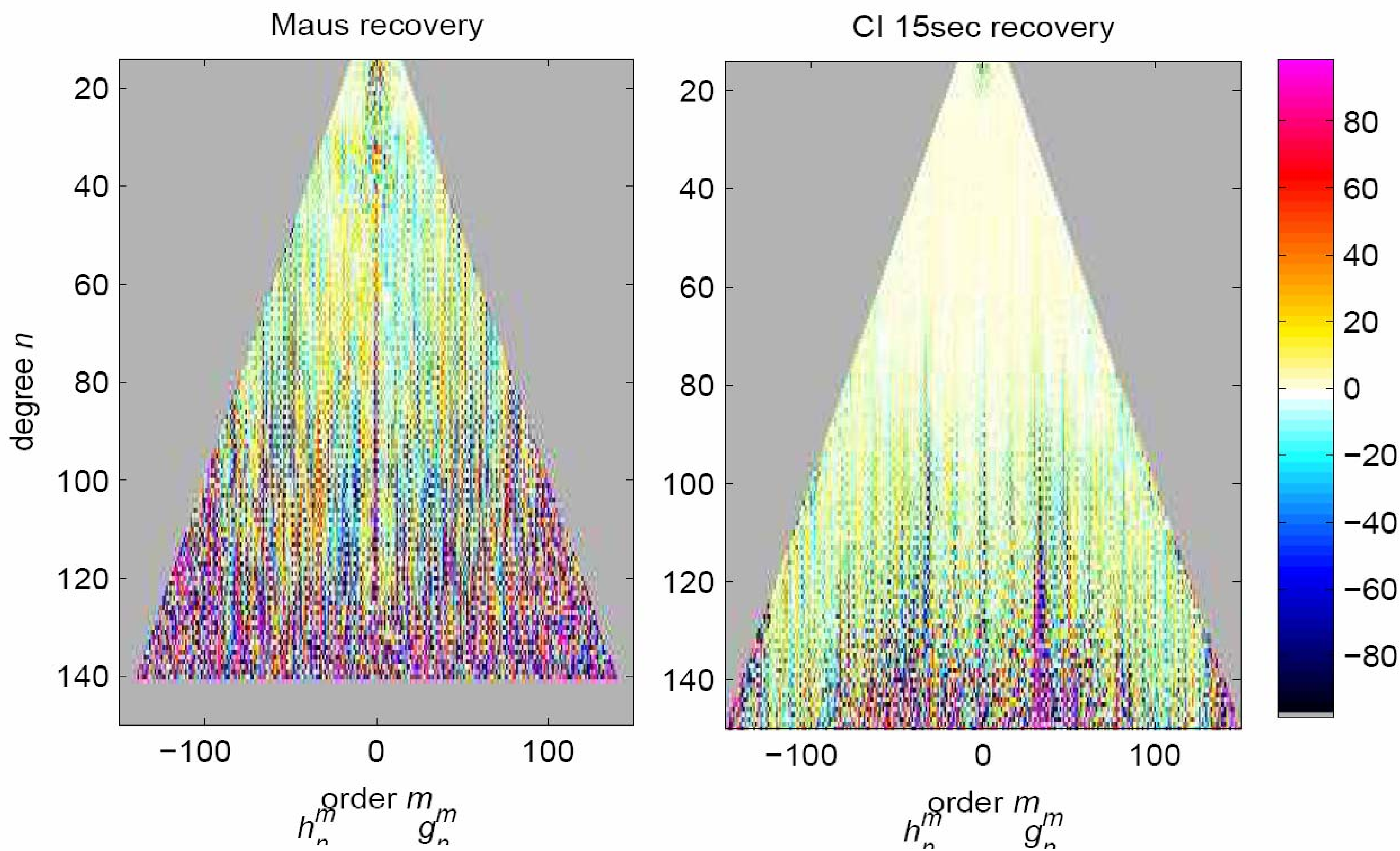
- Filter method is superior for $n > 70$
- CI superior at $n<70$, especially for near-zonal terms (m close to 0)



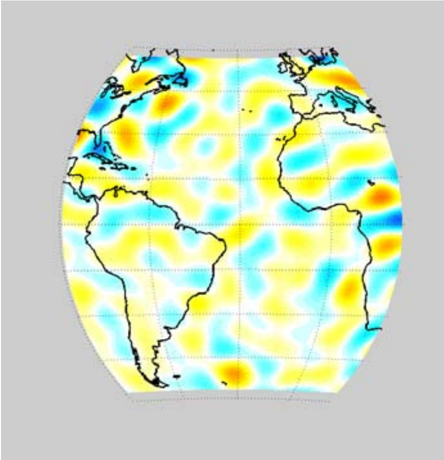
Assessment: Improved Lithospheric Field



Assessment: Improved Lithospheric Field

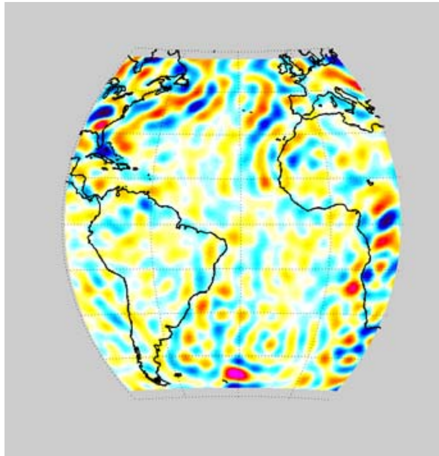


Improvement of Lithospheric Field Model



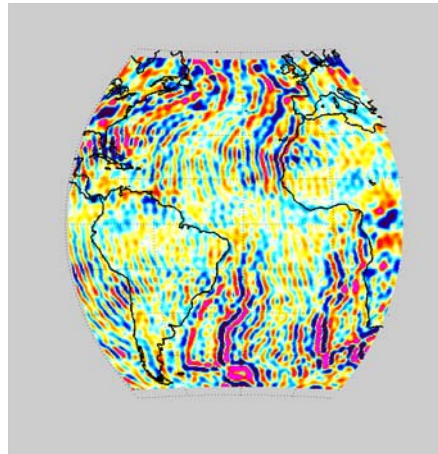
Before Ørsted ...

N = 30, resolution: 1330 km



with Ørsted & CHAMP

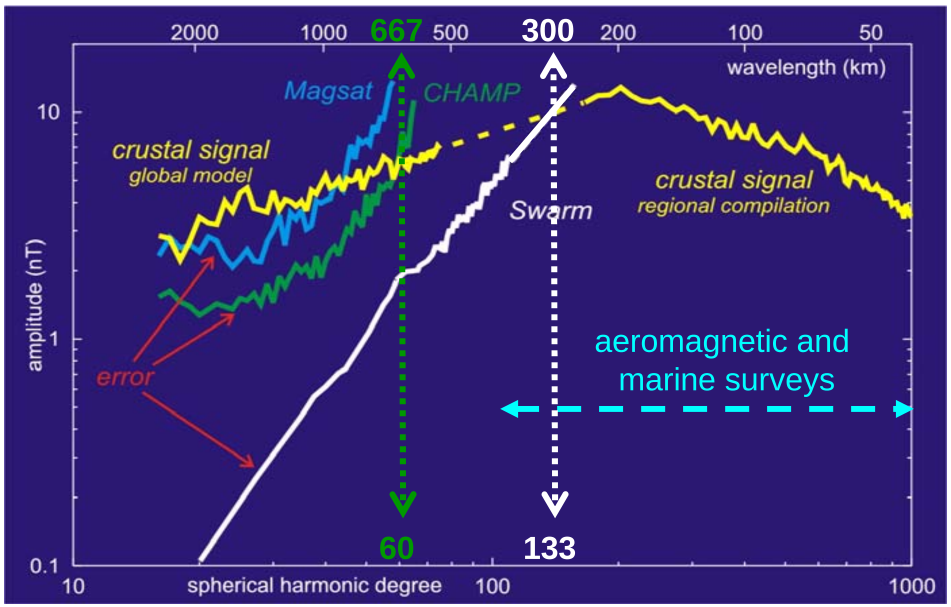
N = 60, resolution: 670 km



and with *Swarm*

> N = 133,
resolution: 300 km

Magnetic field of Earth's crust radial component at 10 km altitude



Product levels

Level 0	Raw measurements and housekeeping data
Level 1b	Magnetic field magnitude and vector Magnetic field vector Ion drift velocity vector Electric field vector Plasma density Ion and electron temperature Acceleration vector, linear and rotational Precise position, velocity and acceleration and attitude of spacecraft
Level 2	Global models of sources of the geomagnetic field Maps of field-aligned currents and their variability Regional models of ionospheric current systems Satellite-based indices Improved global ionospheric and plasmaspheric models. Improved parametrisation of atmospheric models. Thermospheric density and cross track winds. Quality assessment of the products

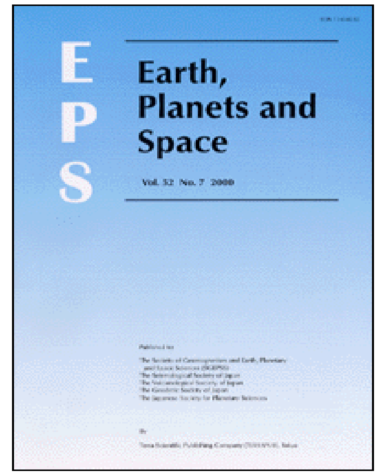
Open issues to be studied

- Develop procedures for correcting night time mid-low latitude ionospheric current and plasma effects
- Determination of thermospheric density information from constellation using ACC and GPS (current performance relates to a single satellite (CHAMP))
- Enhancement of the Phase A procedure to a full 3D-mantle conductivity retrieval
- Determination of ionosphere/plasmasphere electron density distributions from EFI and GPS from constellation analysis (current performance relates to a single satellite (CHAMP))
- Refinement of Ocean modelling/correction
- Any other new possibilities offered by the Swarm constellation with multi-instrument package

Scientific Interaction

- Dedicated Swarm workshops (like 1st Nantes, France '06)

- Special Issue of Earth, Planets and Space on Swarm
  Vol. 58 (No. 4), pp. 349-496, 2006
  http://www.terrapub.co.jp/journals/EPS/toc/5804.html



(Study) reports available at
http://www.esa.int/esaLP/LPswarm.html

- Announcements of Opportunity