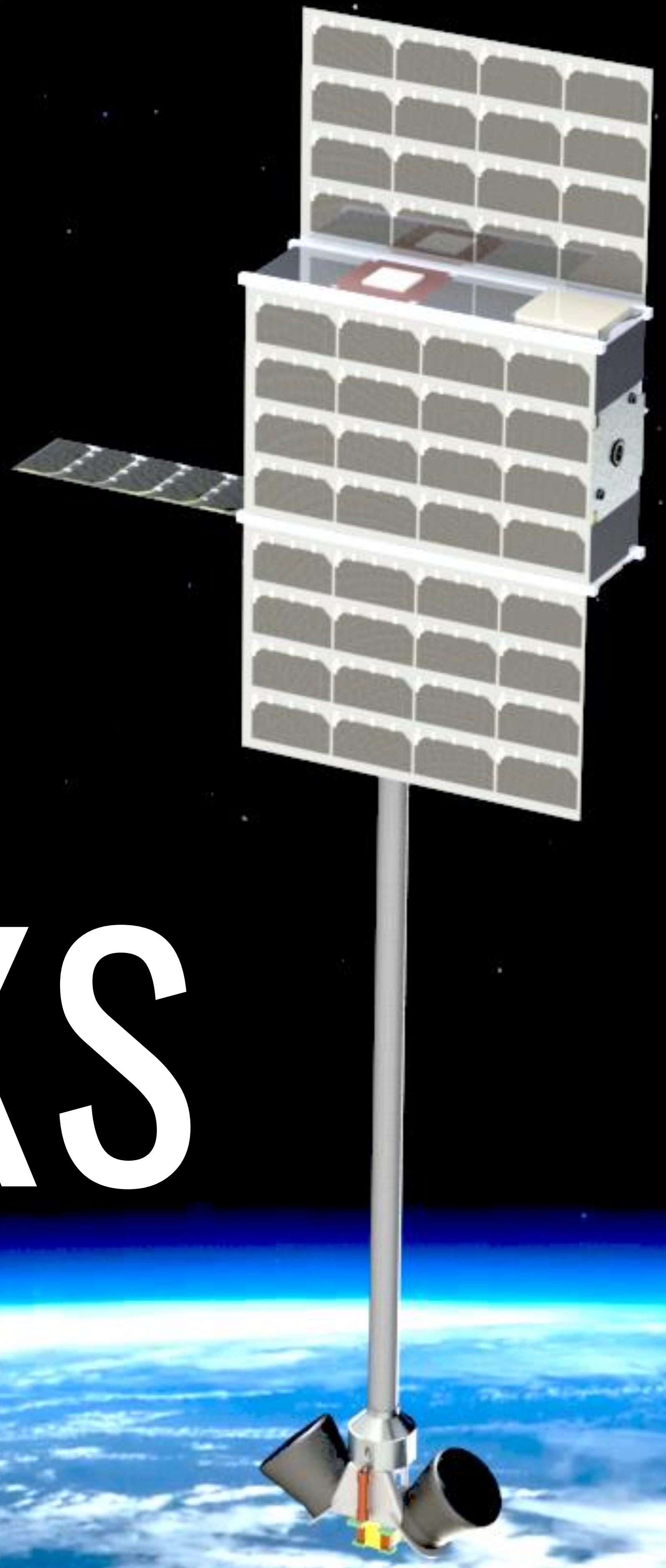
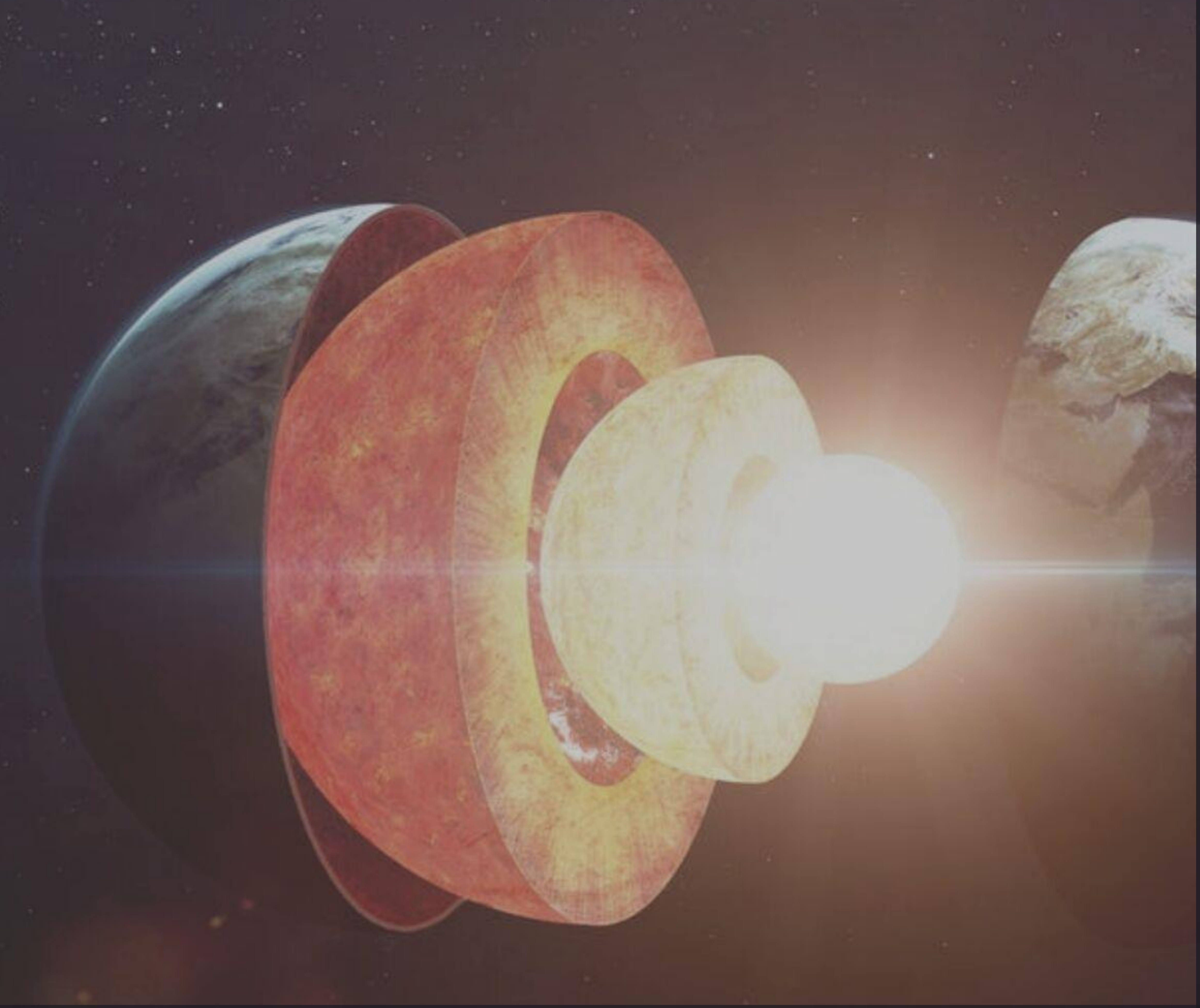
ALPBACH
SUMMER
SCHOOL
2019



TEAM RED

RUBIKS



MISSION OBJECTIVES

INVESTIGATE MANTLE COMPOSITION AND DYNAMICS, PARTICULARLY MANTLE PLUME FORMATION AND THEIR ROLE IN PLATE TECTONICS

MAGNETIC FIELD & GRAVITY FIELD MISSION

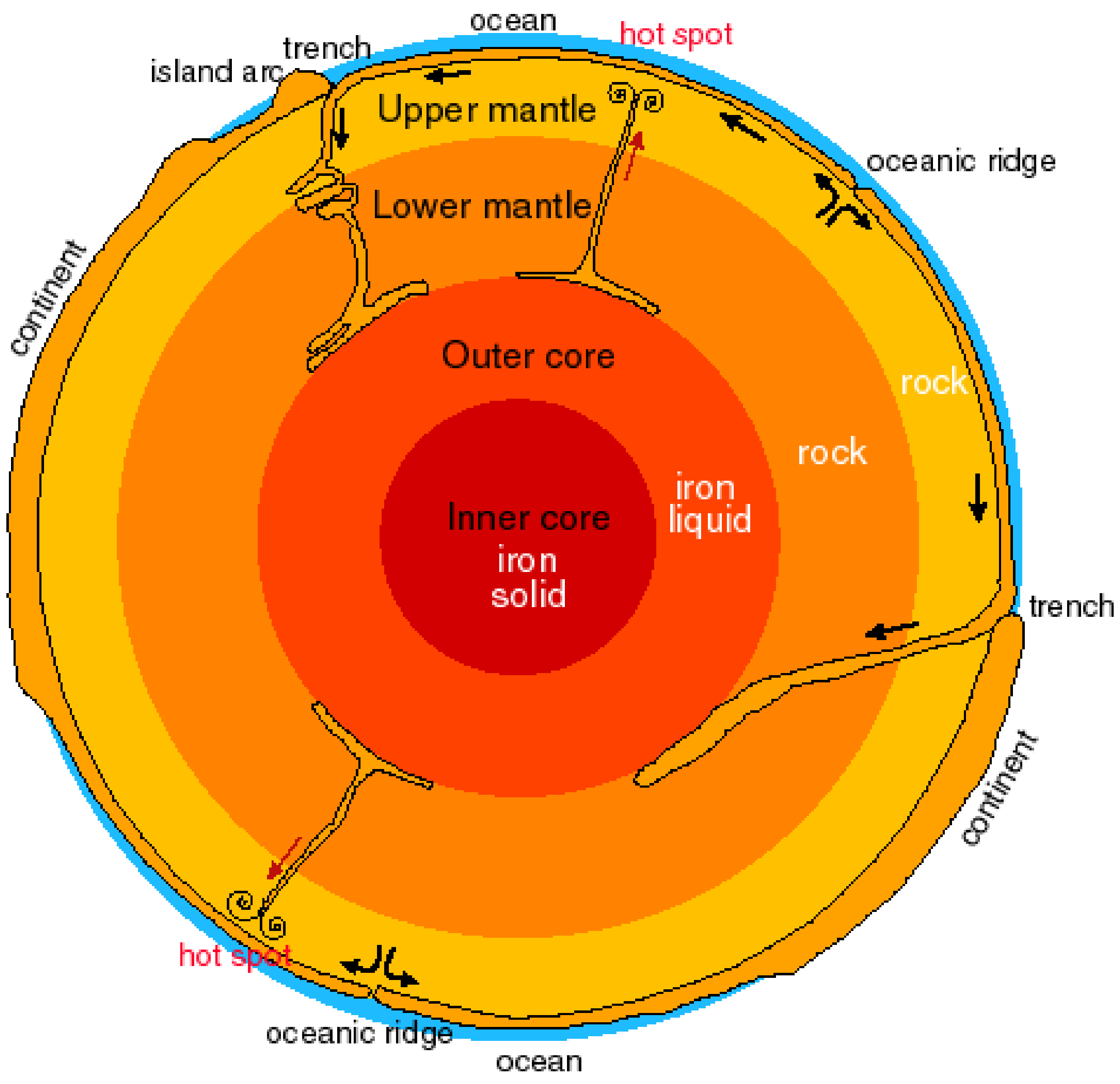
2 CONSTELLATIONS OF 4 CUBESATS EACH

PRESENTATION OVERVIEW

SCIENCE CASE | REQUIREMENTS | PAYLOAD | ORBIT | PLATFORM | COST | CONCLUSION

SCIENCE CASE

THE PROBLEM

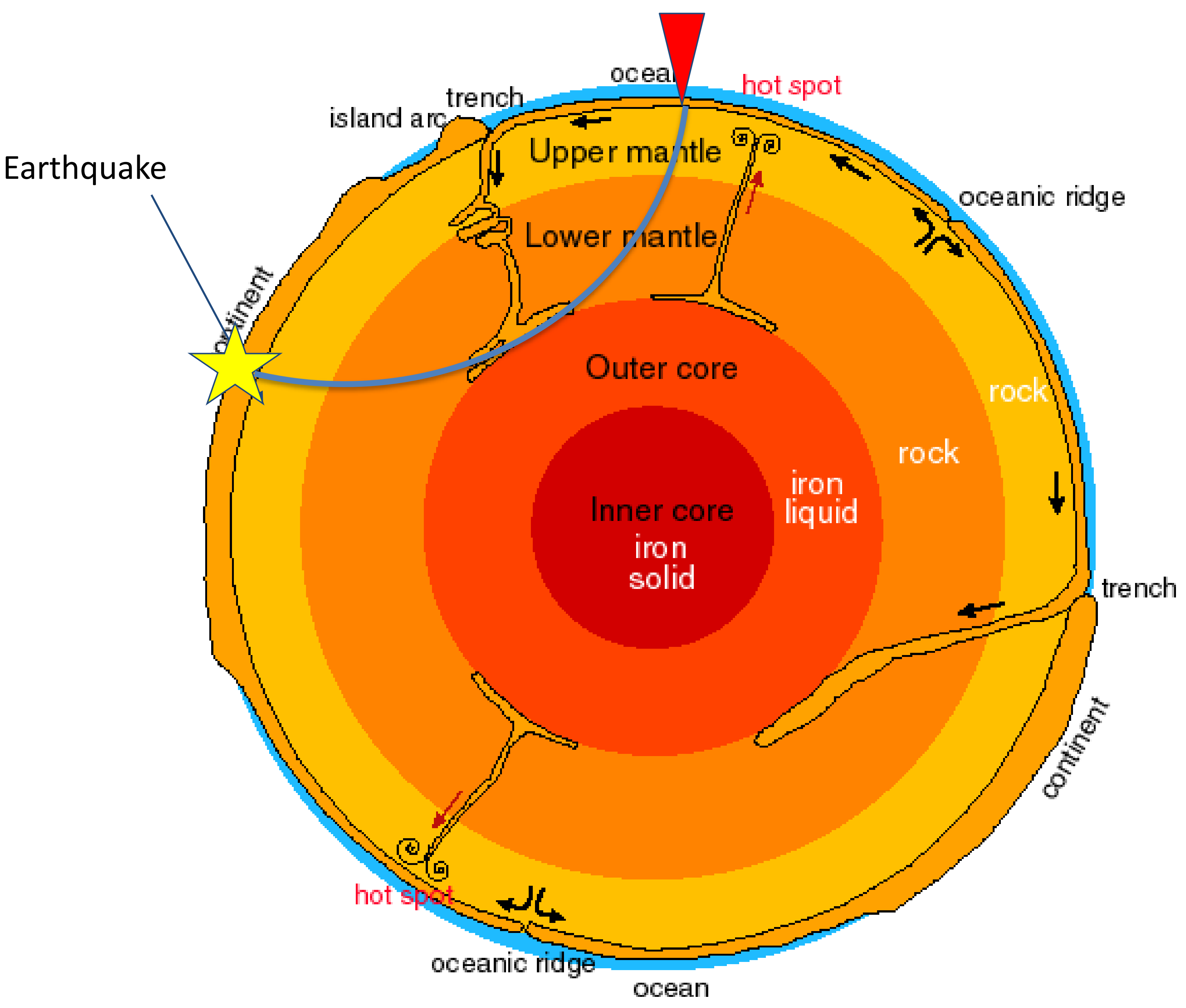


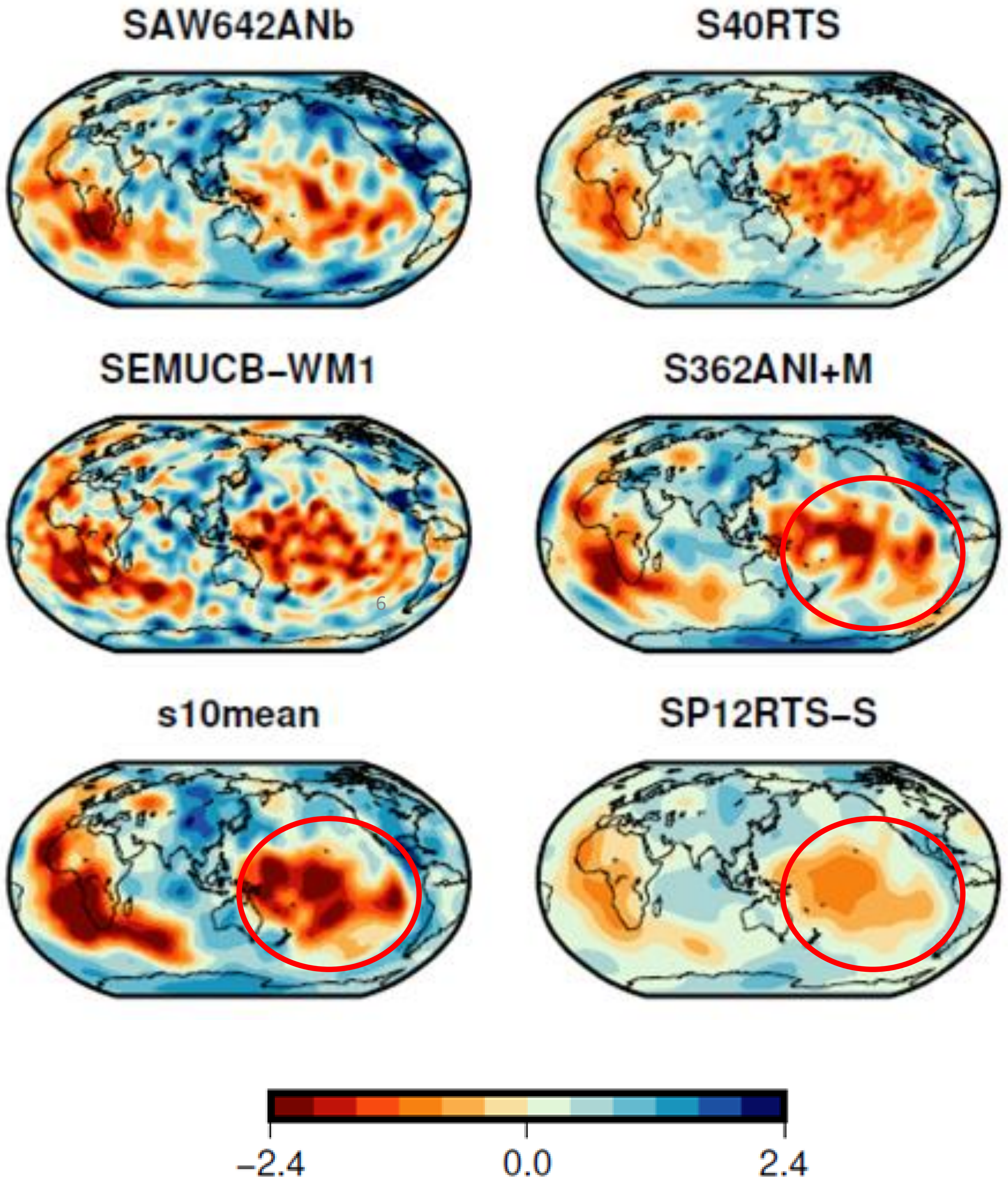
WE DON'T UNDERSTAND THE MANTLE

Unknowns:

- Composition
- Dynamics
- Influence on plate tectonics

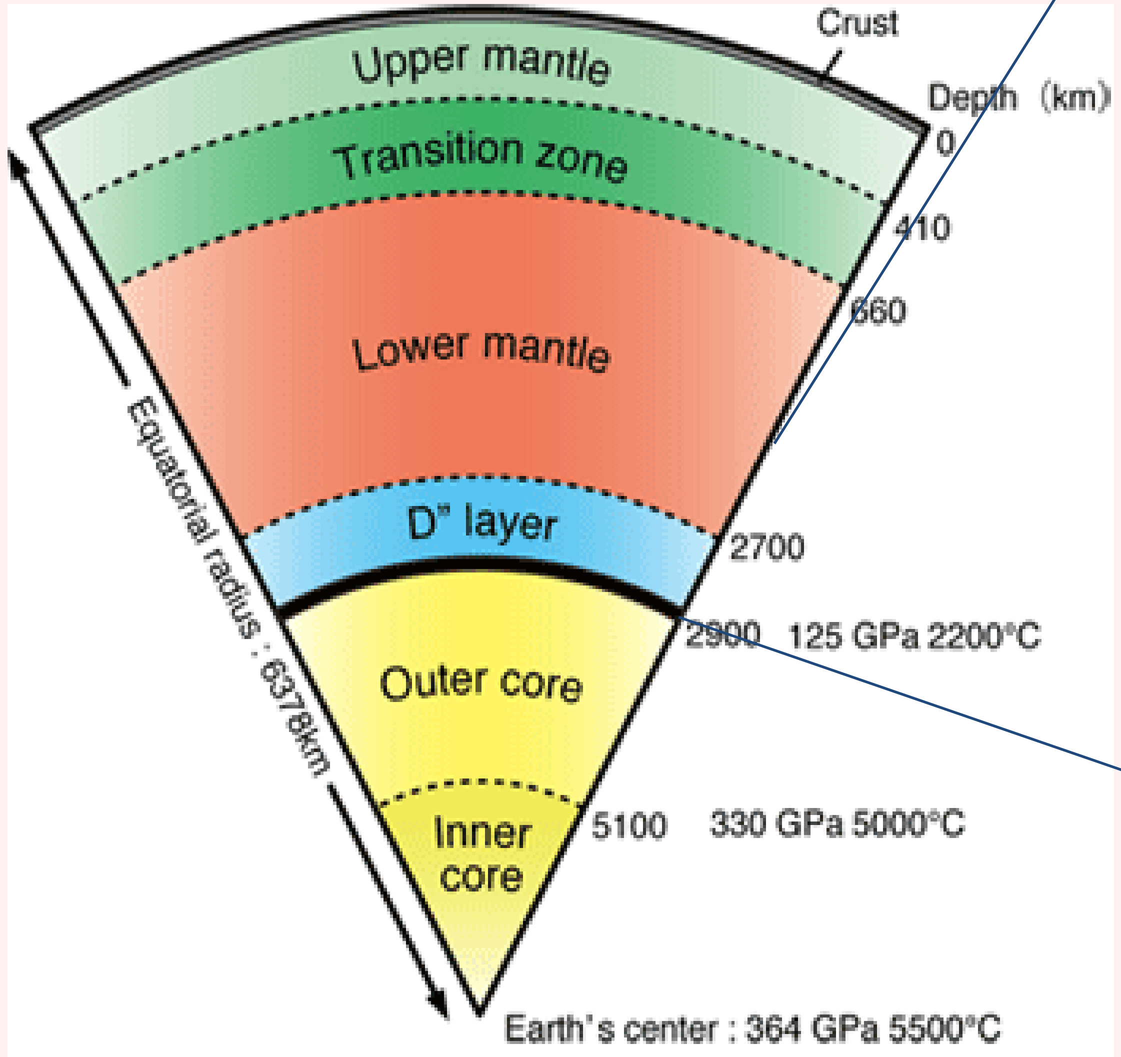
CAN WE REALLY TRUST SEISMICS?

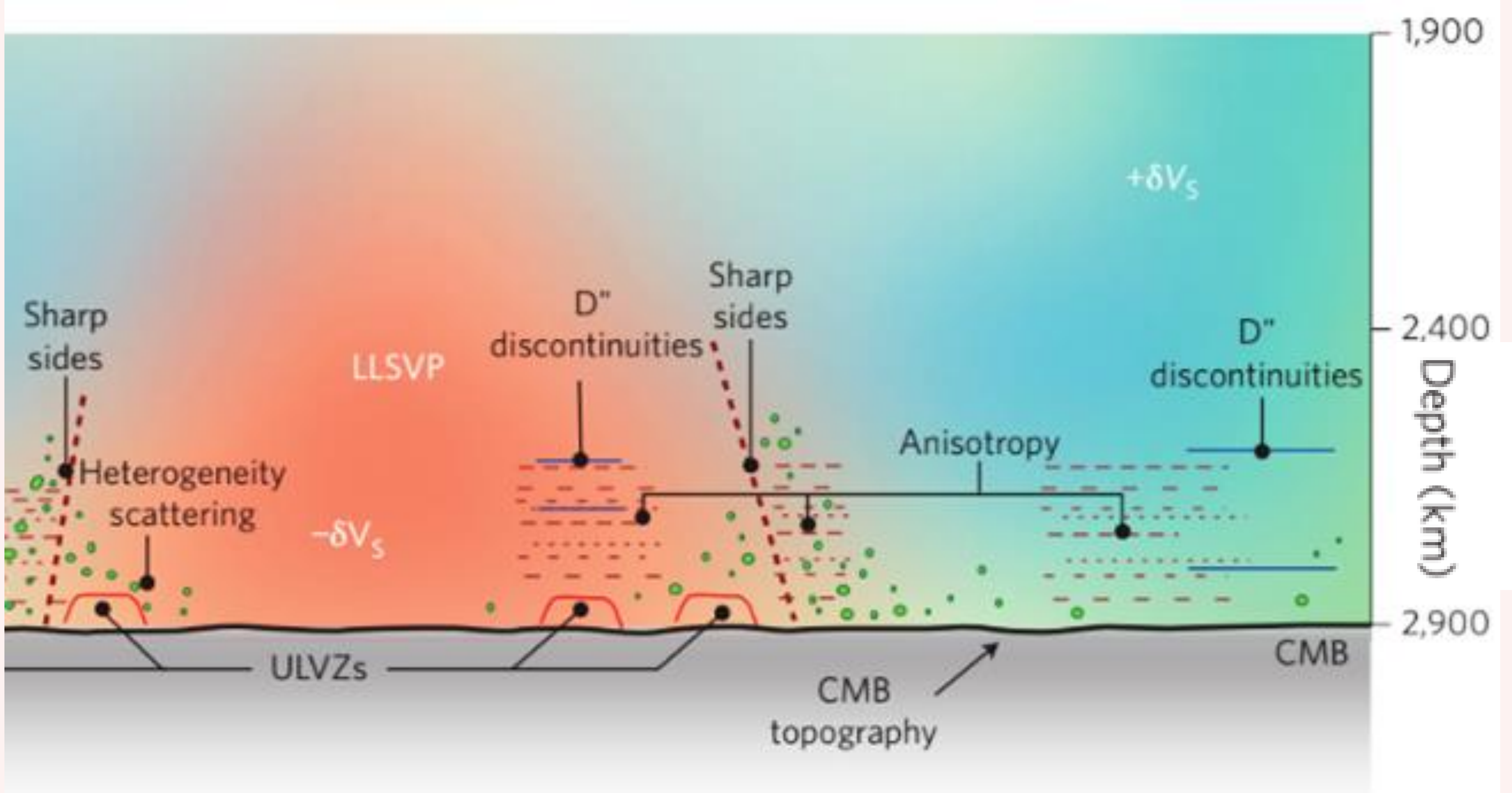




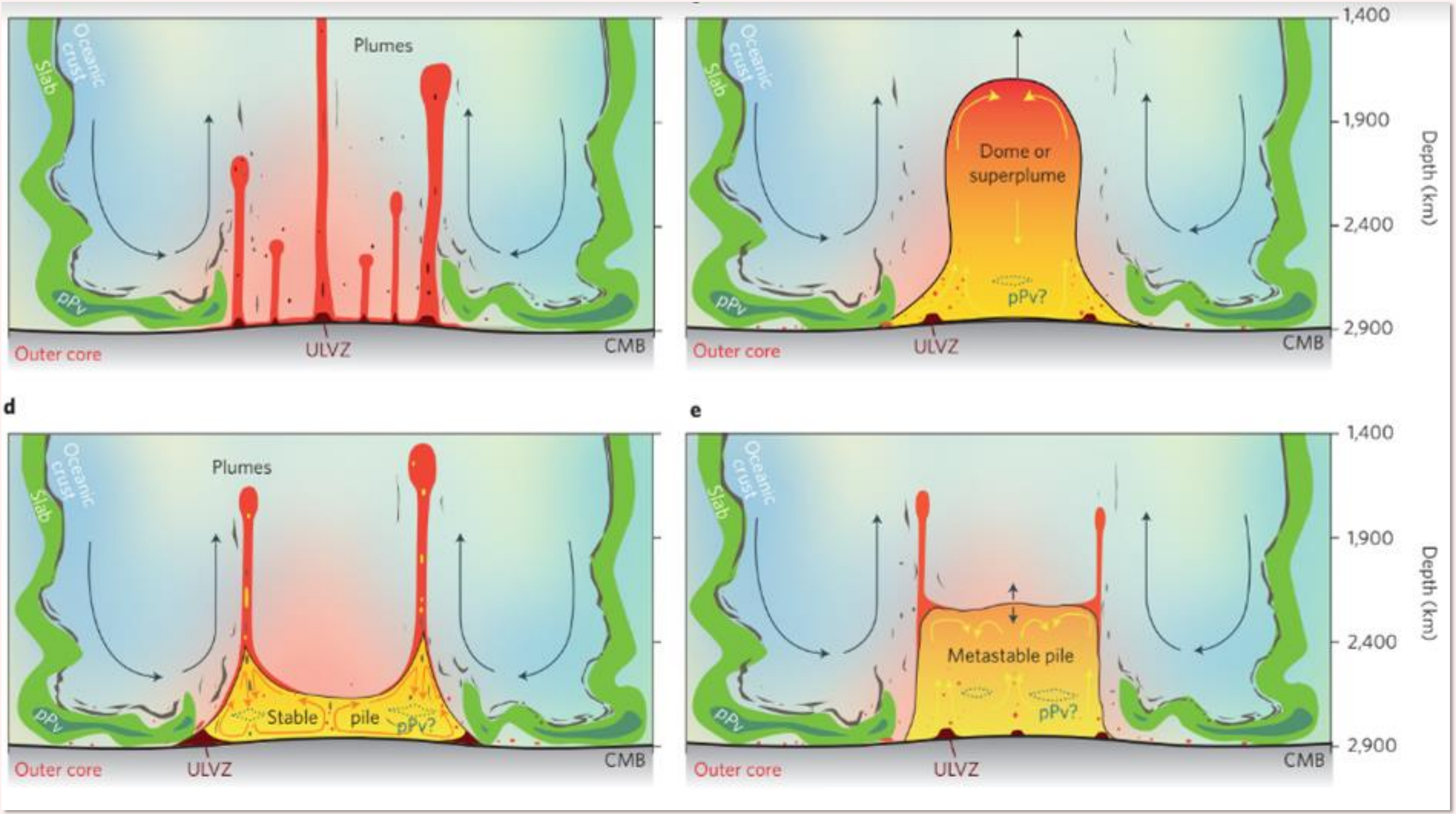
Seismic velocity anomaly @ depth 2850 km

LOWER MANTLE HETEROGENEITIES

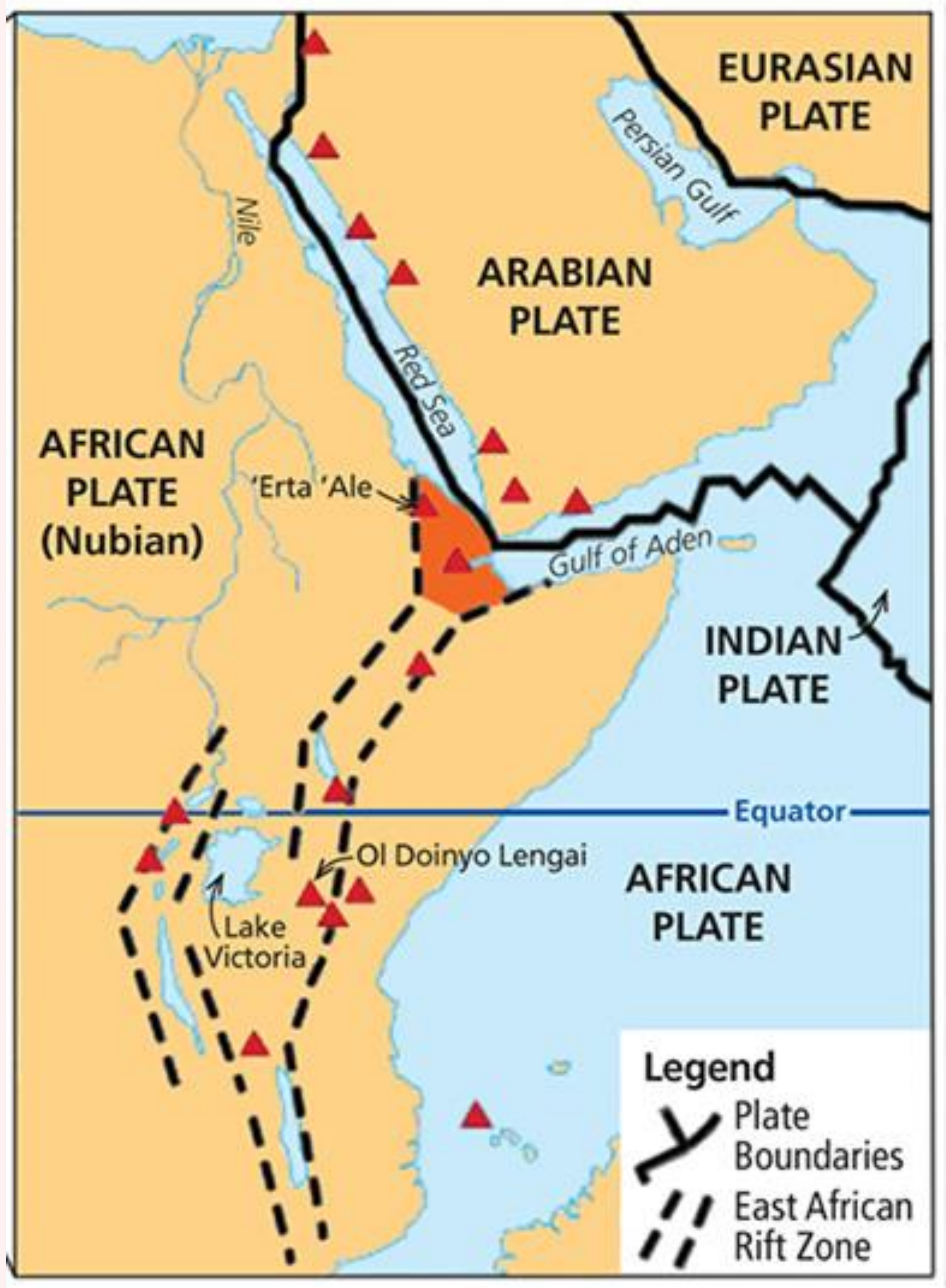


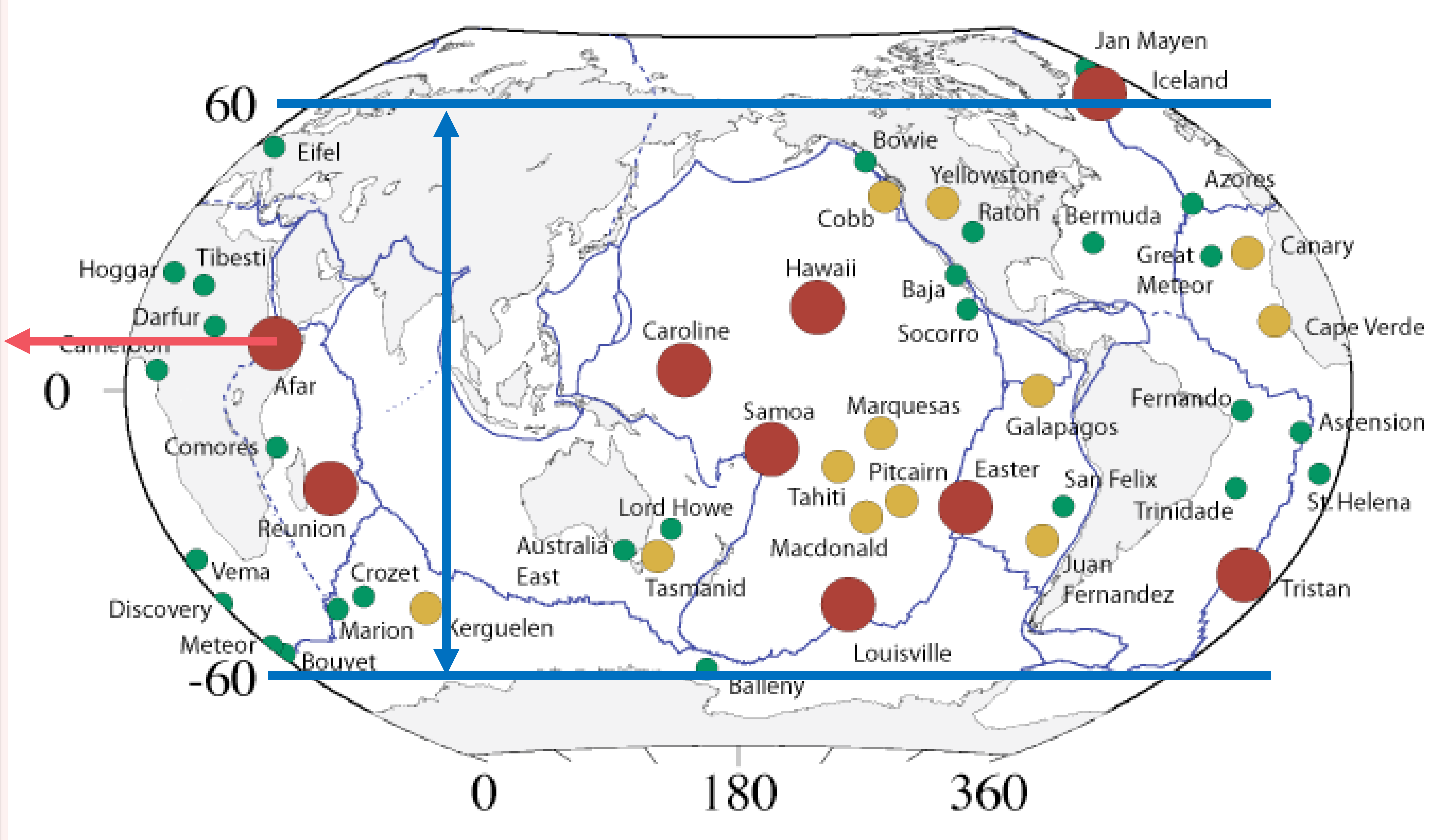


MANTLE PLUMES



Source: Garnero et al, 2016



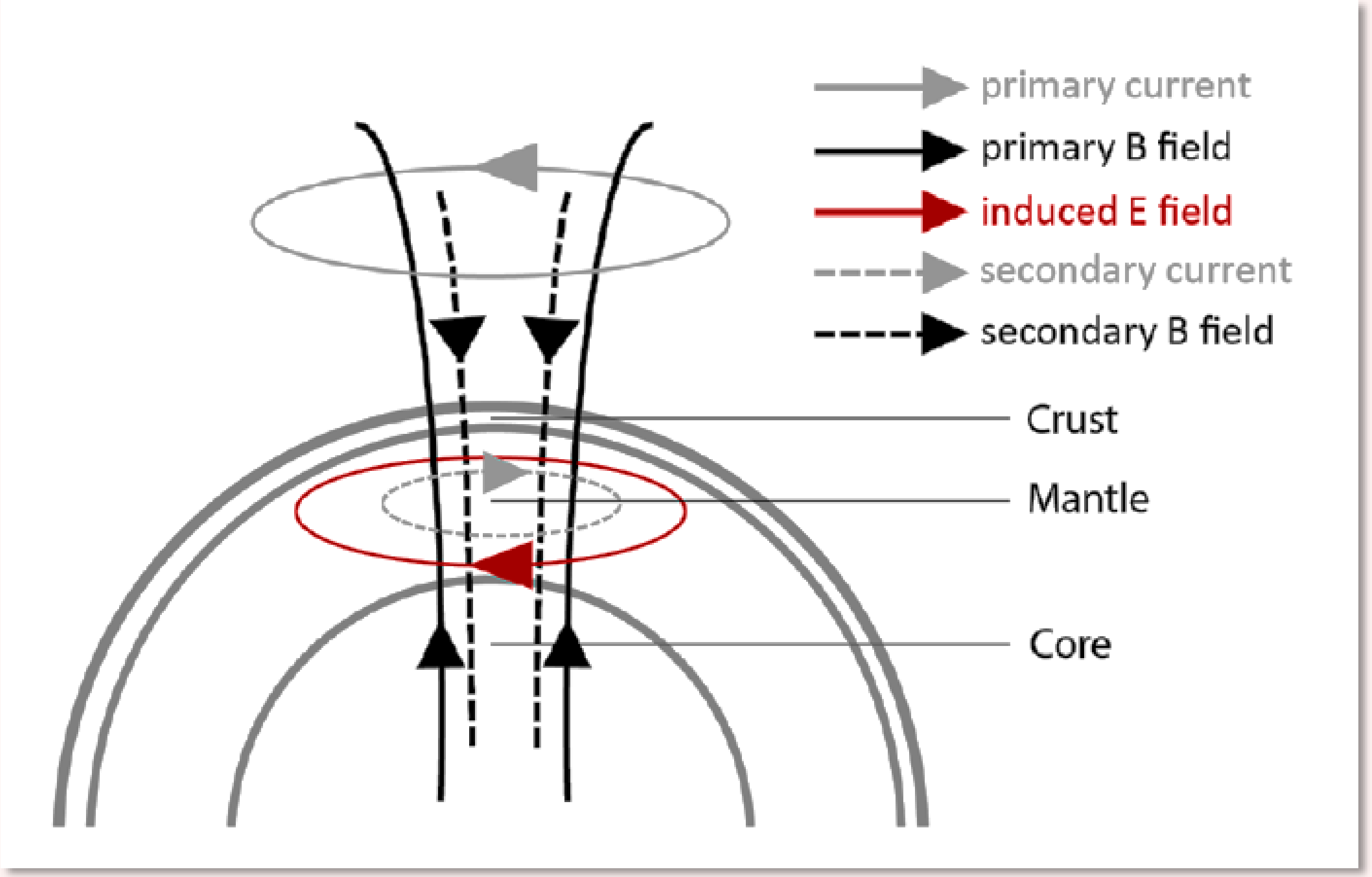


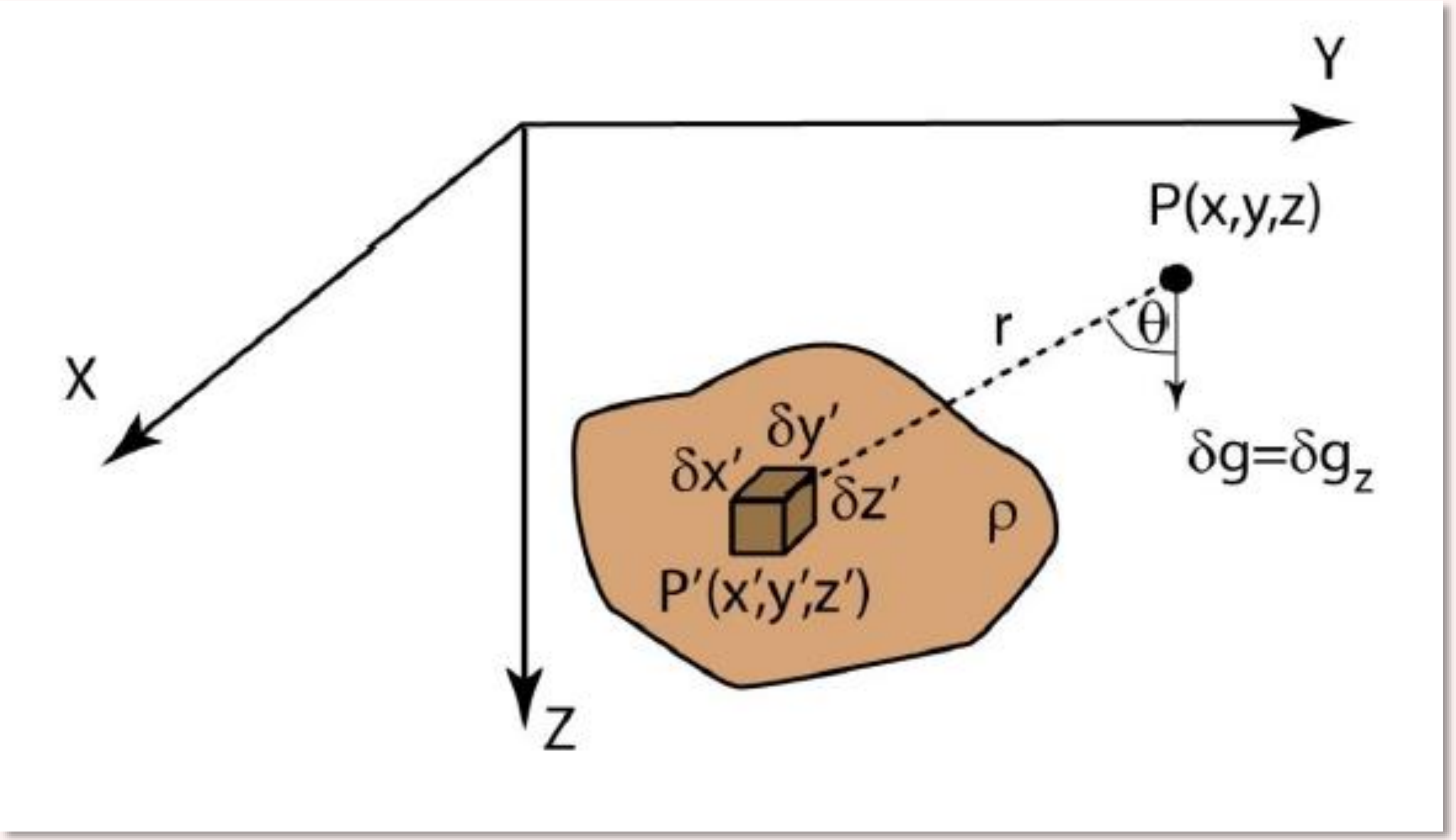
LINK WITH PLATE TECTONICS?

Latitudinal coverage +75° to -75 °

Source: Foulger, 2010 & NPS

HOW CAN WE EXPLAIN HETEROGENEITIES IN THE MANTLE?





Magnetic Induction

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \wedge (\mathbf{v} \wedge \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\eta = 1/\mu_0 \sigma$$

Gravity Anomalies

$$\delta g = \frac{G\rho(z' - z)}{r^3} \delta x' \delta y' \delta z'$$

σ Electrical conductivity

ρ Density

HOW CAN WE EXPLAIN HETEROGENEITIES IN THE MANTLE?

Magnetic field → Conductivity

Gravity field → Density

Conductivity + Density = (3D joint inversion) **Composition, Temperature**

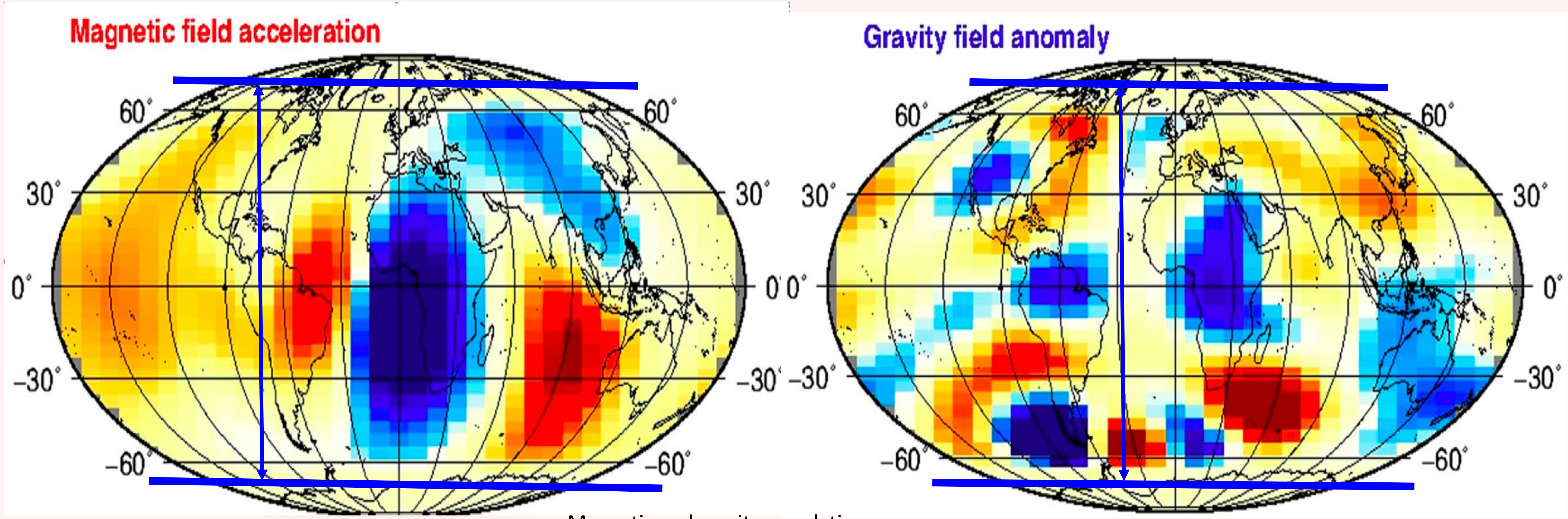
3D joint inversion

Composition
Temperature

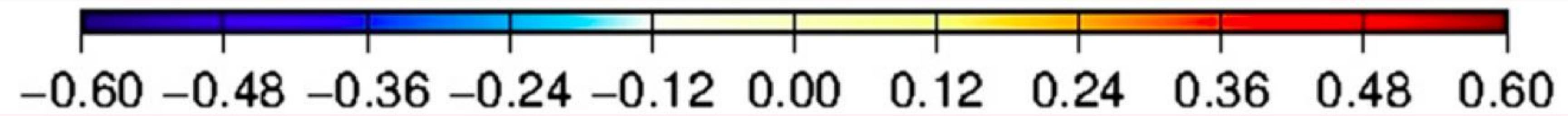
Add constraints from seismic data & petrology information

COUPLING BETWEEN MAGNETISM AND GRAVITY

Latitudinal coverage +75° to -75 °

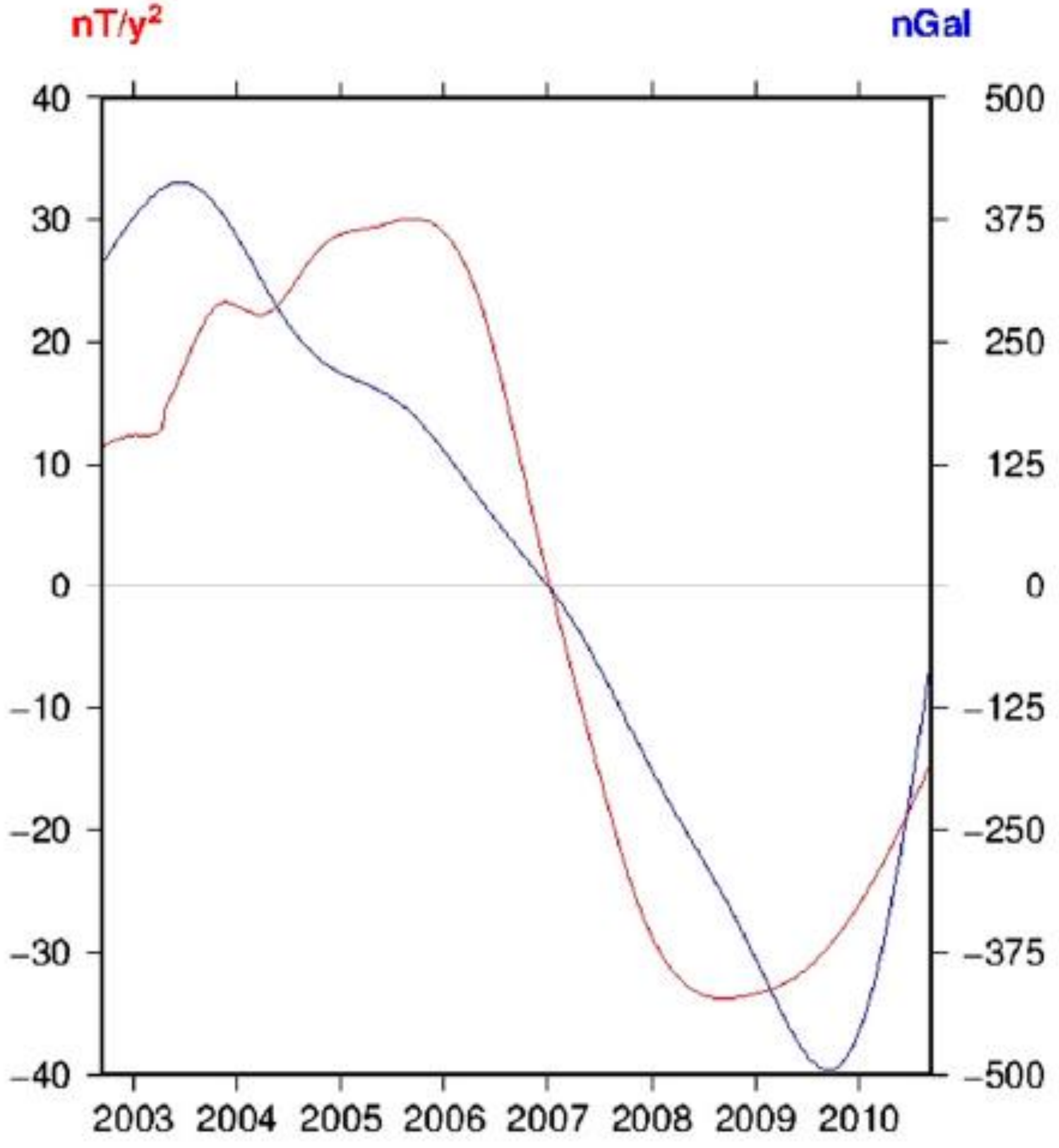


Magnetic and gravity correlation



Source: Mandea et al, 2012

COUPLING BETWEEN MAGNETISM AND GRAVITY



Source: Mandea et al, 2012

SWARM

TAKES 4 YEARS TO GET 3 MONTHS LOCAL TIME COVERAGE

- Not ideal for short-term temporal variations in magnetic field
- Problems in separation of internal and external field contributions

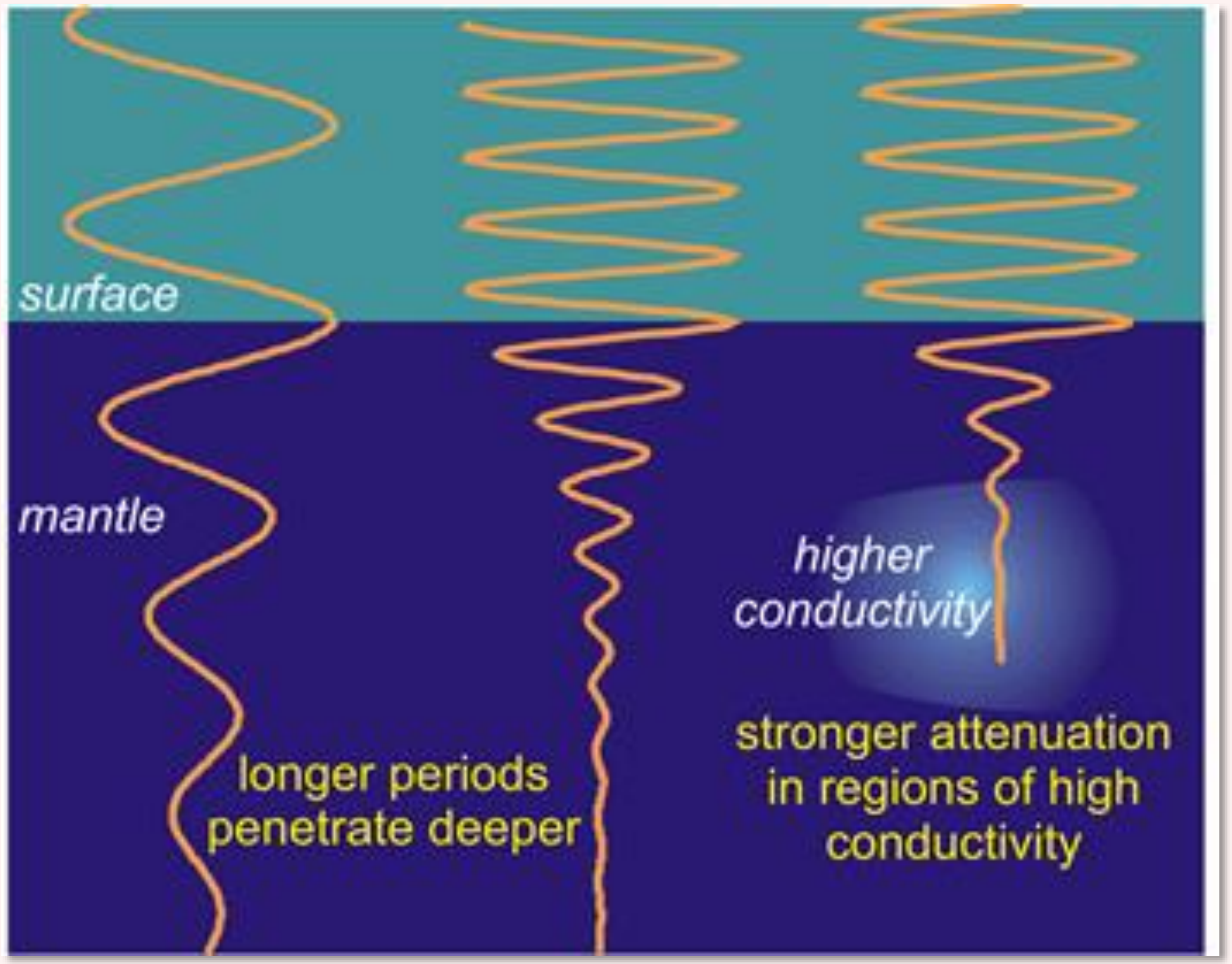
Estimated re-entry:

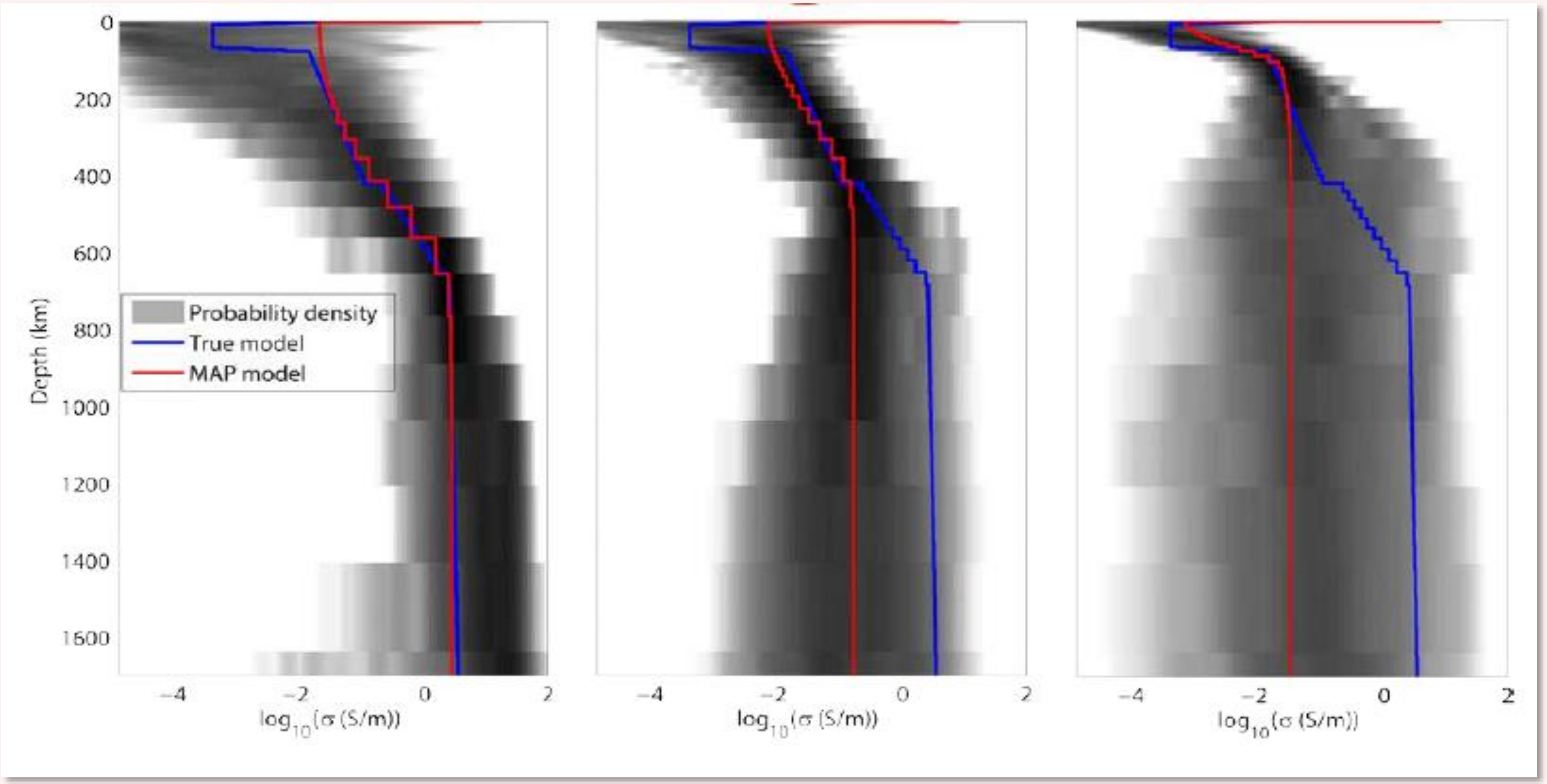
2023 - 2024

SWARM

Not able to resolve for the lower mantle > 1600 km depth

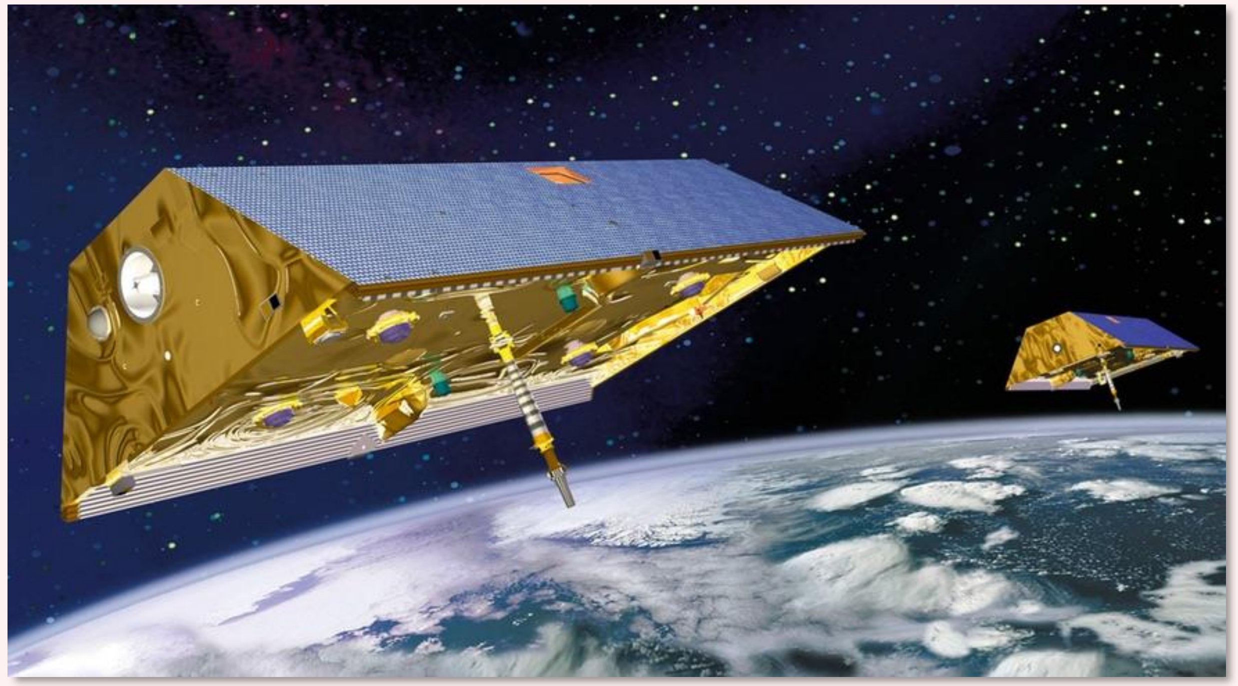
- need for higher sensitivity to signal from induction in mantle and to external sources
- higher temporal resolution (months to hours)
- sounding of longer periods necessary (180 days +)



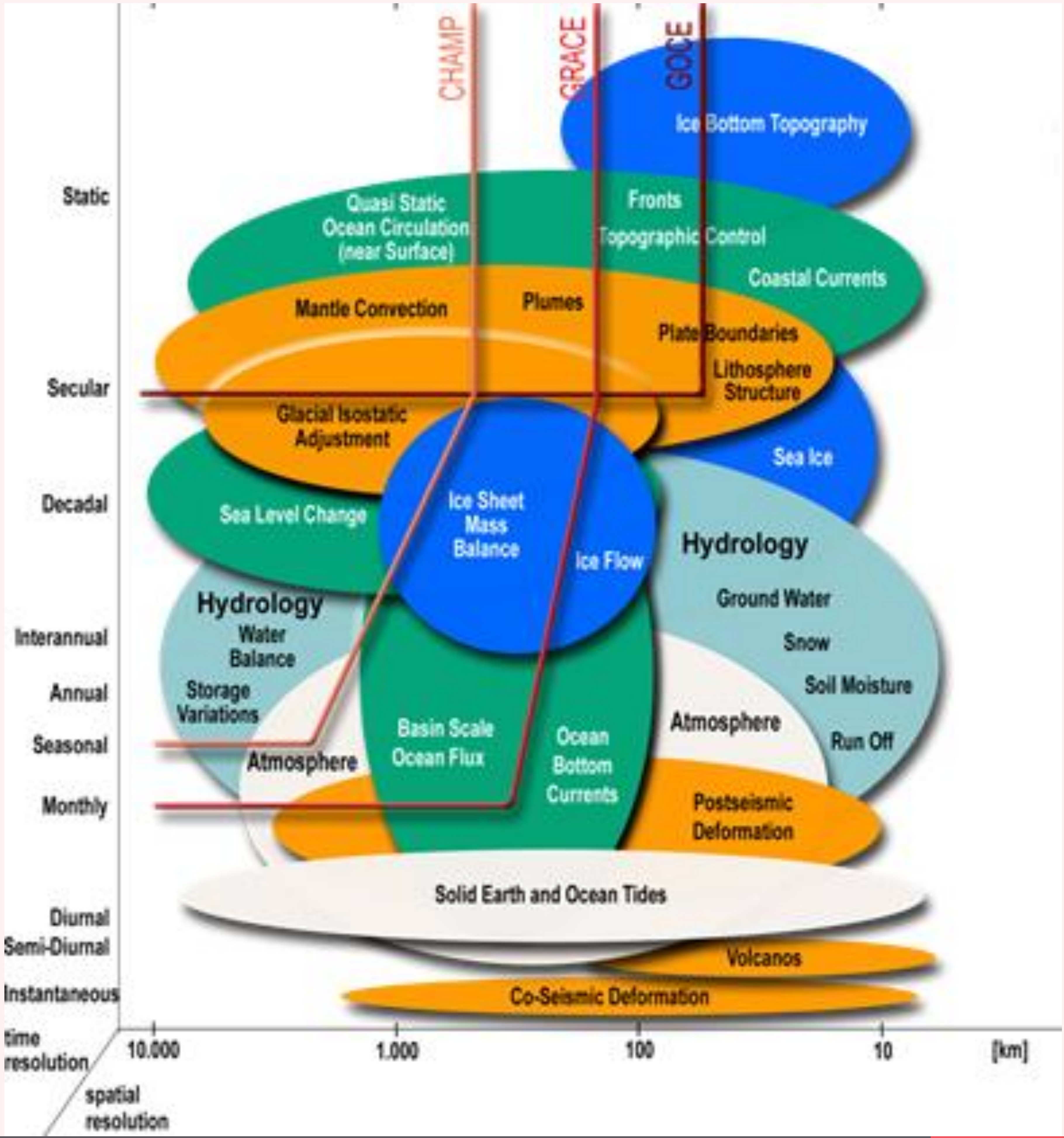


Source: Kuvshinov et al., 2017

GRACE/GOCE



Not able to detect gravity anomalies from lower mantle in semi-diurnal interval



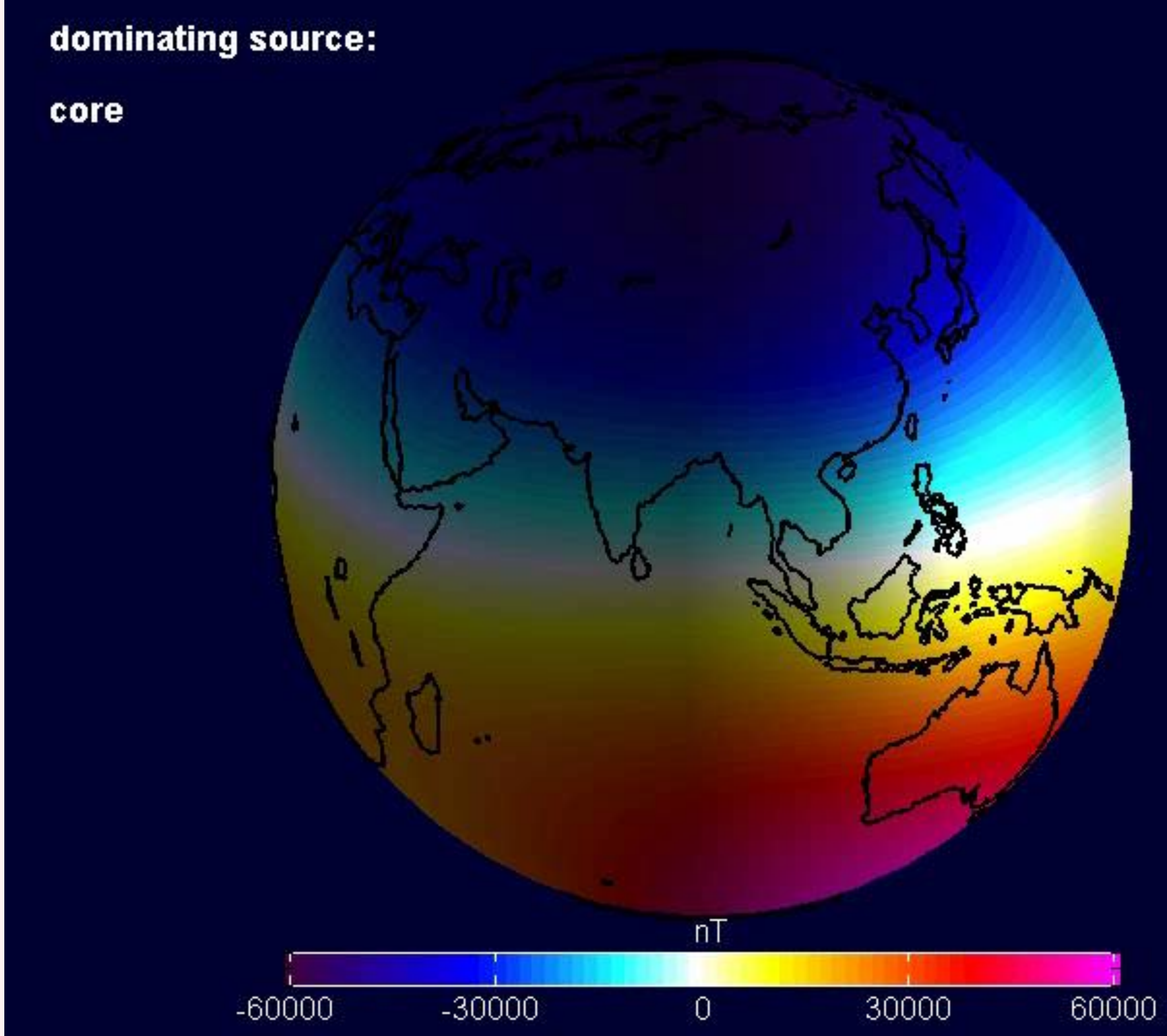
RUBIKS

- First mission to look at the coupled effect of **gravity** and **magnetic induction** in the lower mantle
- Improvement of 3D joint inversion results of composition and water content
- Insight in mantle dynamics and plume influence on plate tectonics

REQUIREMENTS

MAGNETIC FIELDS COMPONENTS

- Core
- Magnetospheric
- Solar Quiet
- Lithosphere
- Ocean Currents



Source: ESA

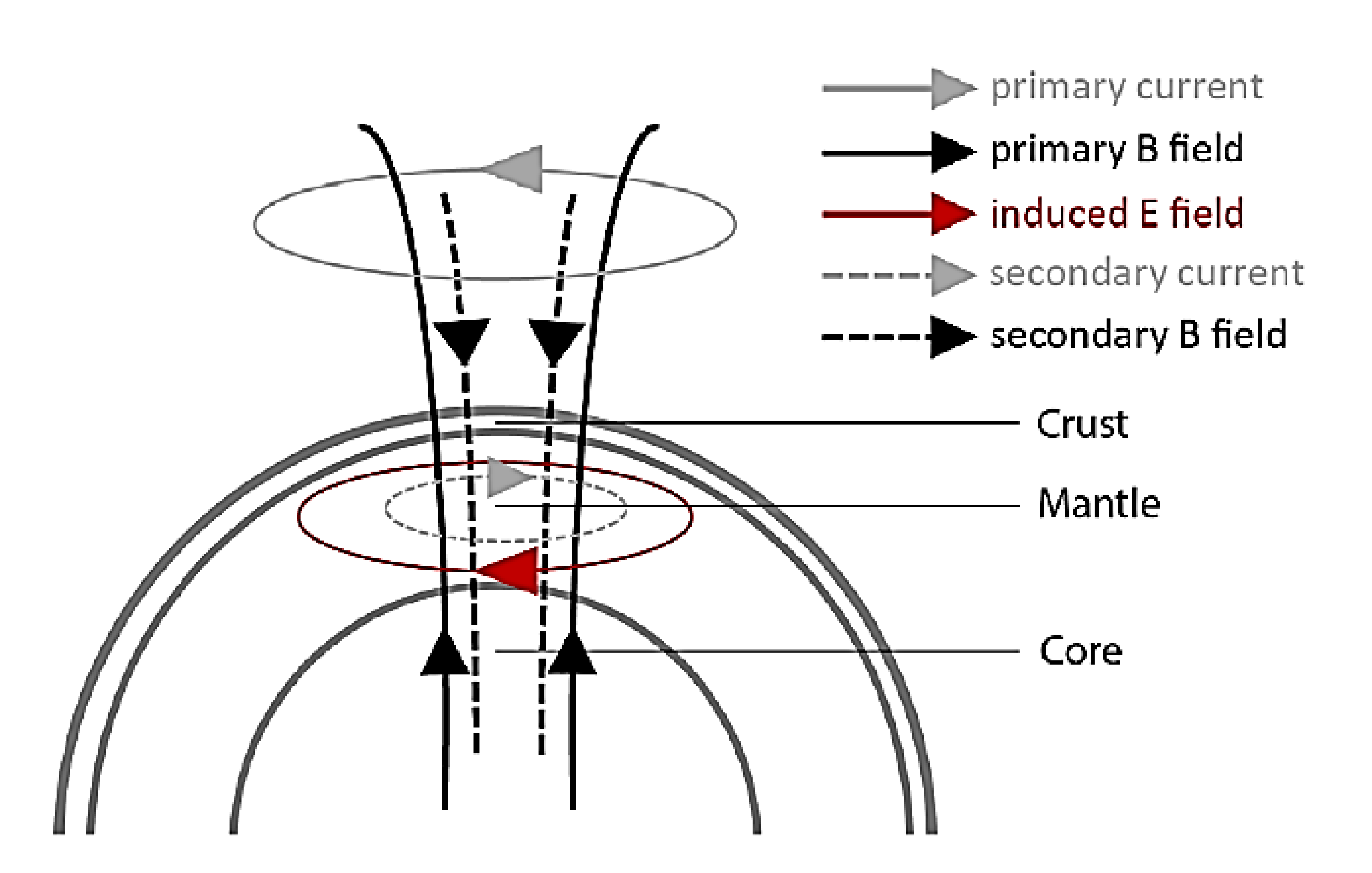
NEEDS FOR COMPREHENSIVE INVERSION

OBJECTIVE: DETECT AND MEASURE THE MAGNETIC FIELD OF THE INDUCED CURRENT

Signal strength of the induced current: 0.5 nT at Satellite altitude (400 km)

Field sources to be removed:

- Core field
- Lithospheric fields
- Ionospheric currents
- Induced ocean field



What do we have to expect?

Solar Quiet variation:

- Highly variable (hours), sun-fixed
- Source: E Region 80 km - 120 km altitude
- Signal strength at 400 km: +/- 30 nT
- Reference Model: difi-3
- Degree/order in spherical harmonics: 12
- Spatial resolution: 2h mag. local time (mLT), 15° mag. Lat
- Periods for EM-Induction: 4h - 24h, depth 150 km - 500 km
    - Requires temporal resolution (model update rate) 2h for low depths

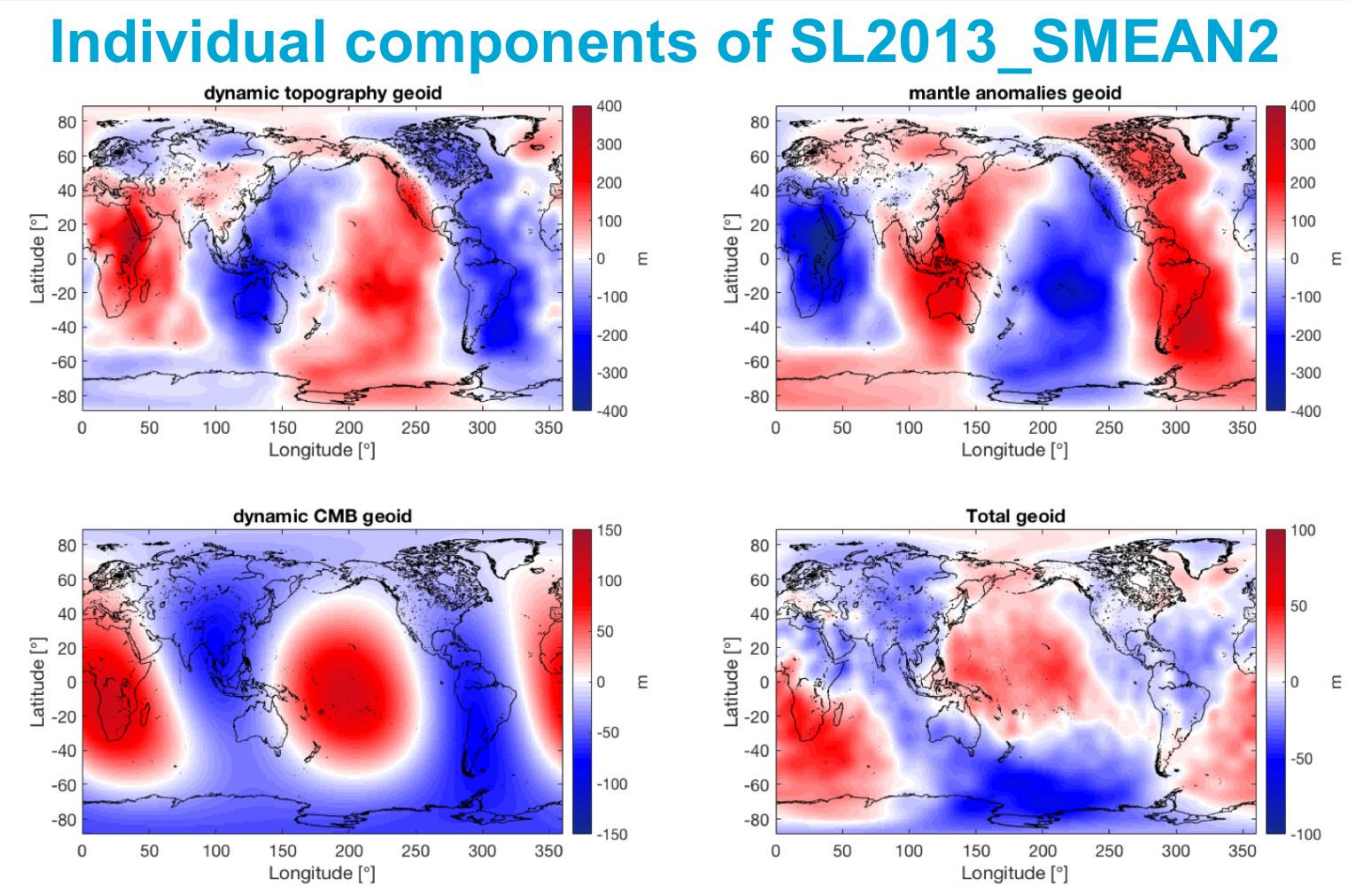
      Not current free! Therefore, we need the Full Gradient Tensor to determine B field rotation

MODELS TO BE RESOLVED

	Model resolution d/o	Model Update	Signal	Coordinate System
Core	16 (22.5° Lon)	1d	50.000nT +/-150 y	Dipole
Solar Quiet	12 (2h mLT)	2h	30 nT	mLT/mLat
FAC	Local (10-400 km)	2h	Few hundred nT	mLT/mLat
Ring current	4 (90°Lon)	1.5d	5nT(Quiet) 600 (Storm)	Dipole
Ocean Tides	12 (30° Lon)	6h	2nT	Earth fixed
Lithosphere Filed	160 (existing model)	static	10 nT	Earth fixed

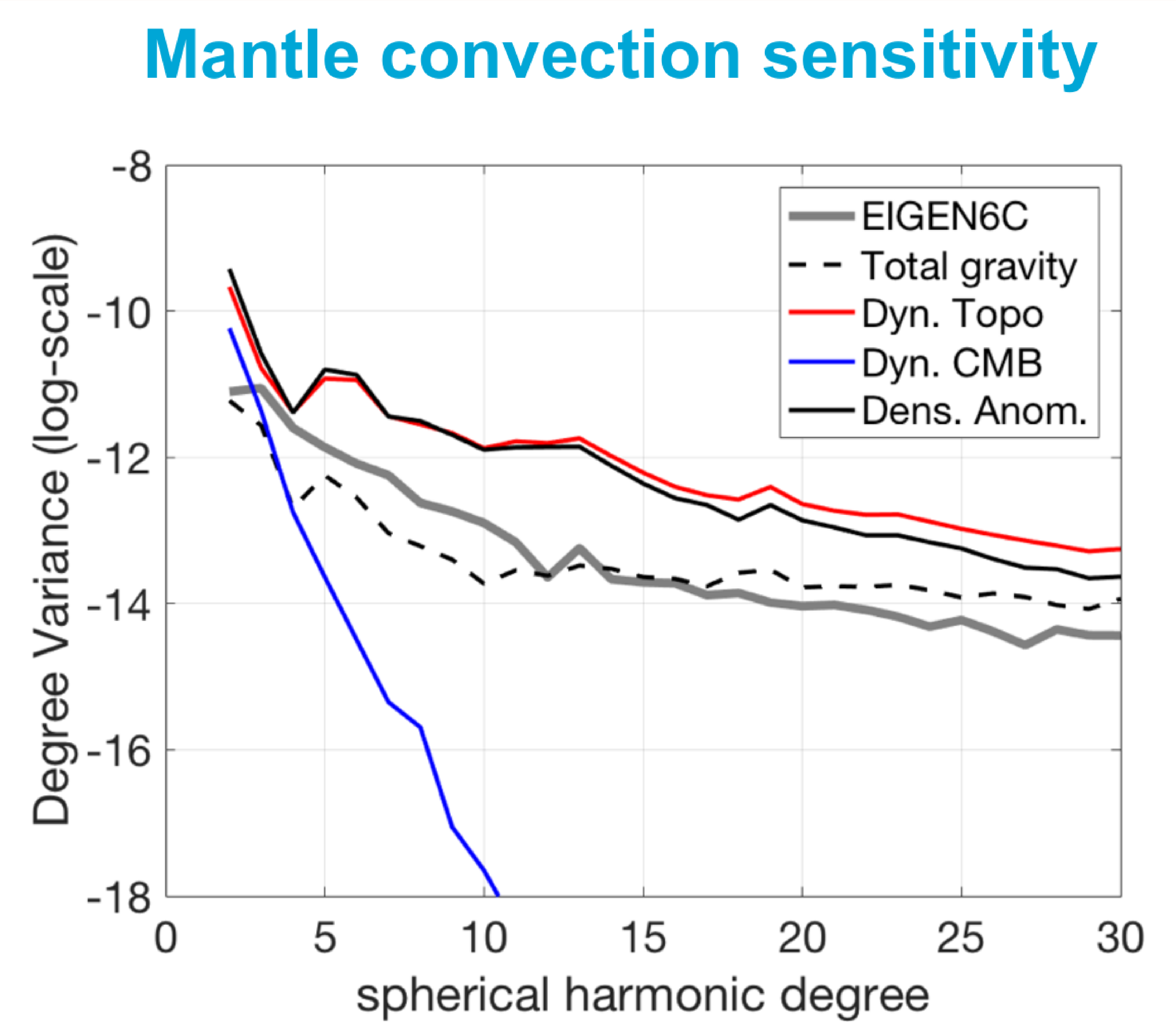
In addition small scale features (like plasma bubbles, 10 km - 1000 km) needs to be detected and removed from the data

LOWER MANTLE DENSITY FROM GRAVITY MEASUREMENTS



Spatial resolution: 72°
Temporal resolution: 0.5 d
Centimeter accuracy can be archived using GPS only.

LOWER MANTLE DENSITY FROM GRAVITY MEASUREMENTS

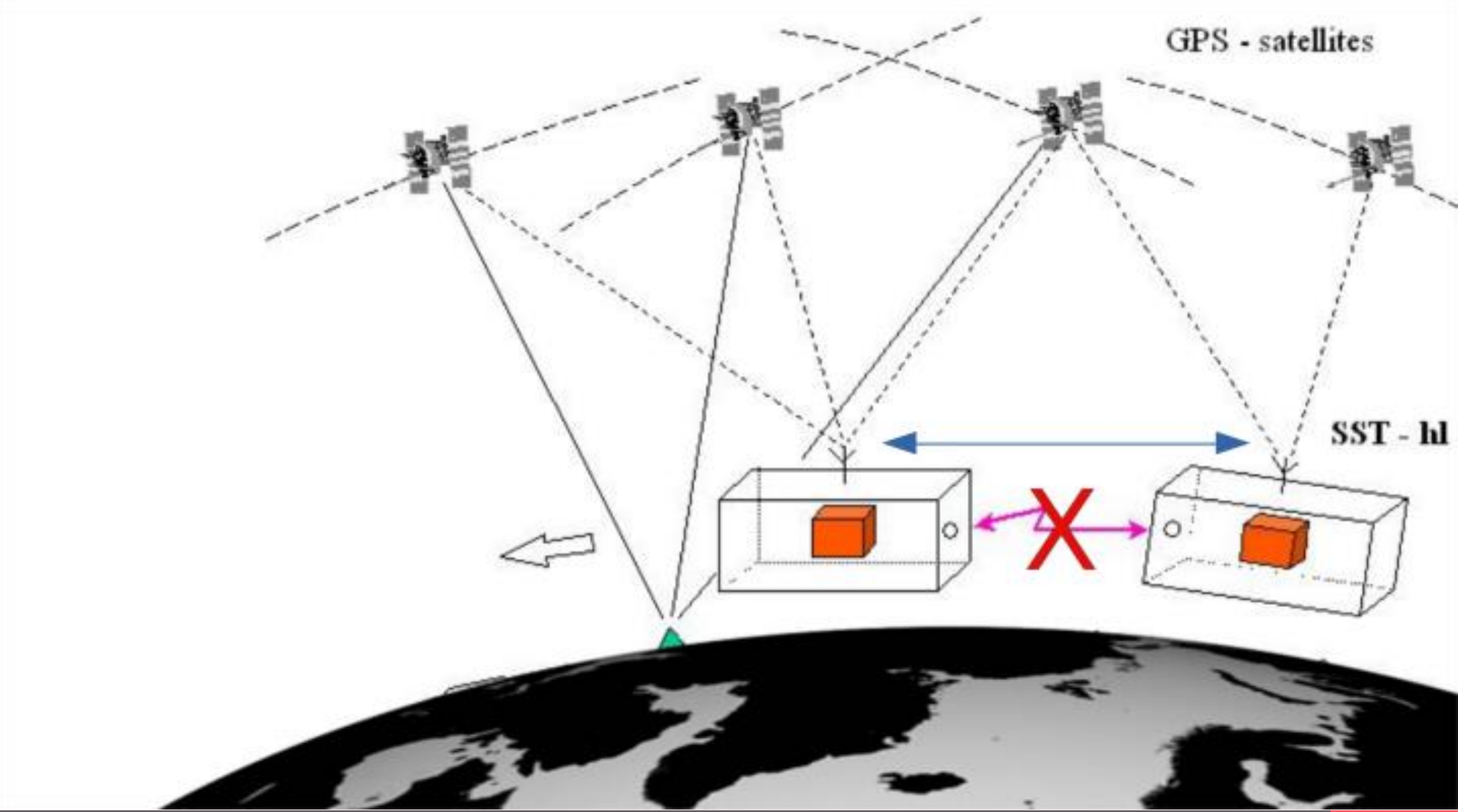


Spherical Order Degree 5 sufficient for CMB

Spatial resolution: 72°
Temporal resolution: 0.5 d
Centimeter accuracy can be archived using GPS only.

GRAVITY MEASUREMENTS

- High Low Satellite to Satellite tracking for Single Satellite (0.1 Hz, 1-3 cm)
- 100 km GNSS Baseline double differencing for 1 cm geoid height accuracy
- “Gradiometer” constellation allows to obtain the full gravity gradient Tensor



OBSERVATIONAL REQUIREMENTS

Capture magnetic signal with amplitude of induced current (source at -100 km from surface):

Signal / Altitude:

0.8 nT	0.5nT	0.35 nT	0.25 nT	0.1 nT
300 km	400 km	500 km	600 km	1000 km
Scientist Happy				Engineer Happy

0.5 nT amplitude implies a sensitivity of about **0.2 nT** to recover the signal

Most demanding spatial and temporal resolution:
Solar Quiet: 6h LT, 45° mLat, with full gradient Tensor (low/mid latitudes) in 2h
Core Field: 22.5° Vector only in 12 h

Not critical: Gravity field: 12h with 72° Lon

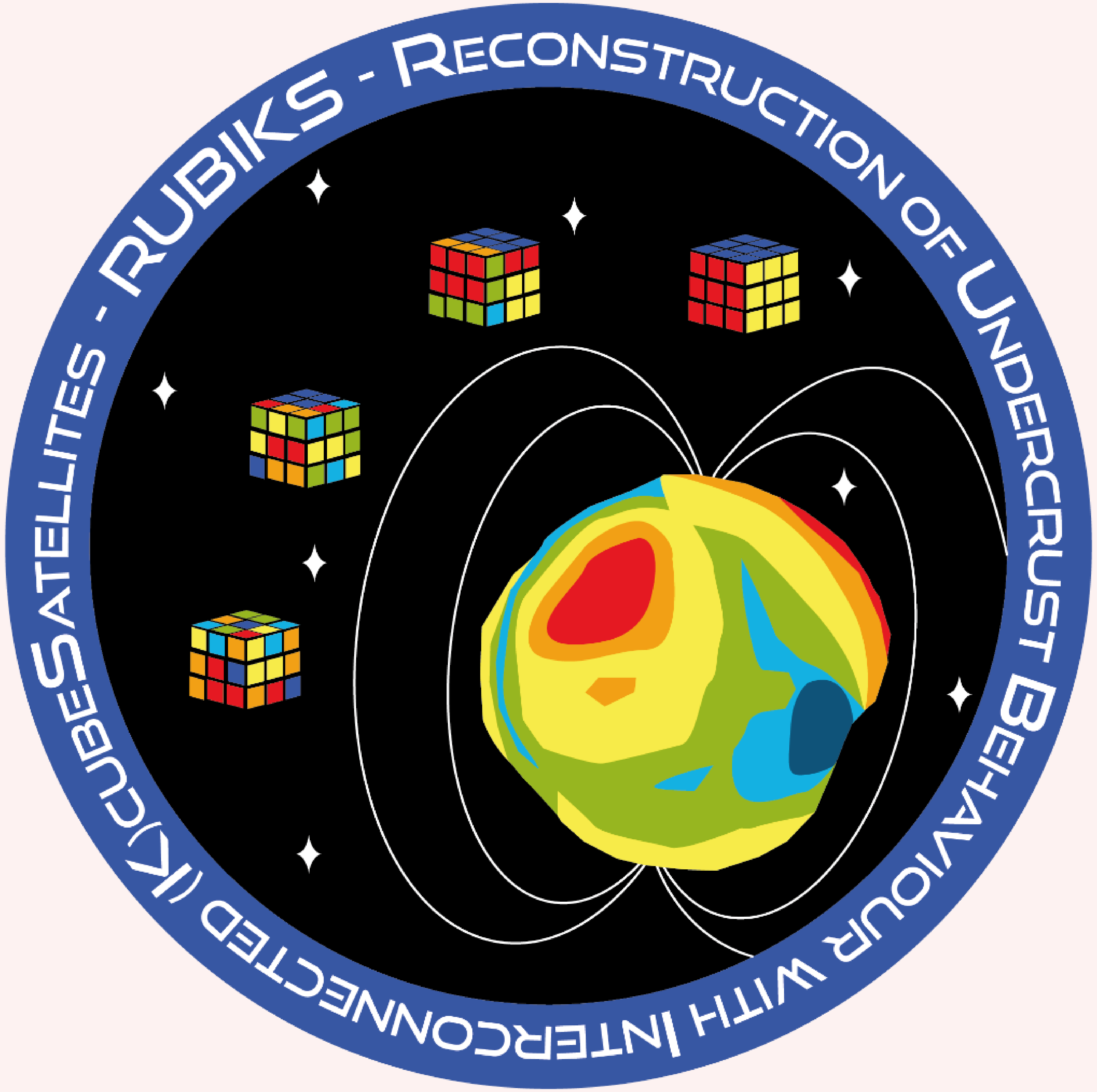
COMPARING RUBIKS TO SWARM, GRACE, AND GOCE

	Swarm	GRACE(-FO)	GOCE	RUBIKS
Solar Quiet	Too few passes	No mag	no	yes
Ocean Field	yes	no	no	yes
Field aligned currents	yes	no	Large noise	yes
Core Field	yes	no	no	yes
Ring current	yes	no	no	yes
Gravity model	Too few passes in 6h	Too few passes, sensitive in only one direction		yes

MISSION IDEA

To archive the scientific requirements we will use:

- CubeSat mission (8 CubeSats)
- High precision magnetometers
- Two cartwheel-helix formations separated by 6 h in LT
- Distance between the Satellites in one formation: 100 km - 200 km
- Mission Lifetime 3 years

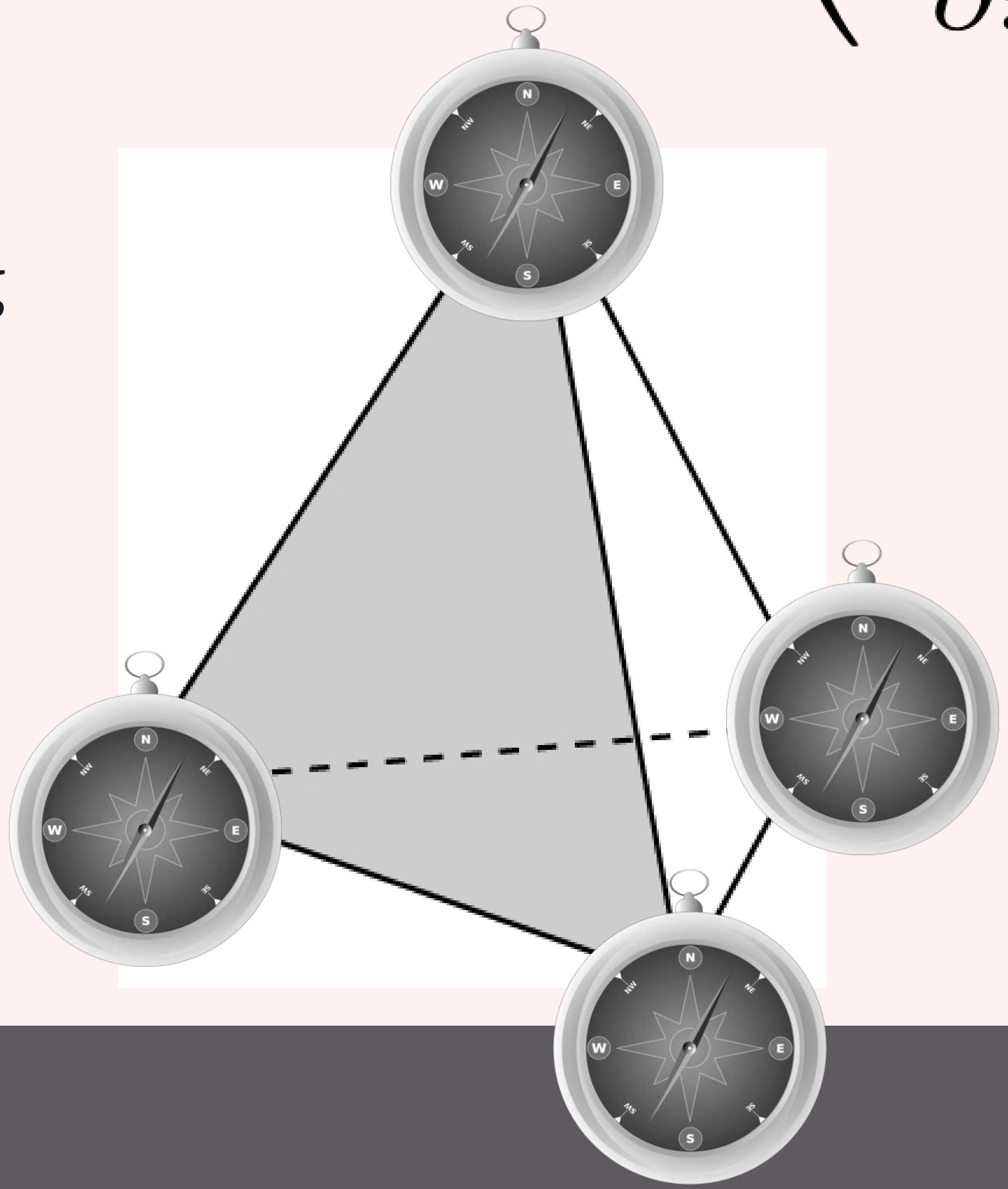


PAYLOAD

Science Instruments

$$grad\vec{B} = \begin{pmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{pmatrix}$$

- Vector magnetometer with 0.2 nT measurement accuracy, 1Hz sampling, Position accuracy within 10 m range.
- Dual frequency GPS receiver with 1-3 cm accuracy in precise point positioning (PPP) 0.1 Hz sampling.
- Virtual instrument (tetrahedral like constellation) with 100 km-200 km distance. Only rates of the relative distance are important. No fixed distance necessary.



FGM

ELFIN, UCLA

INPUTS (SCIENTIFIC REQUIREMENTS)

Dynamic range: +/- 50000 nT

Accuracy: <0.2 nT

ENGINEERING REQ.

Power consumption: <1W

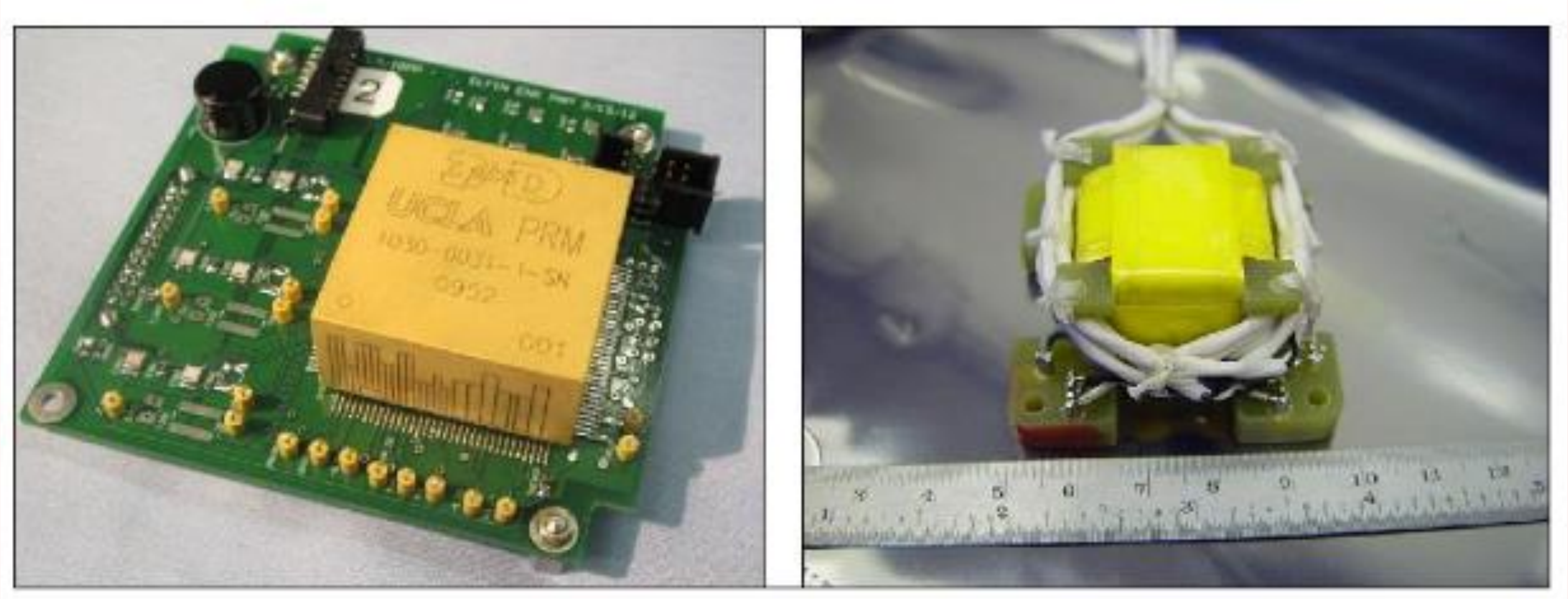
Supply Voltage: 8V

Size: 90mm x 90mm x 25mm (PCB)

48mm x 48mm x 25mm (SH)

Mass: 100g (PCB)

58 g, 106g with 1m cable (SH)



PERFORMANCES

3 axis field measurement

Dynamic range : +/- 55 000 nT

Resolution : 6.5 pT

Noise resolution : 0.2 nT/ $\sqrt{}$Hz@1Hz

- Recalibration every ~20 minutes

Relative stability : 0.5 nT/hr

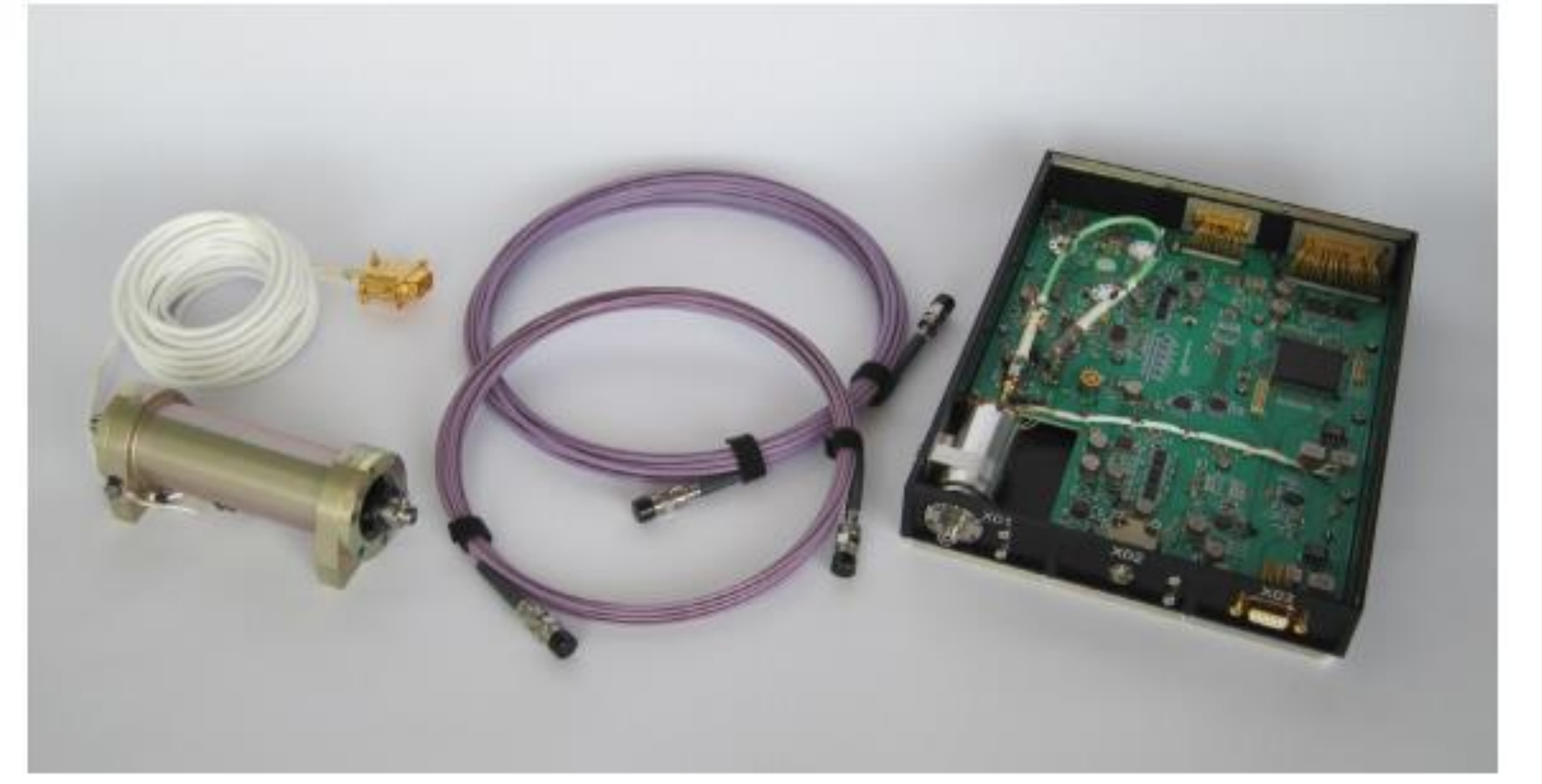
CDSM

CSES

INPUTS (SCIENTIFIC REQUIREMENTS)

Absolute error < 0.2 nT

Calibration error < 0.03 nT



ENGINEERING REQ.

Power: 2.836 W (PCB)
0.72 W (SH)
3.394 W (Overall)

Size: ~ 20mm x 100mm x 100mm (PCB)
~50 mm x 10mm x 10 mm (SH)

Mass: 1033 g (PCB)
340 g (SH)
299 g (Harness)
1672 g (Overall)

PERFORMANCES

Range: 20000nT~100000nT

Noise: < 30pT/√Hz@1Hz

STAR TRACKER

TERMA T1

INPUTS (SCIENTIFIC REQUIREMENTS)

Attitude accuracy : 1 arcsecond

ENGINEERING REQ.

Power : 2.5W (Electronic box)
0.75W (Optical head)
Size : 100mm x 100mm x 40mm (Electronic box)
Ø92mm/68 mm height (Optical head).
Mass : 450g (Electronic box)
310g (Optical head)

PERFORMANCES

Actual attitude accuracy : 1.5 arcseconds, which provides an accuracy of 0.24 nT, slightly above scientific requirement.
It still fulfills the mission requirements.

GNSS RECEIVER

FOTON

INPUTS (SCIENTIFIC REQUIREMENTS)

Sampling: 0.1 Hz

Accuracy: < 3 cm

Dual frequency

ENGINEERING REQ.

Power: 4.8W

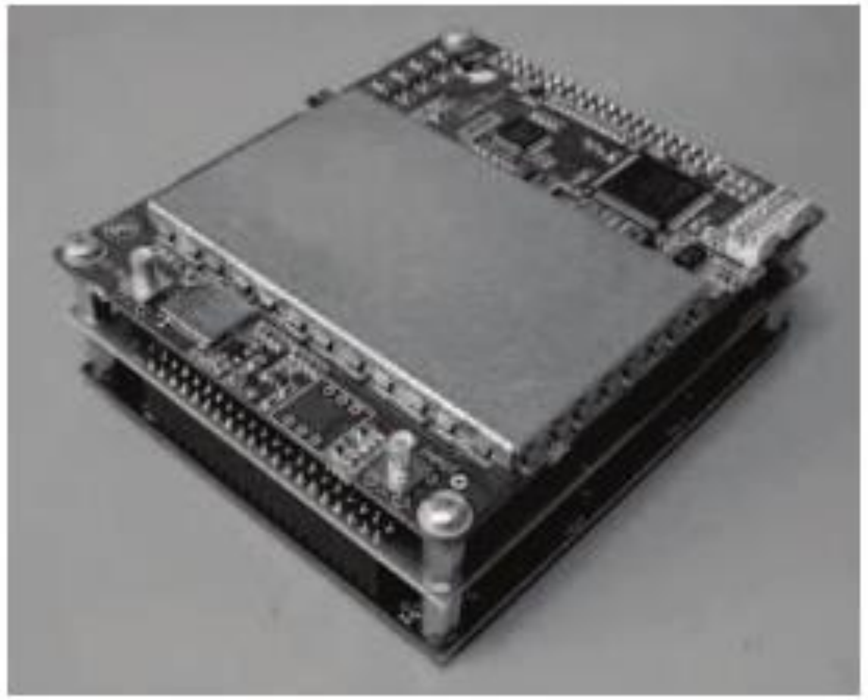
Size: 83 mm x 96 mm x 38 mm

Mass: 350g

PERFORMANCES

Total dose radiation: 10 krad Si (estimated <1 krad/y)

Carrier tracker sensitivity: High



BOOM

$$\frac{\Delta B}{V} = \frac{B_0}{d^3}$$

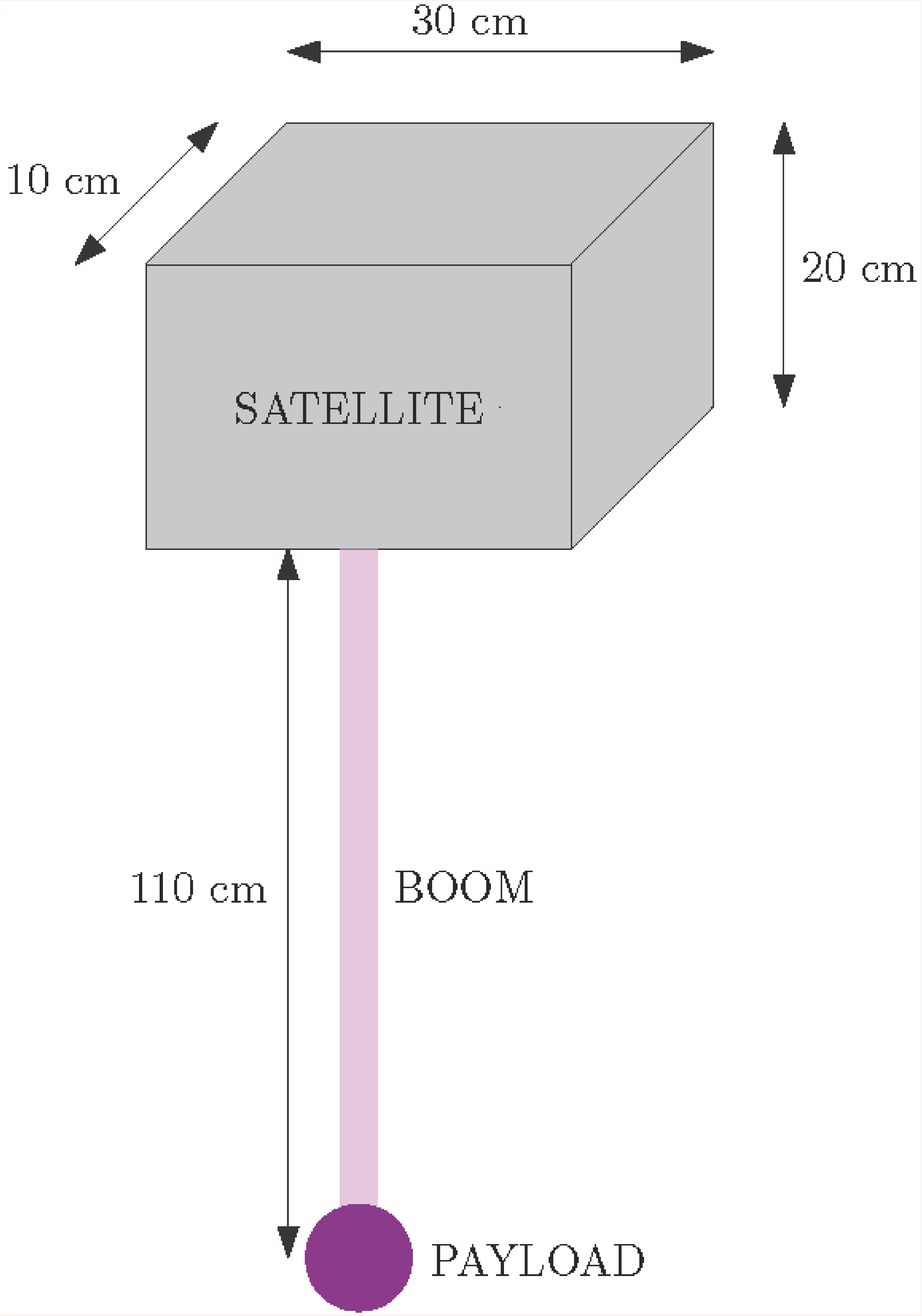
$$d = \sqrt[3]{\frac{B_0}{\Delta B} V} = 1.1m$$

On the Boom:

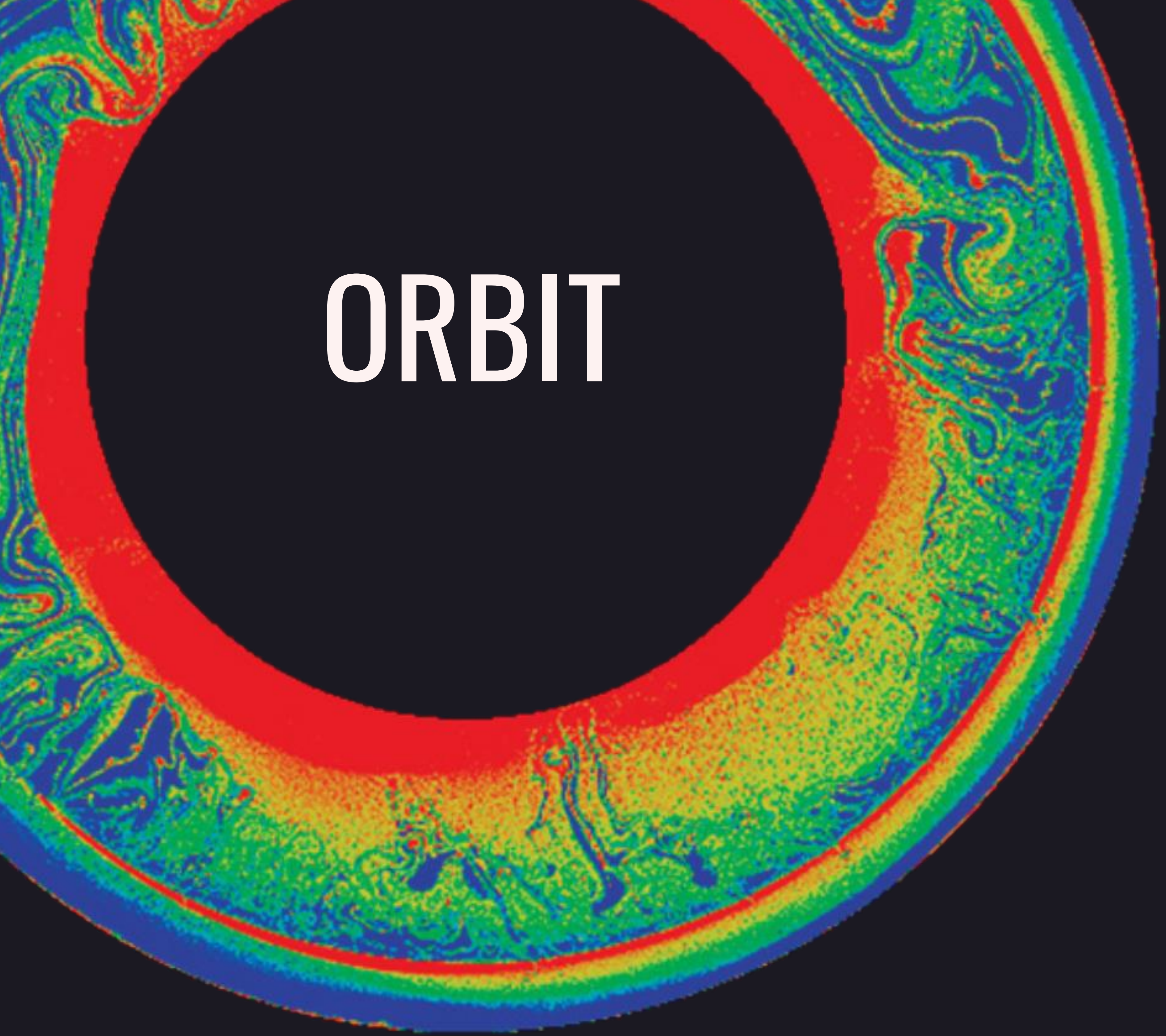
- FGM
- ASM
- 2 Star trackers

$B_0 \cong 50\ nT$ Estimation of the dipole term of all the bus

$\Delta B < 0.2\ nT$ Scientific requirement



ORBIT



ORBIT / CONSTELLATION DESIGN REQUIREMENTS

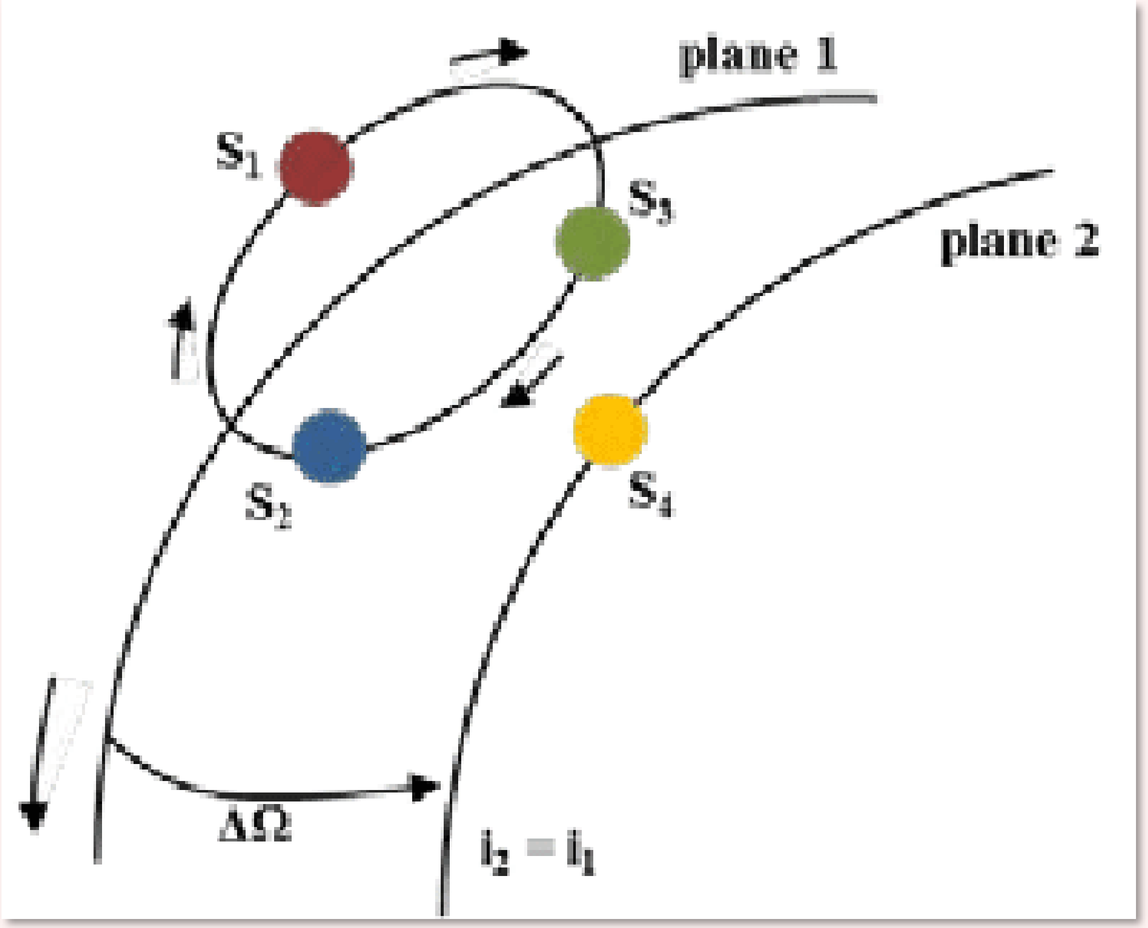
RELATED SCIENCE REQUIREMENTS

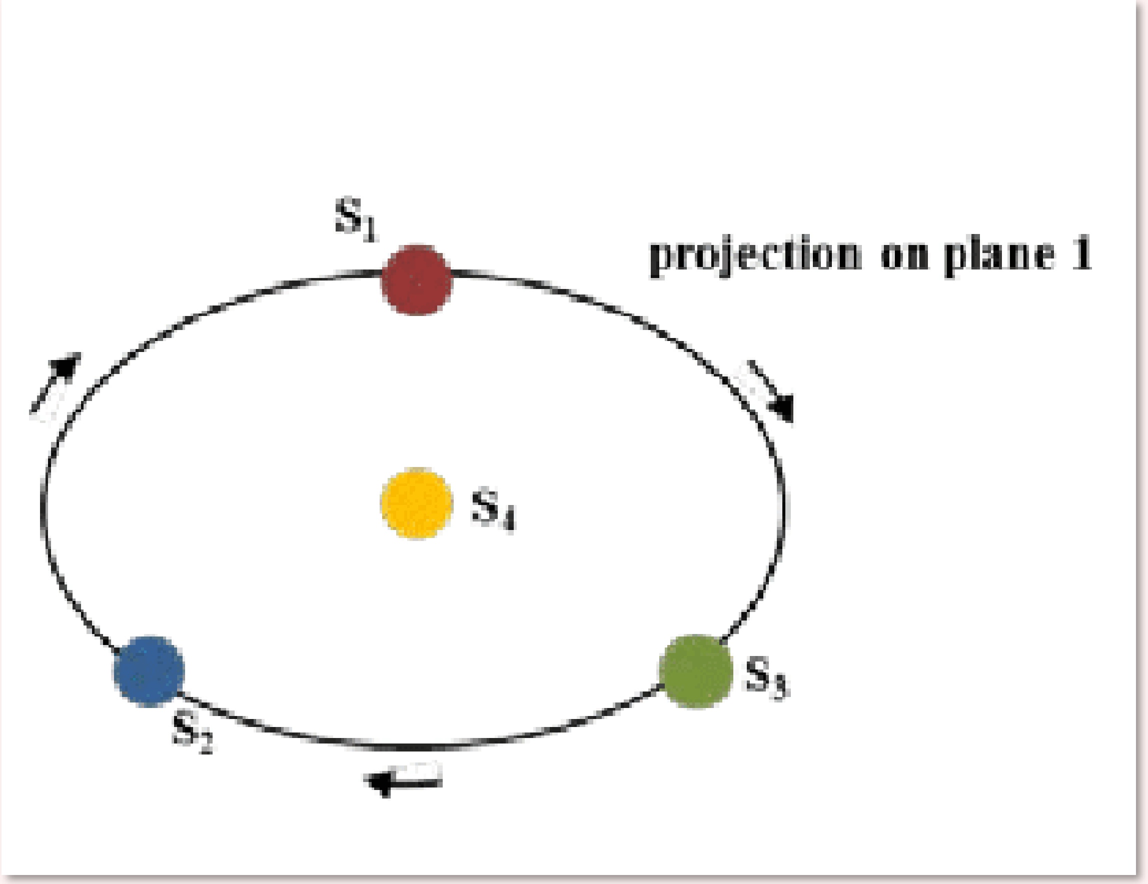
- 3D measurements of the Earth's magnetic field (full tensor gradient in equatorial regions)
- Distance between each measuring instrument for ionospheric measurements 100 km-200 km
- spatial / temporal resolution
  - 90°/2h (mLT/mLat with full tensor below 65° mLat)
  - 22.5°/12h (earth fixed)
  - 72°/12h (for gravity, satisfied by previous condition)
- Measurement gaps are only permitted above the poles (latitude >75°)
- Mission lifetime of 3 years

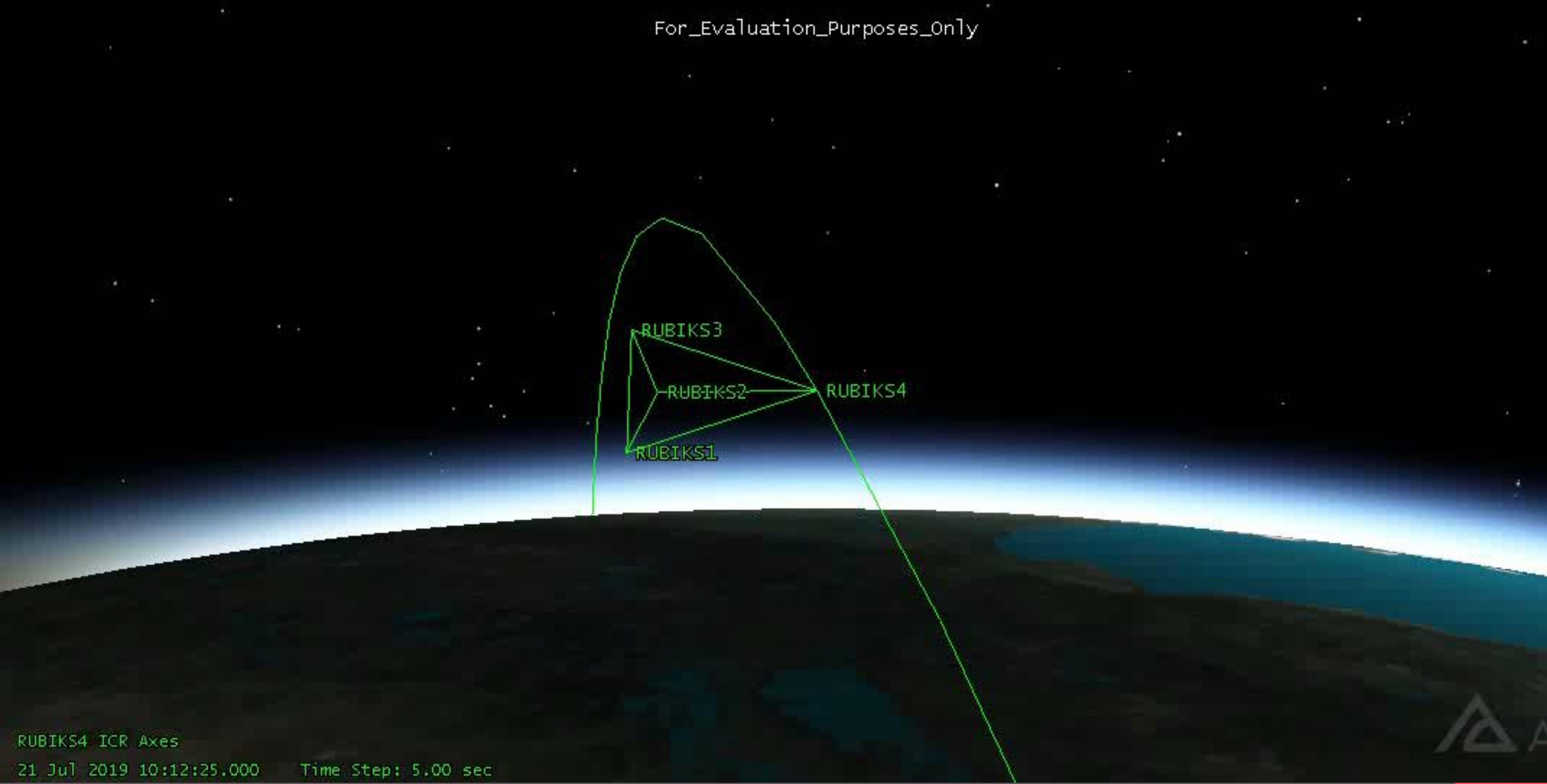
CARTWHEEL HELIX FORMATION FLIGHT

TO HAVE MEASUREMENTS OF THE EARTH MAGNETIC FIELD IN THE THREE DIRECTIONS WE NEED:

- 3 satellites on a Cartwheel formation flight on the same orbital plane.
- 1 satellite on a nearly-circular orbit which crosses the triangle in the polar region (measurement gap)
- Altitude was chosen as a trade-off between the required lifetime (3 years) of the mission and the sensitivity of the instruments.
- The orbits are both sun-synchronous to fulfill the requirement of a fixed local time.






For_Evaluation_Purposes_Only
RUBIKS3
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RUBIKS4 ICR Axes
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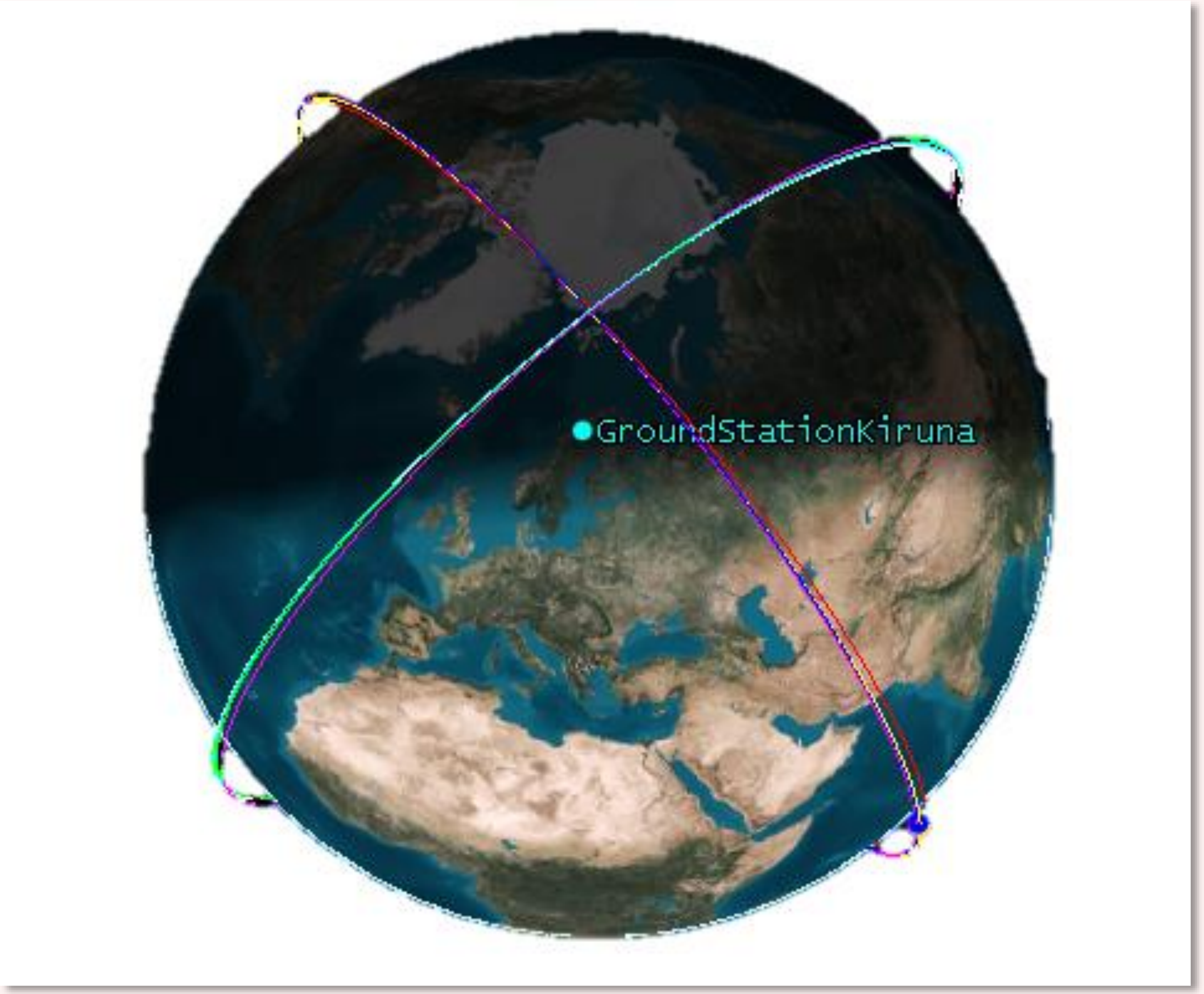
Time Step: 5.00 sec

OVERVIEW OF ORBITS

- 2 Constellations to achieve the temporal resolution requirements → 8 satellites
- 2 different orbital planes to achieve the spatial resolution requirements
  → LTAN shift of 6h for the second constellation
- LTAN of 9am and 3pm to use the same solar panel configuration for all satellites



Science Requirement resolution / revisit time	2 constellations 1 orbital plane	2 constellations 2 orbital planes
90° / 2 h (local time-fixed)	✗	✓
22.5° / 12 h (earth-fixed)	✓	✓

2 constellations, 2 orbital planes

Requirement (1)

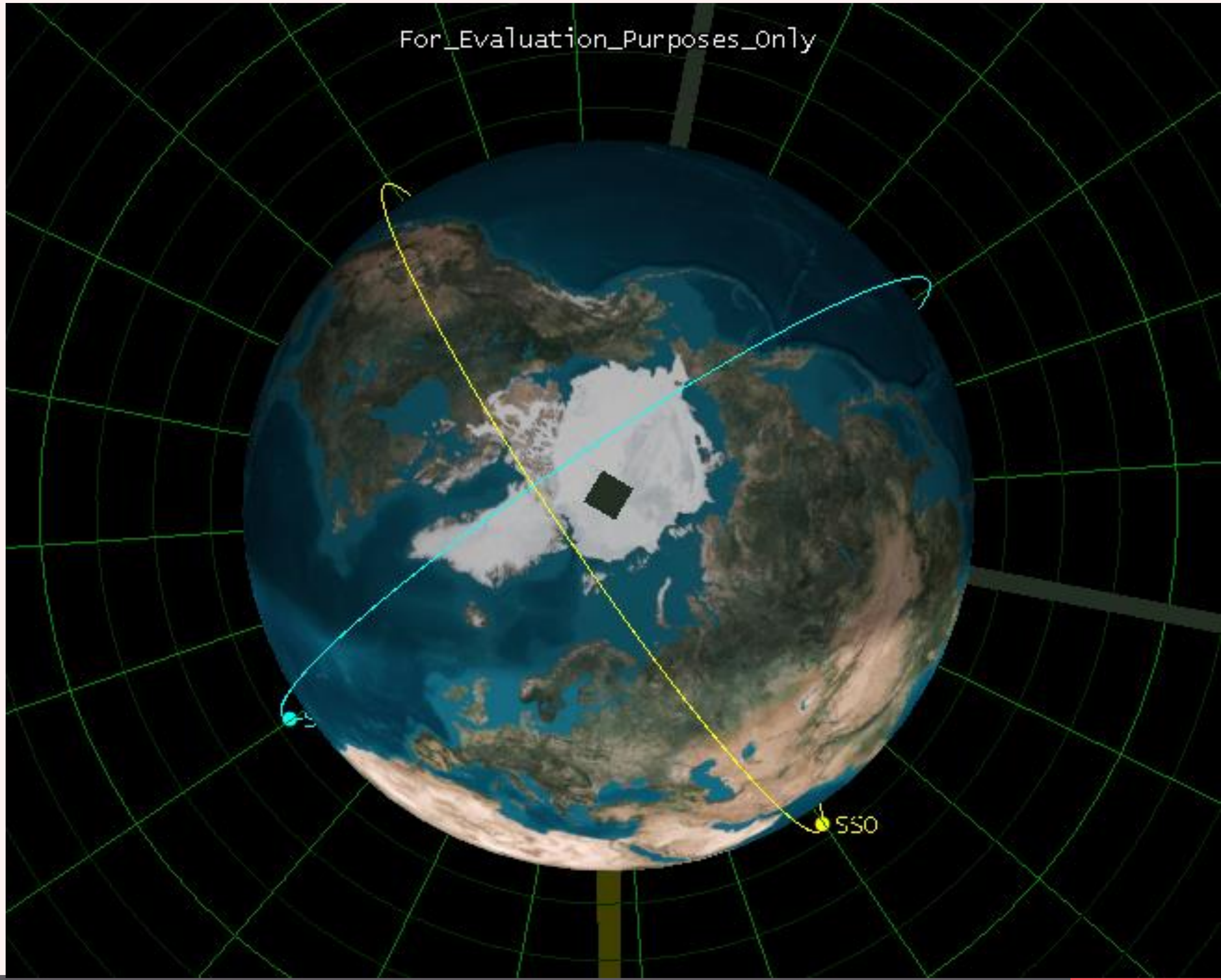
- Spatial resolution 90°
- Revisit time 2 h (local time-fixed)
- Constraint:
  - Magnetic gradient tensor measurement at the equator

Orbit design

- RAAN 90° shift (LTAN 6h shift)
- Orbit period < 2h

Evaluation ✓

- Analysis time of 2h
- Resolution of 90° (Minimum)



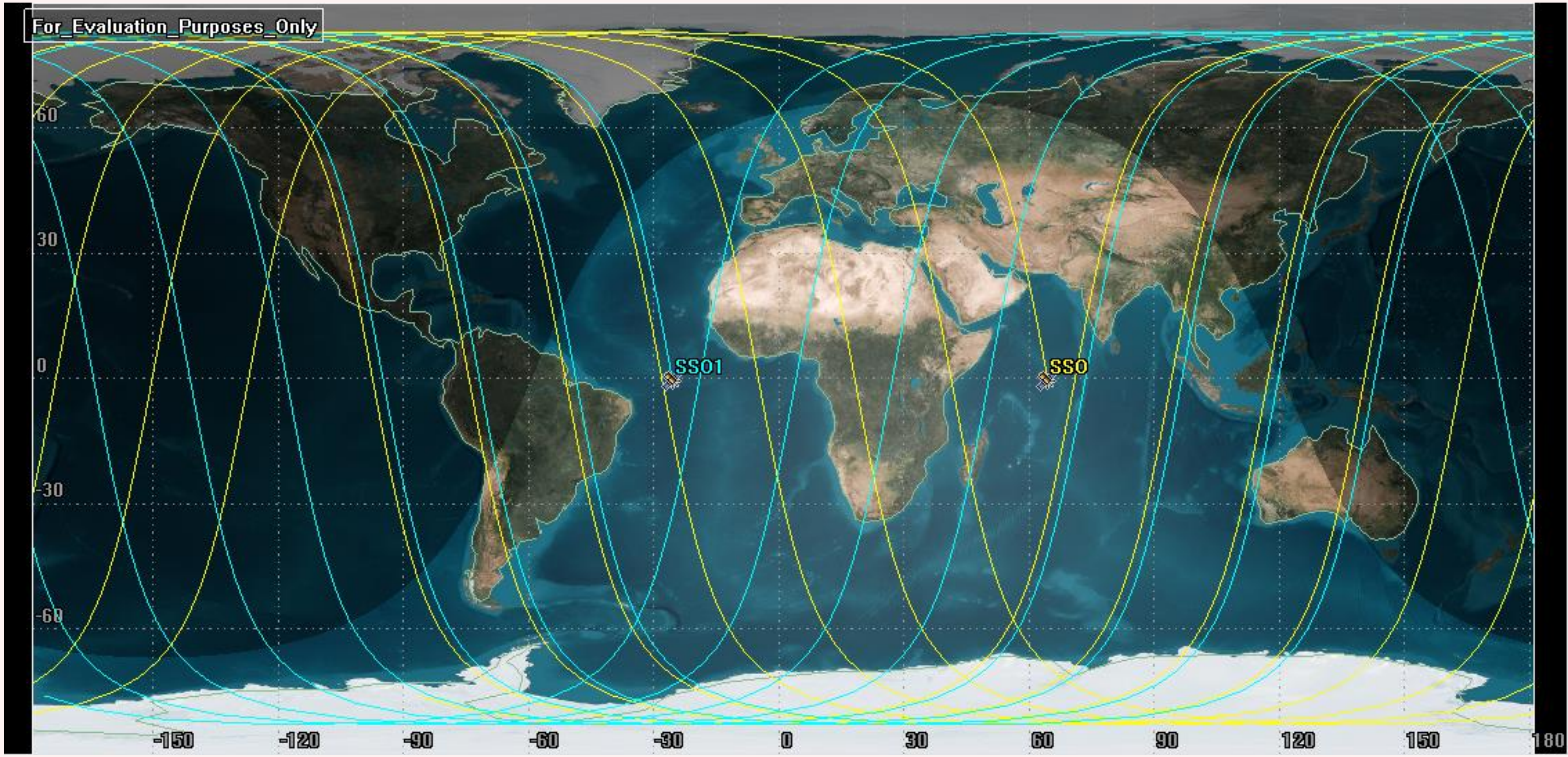
2 constellations, 2 orbital planes

Requirement (2)

- Spatial resolution 22.5°
- Revisit time 12 h (earth-fixed)

Evaluation ✓

- Analysis time of 12h
- Resolution of 20.5° (Minimum)



IN ORBIT RISK MITIGATION & EOL CONSIDERATIONS

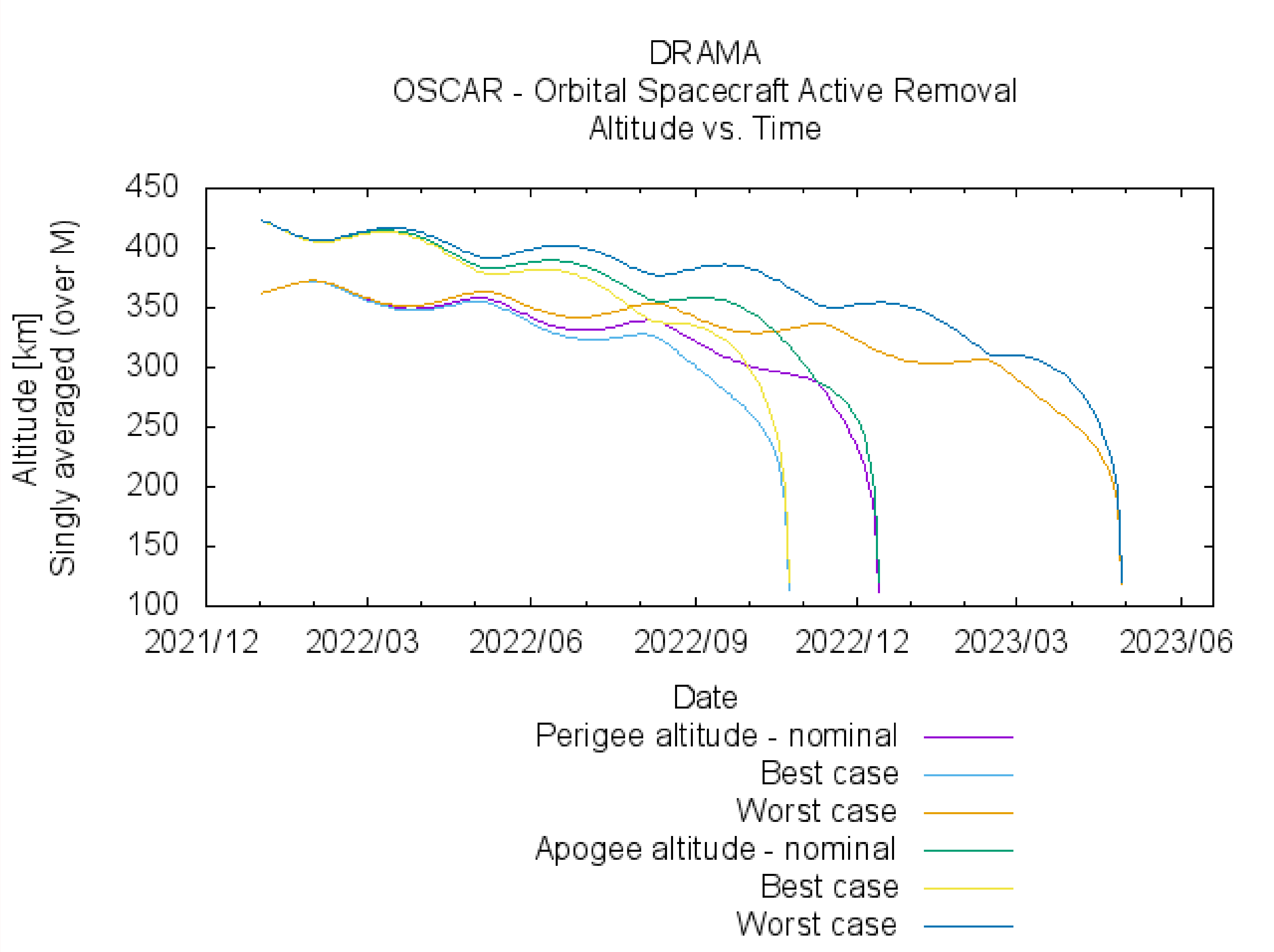
Impact probability with debris over 10 cm for mission the lifetime lower than 0.001.

P=2.3688e-05 (Drama ARES Tool)

NASA-STD-8719.14B (ECSS-M-ST-80C does not provide number)

EOL deorbit time in less than 25 years

Worst case lifetime → 1.4 years



DELTA-V BUDGET

Commissioning of constellation

100 m/s

Perturbation correction

11.4 m/s over 2 months

EOL delta-v

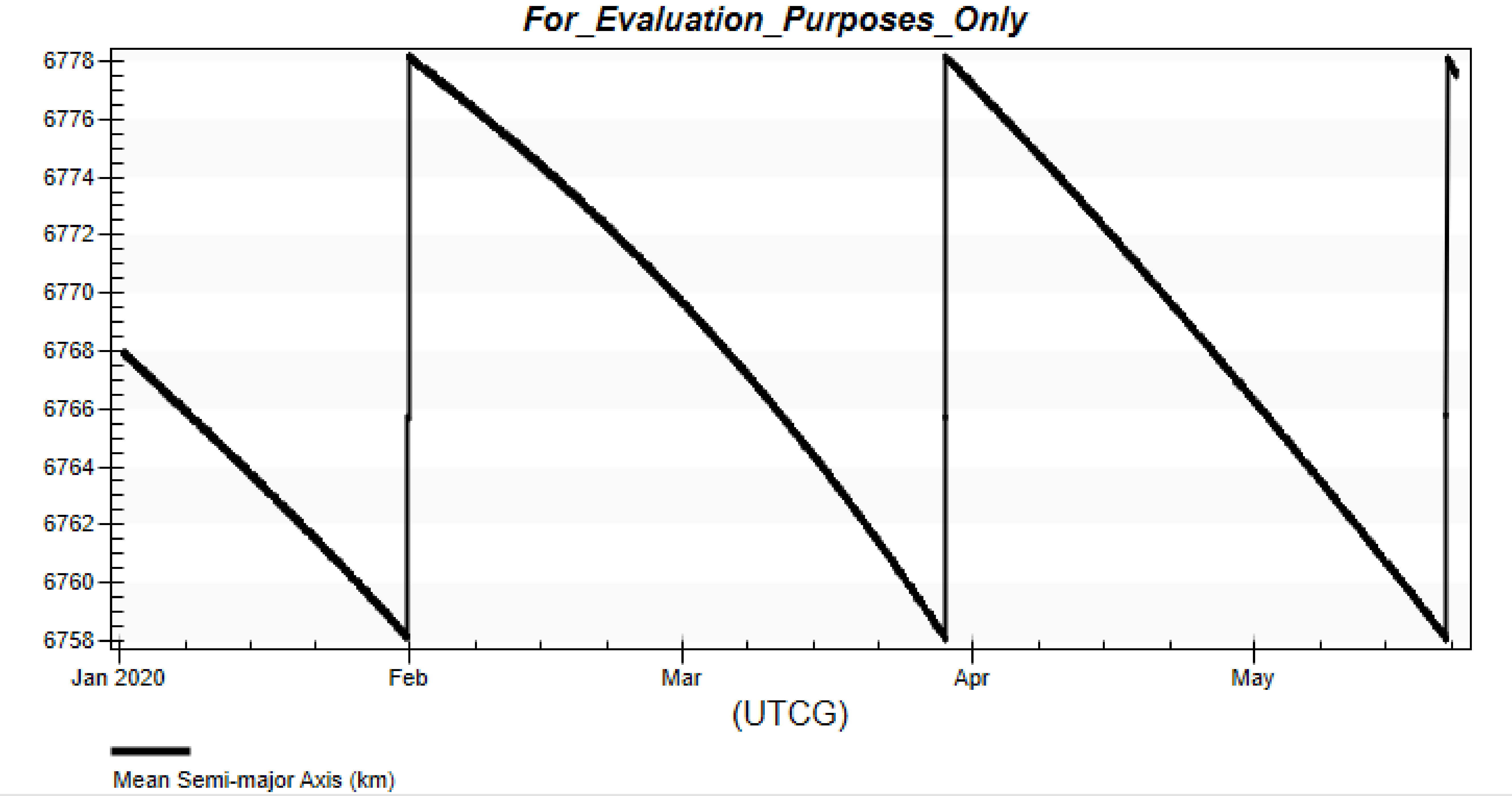
0m/s

Margins

20% over calculated

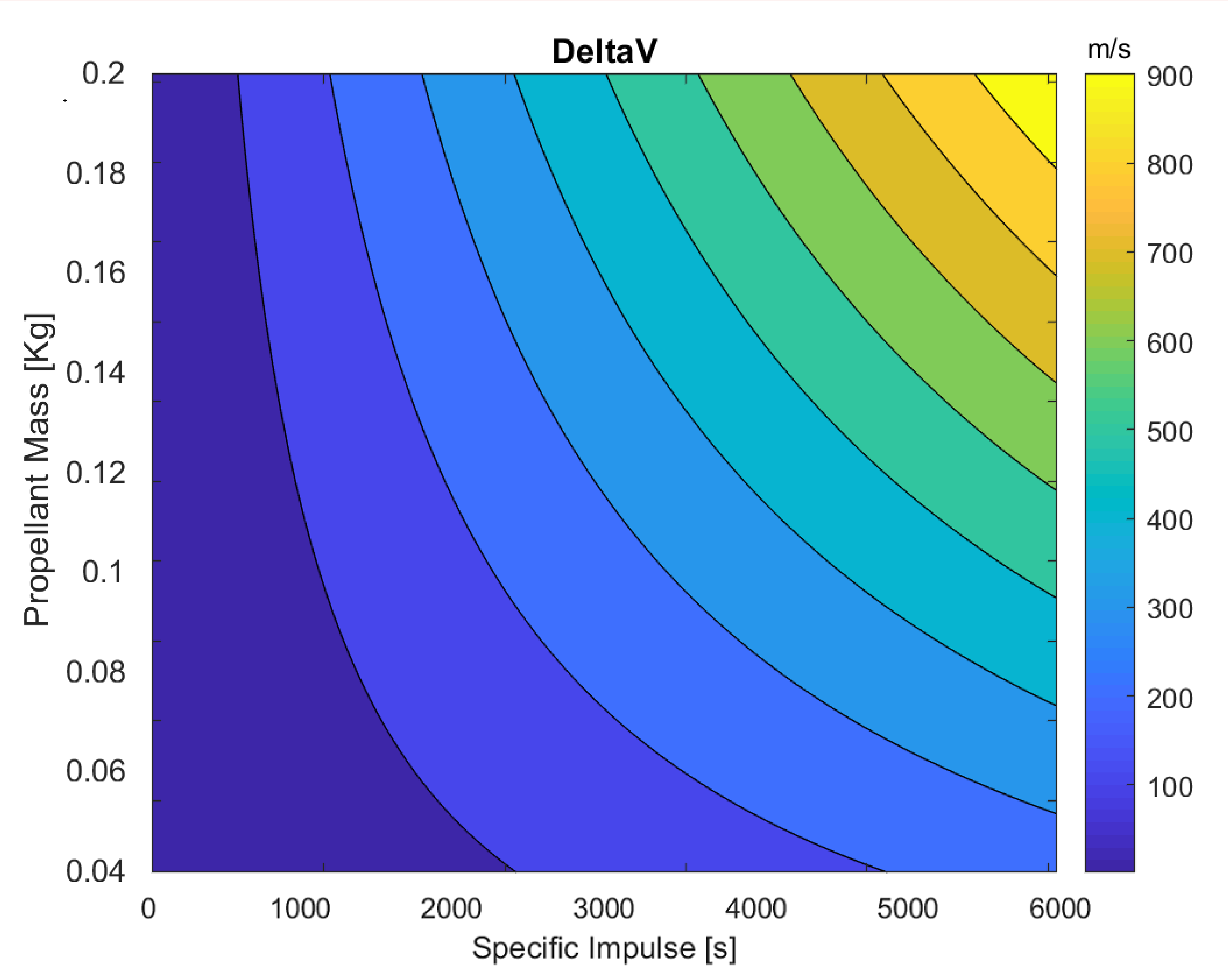
2% remaining at EOL

Required Δv= 372.4 m/s



PLATFORM

TECHNOLOGY OVERVIEW



Type of propulsion	Thrust	Isp [s]	Propellant mass [kg]
Cold Gas	10 mN – 10 N	40 - (70)	6.28
Mono-propellant	0.1 – 10 N	200 - (300)	1.78
Arcjet	0.1N	500-(1500)	0.38
FEEP	1 – 10 mN	(6000) - 10000	0.09
PPT	1 – 1300 µN	650 - (1350)	0.42

SYSTEM DOWN-SELECTION

Type of propulsion	Provider	TRL	Propellant	Power [W]	Isp [s]	Required propellant mass [kg]	Max propellant mass [kg]
Mono-propellant	VACCO	6	ADN	15	190	2.72	0.17
Mono-propellant	Tethers Unlimited	6	Water	20	310	1.73	0.74
Mono-propellant	Nano-avionics	7	ADN	10	200	2.59	0.33
FEEP	Enpulsion	7	Indium	20	3000	0.19	0.23
FEEP	M-Space	4	Indium	15	5000	0.12	0.125
PPT	MarsSpace	6	Teflon	5	640	0.86	N/A
PPT	Busek	5	Teflon	7.5	536	1.03	0.04

Main selection drivers

- TRL status
- Propellant type (Ground handling)
- Power consumption
- Required propellant mass

FEEP advantages

- High Isp
- High efficiency
- Meets propellant mass estimation
- Space flight heritage

FEEP disadvantages

- Low thrust
- Power consumption

PROPULSION OPERATION

Tight requirements on propulsion → Selection of FEEP technology → **Low thrust** (0.5mN)

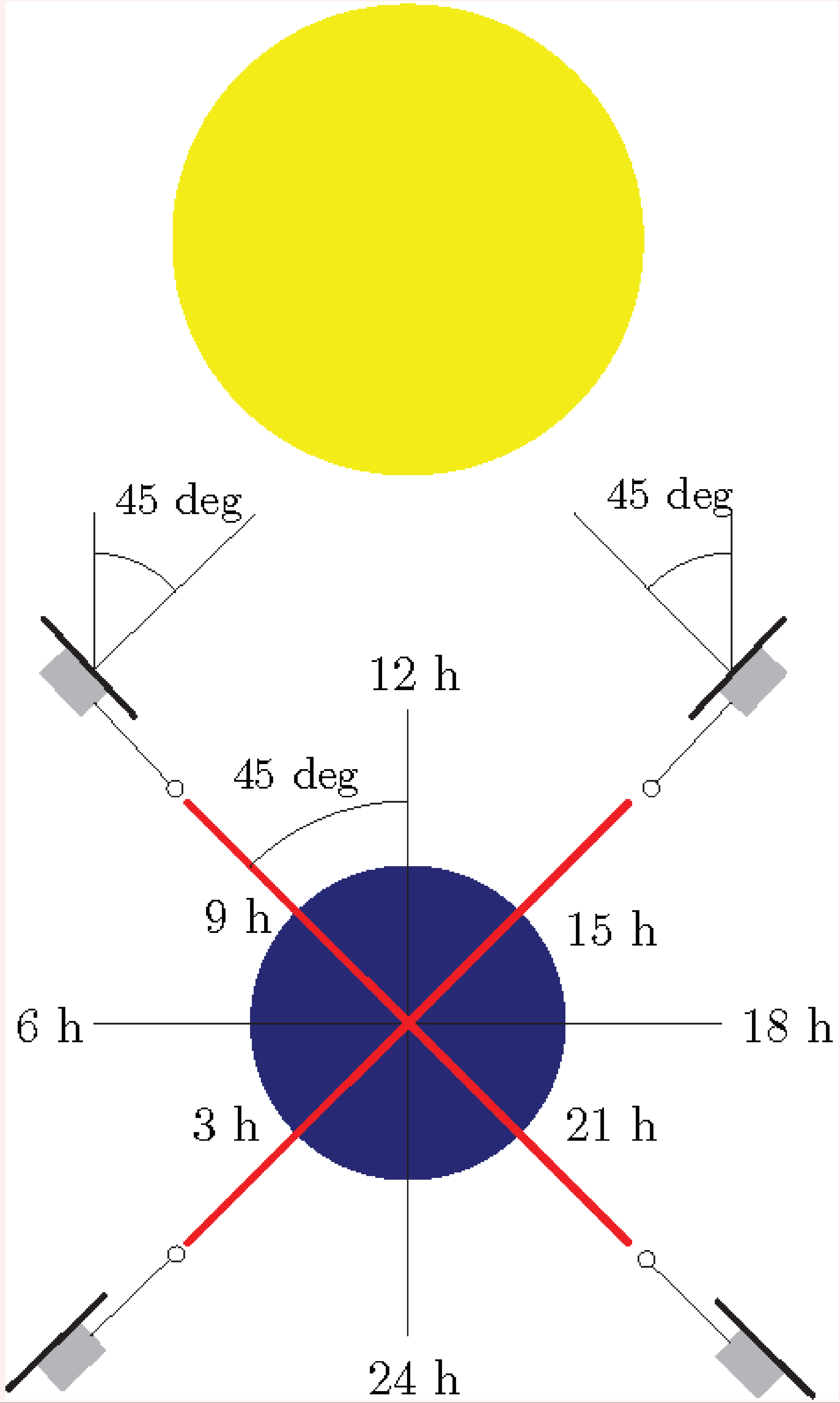
	Time between altitude correction	**Delta v needed per thrust**	**Time needed**	**Science measurement interruption**
Conventional operation	~ 60 days (935 orbits)	11.4 m/s	76 h	Yes
Proposed operation	~ 2-3 orbits	0.04 m/s	10-15 min	No

CubeSat

- Small payload & 8 satellites → Standardization → CubeSat
- Standardization: size & launcher
- Large market & community → COTS
- Flight heritage for bus components
- Needs to look at reliability → main problem for CubeSats

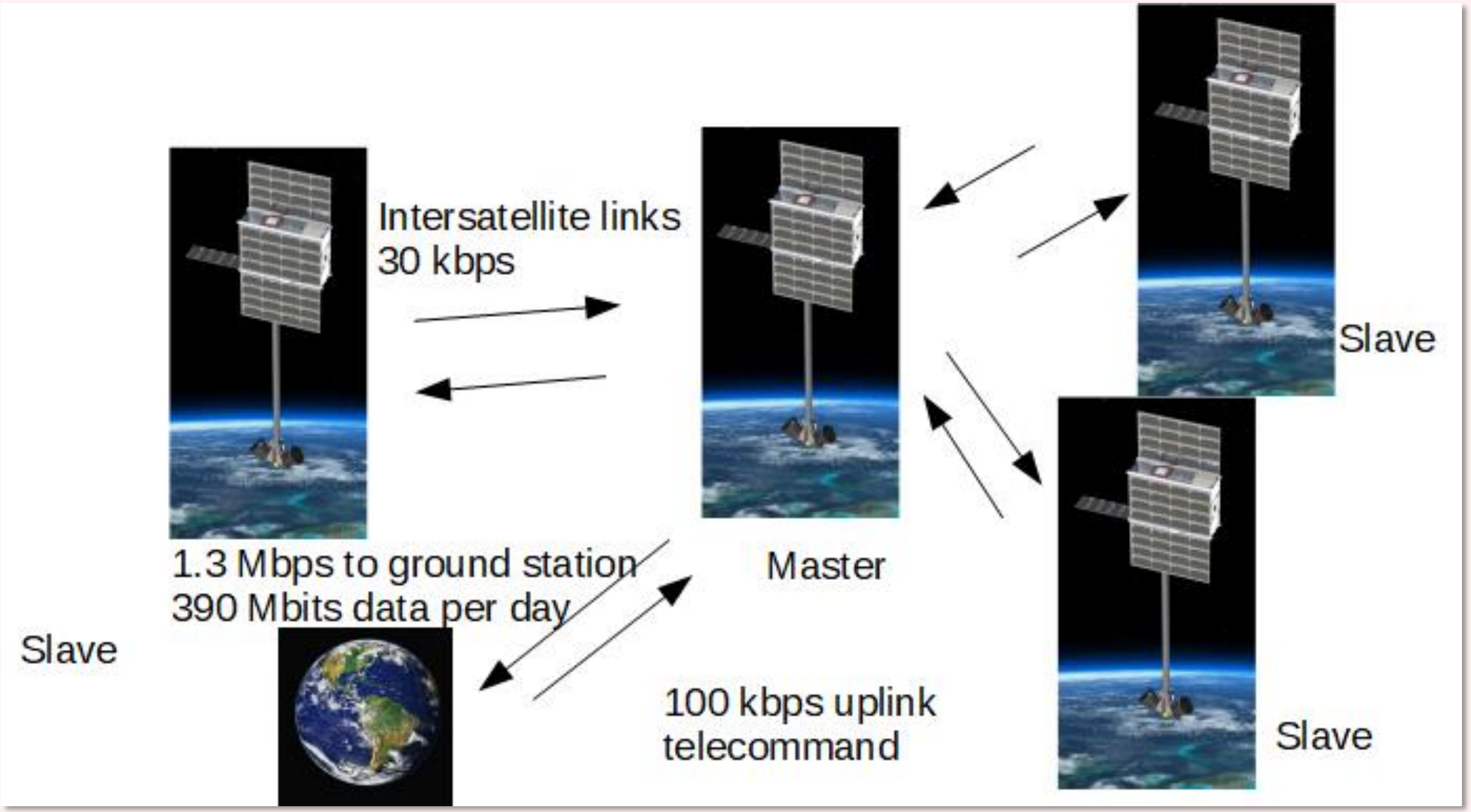
SOLAR PANEL ORIENTATION

- Sun-synchronous orbits: 9 LTAN & 15 LTAN
- β angle around 45°
- Minimization of drag
- Rotation around the normal of the solar panels

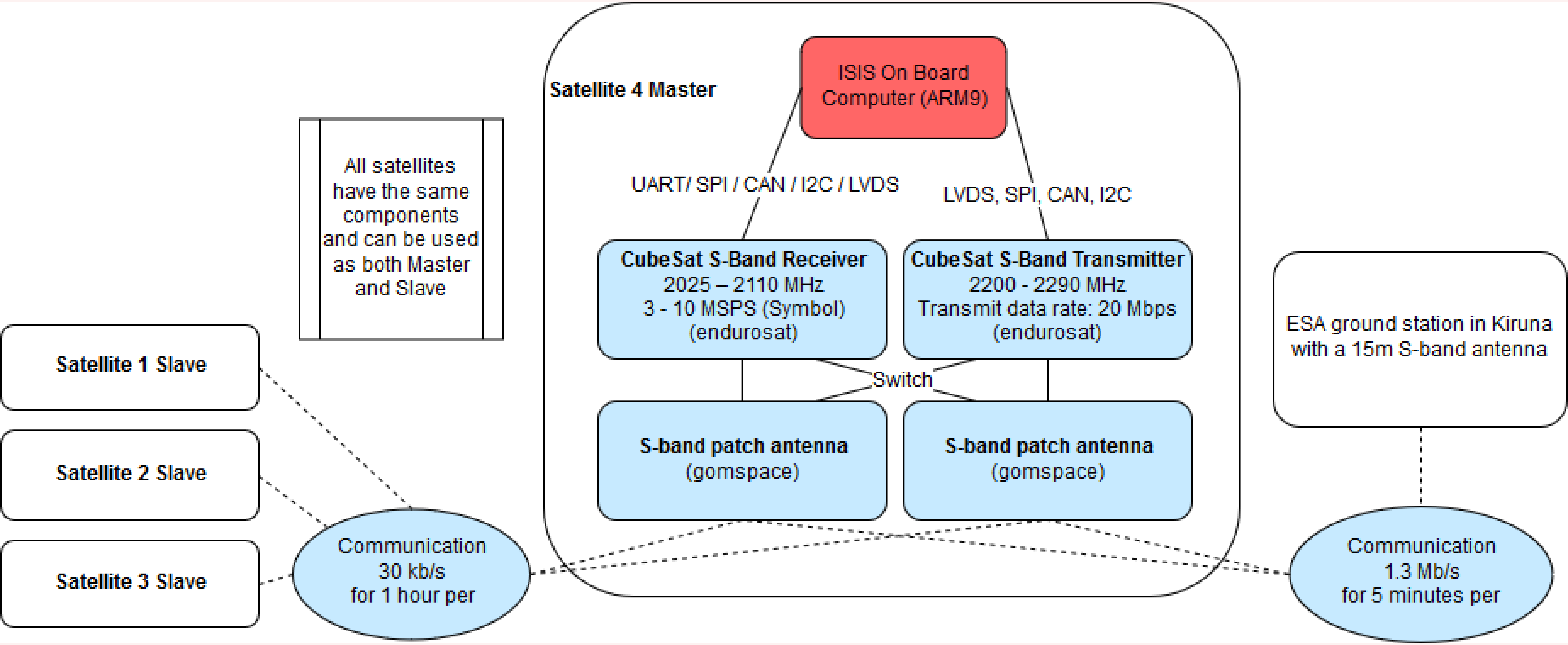


RADIO COMMUNICATIONS

- Communicating with 1 satellite is easier than with 3 for ground operations
- Master/Slave configuration - all satellites have the same configuration for redundancy
- Only the master can communicate with ground
- Intersatellite links between the master and slaves



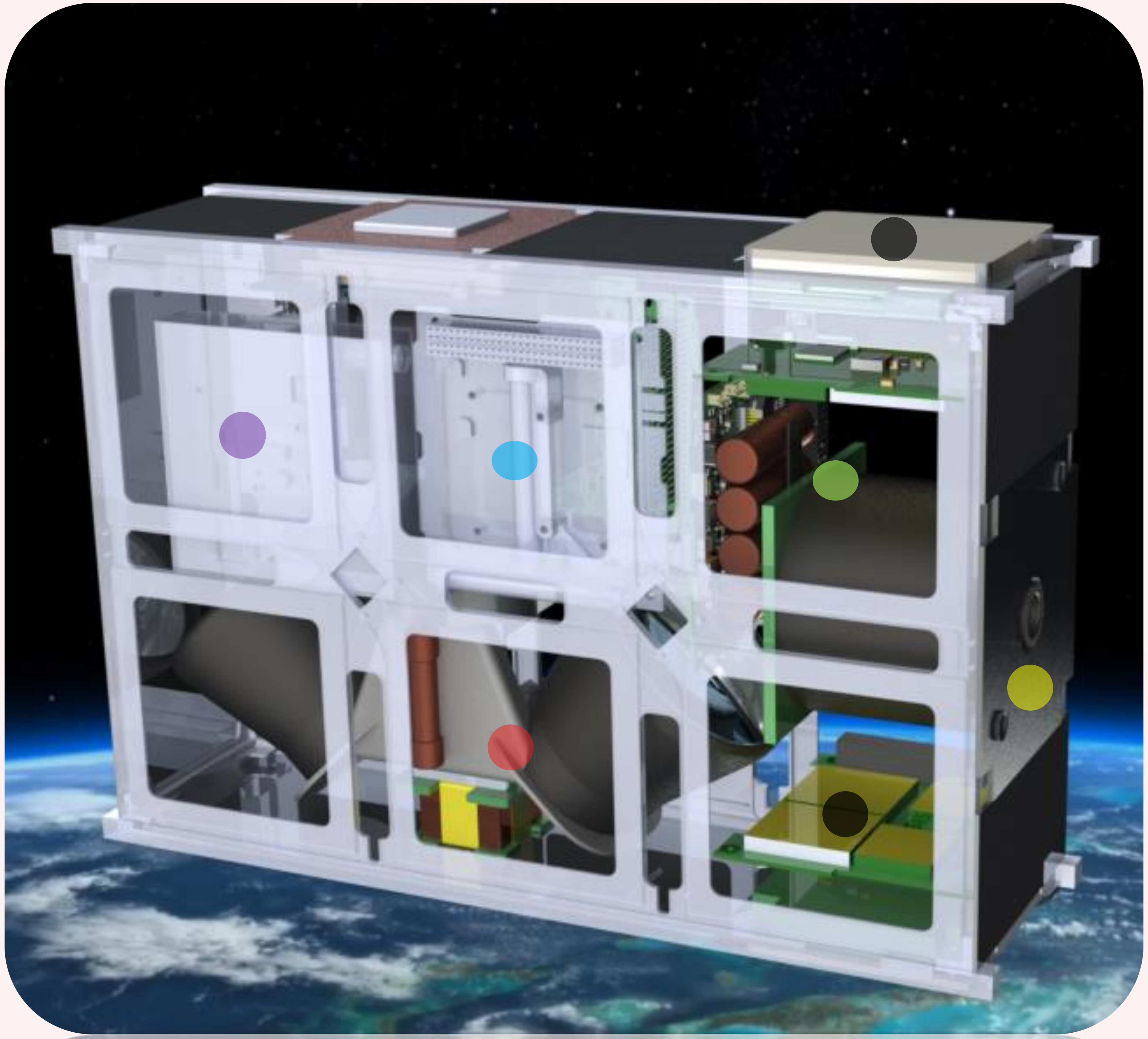
MASTER/SLAVE APPROACH



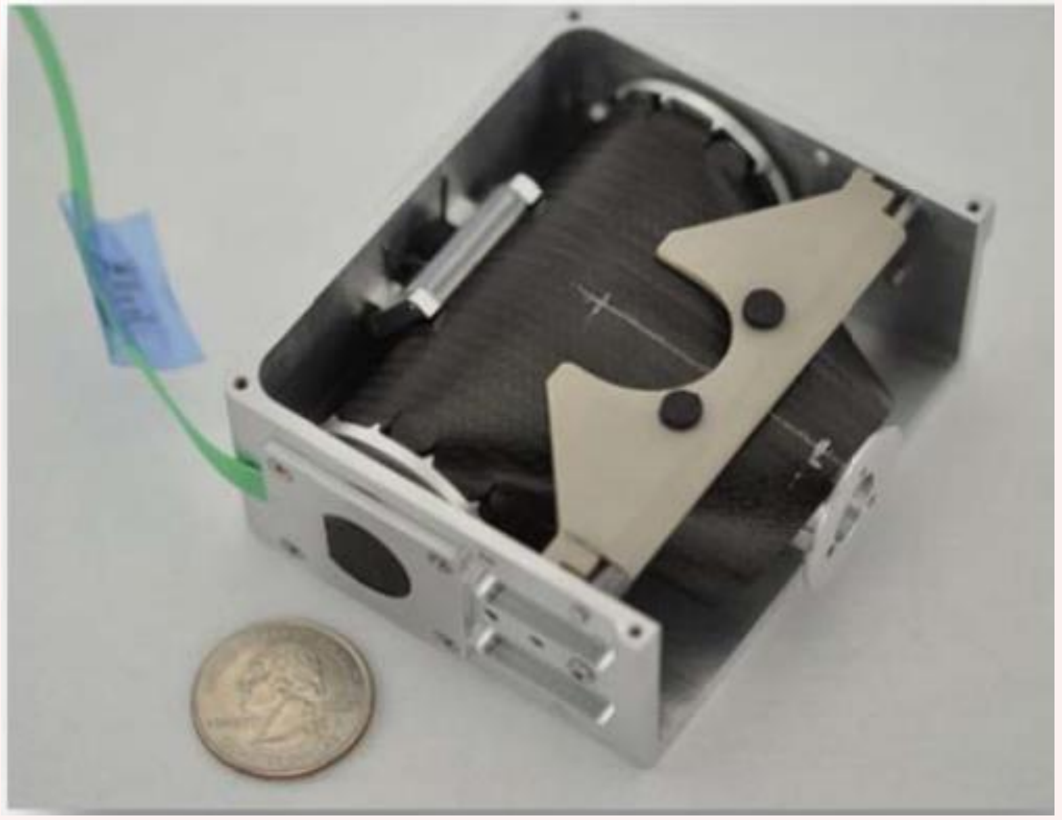
STRUCTURE

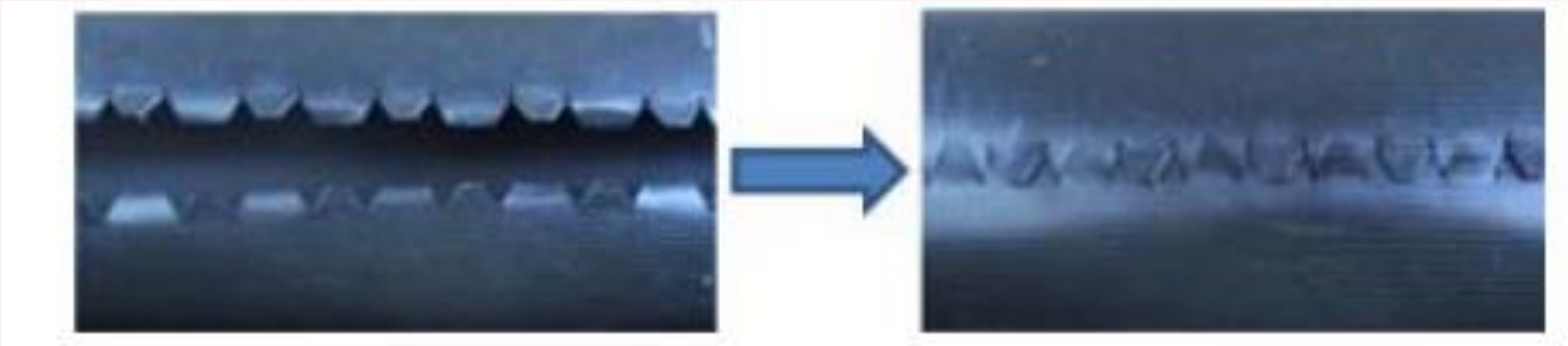
- Payload: 2.5 U
- Propulsion: 1 U
- ADCS: 0.5 U
- Power: 1 U
- OBC: 0.5 U
- COMM: 0.5 U

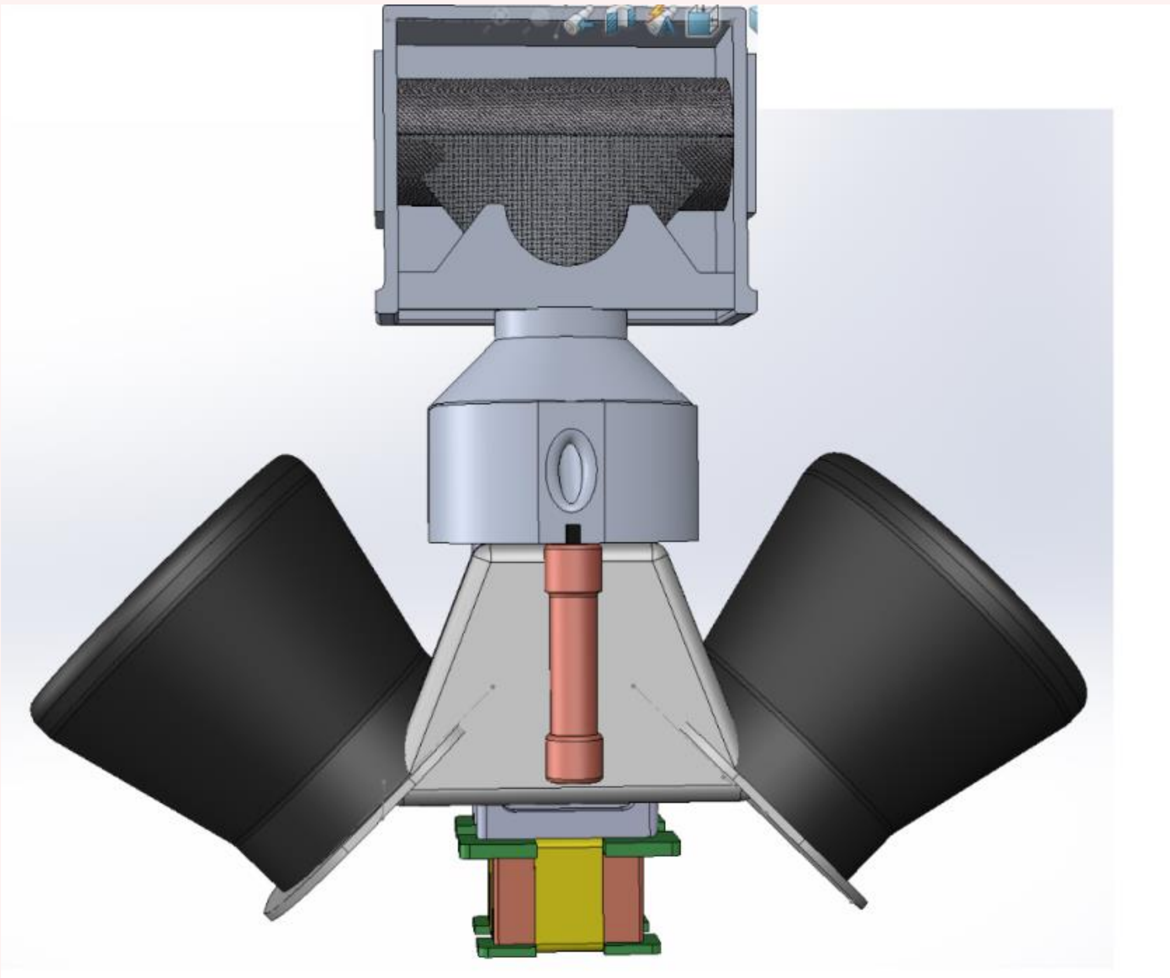
Total Bus Mass
With Margin: **11,1 Kg**



BOOM & DEPLOYER

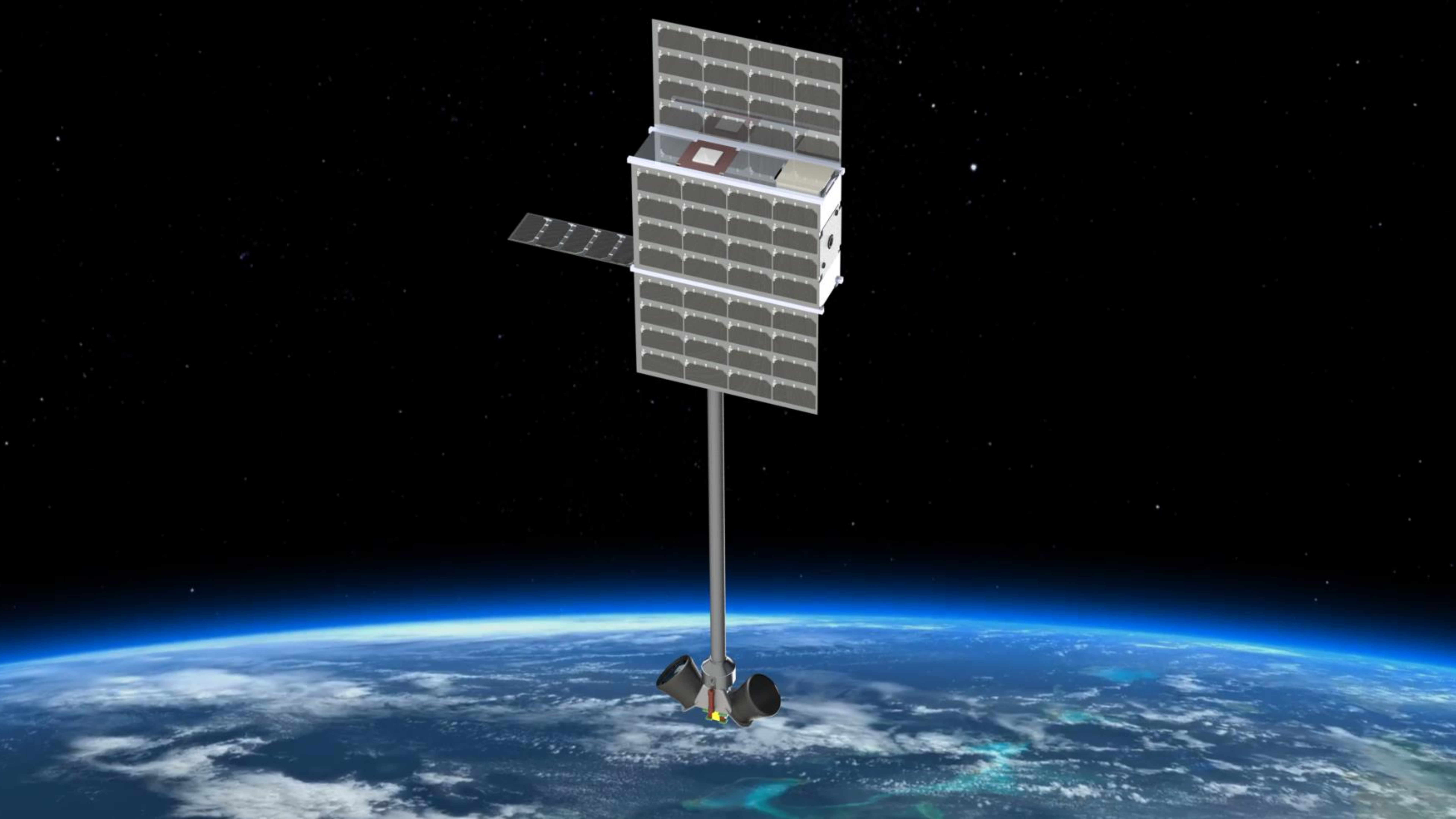






Performance Summary	
Specification	**Performance**
Deployment Power	<0.5 W
Deployment Voltage	6-12 VDC
Boom Stiffness	21.5 N-m2
Deployer+ Boom Mass	200g
Boom Diameter	25.4 mm
Boom Length	<1m to 2m
First Mode Frequency	>1 1Hz (variable)

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.

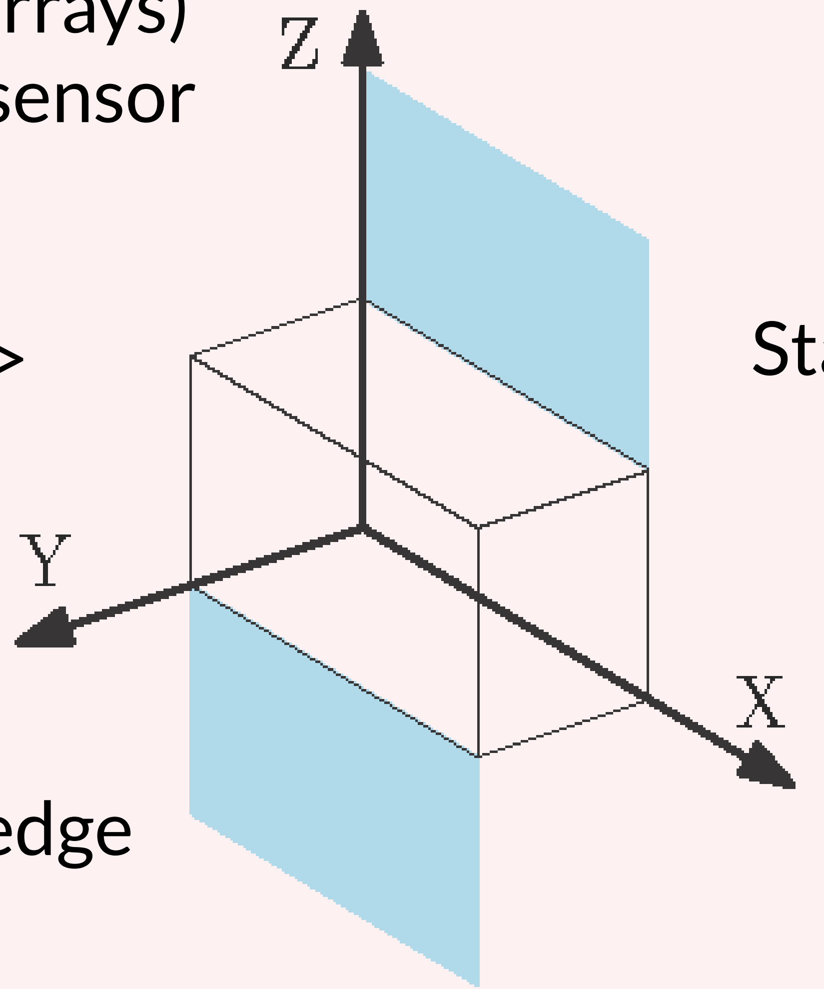


Attitude Determination and Control System

Requirements

Sun pointing
(Solar arrays)
-> Sun sensor

No remnant magnetic field -> 3-axis air core magnetorquer



Stability for propulsion

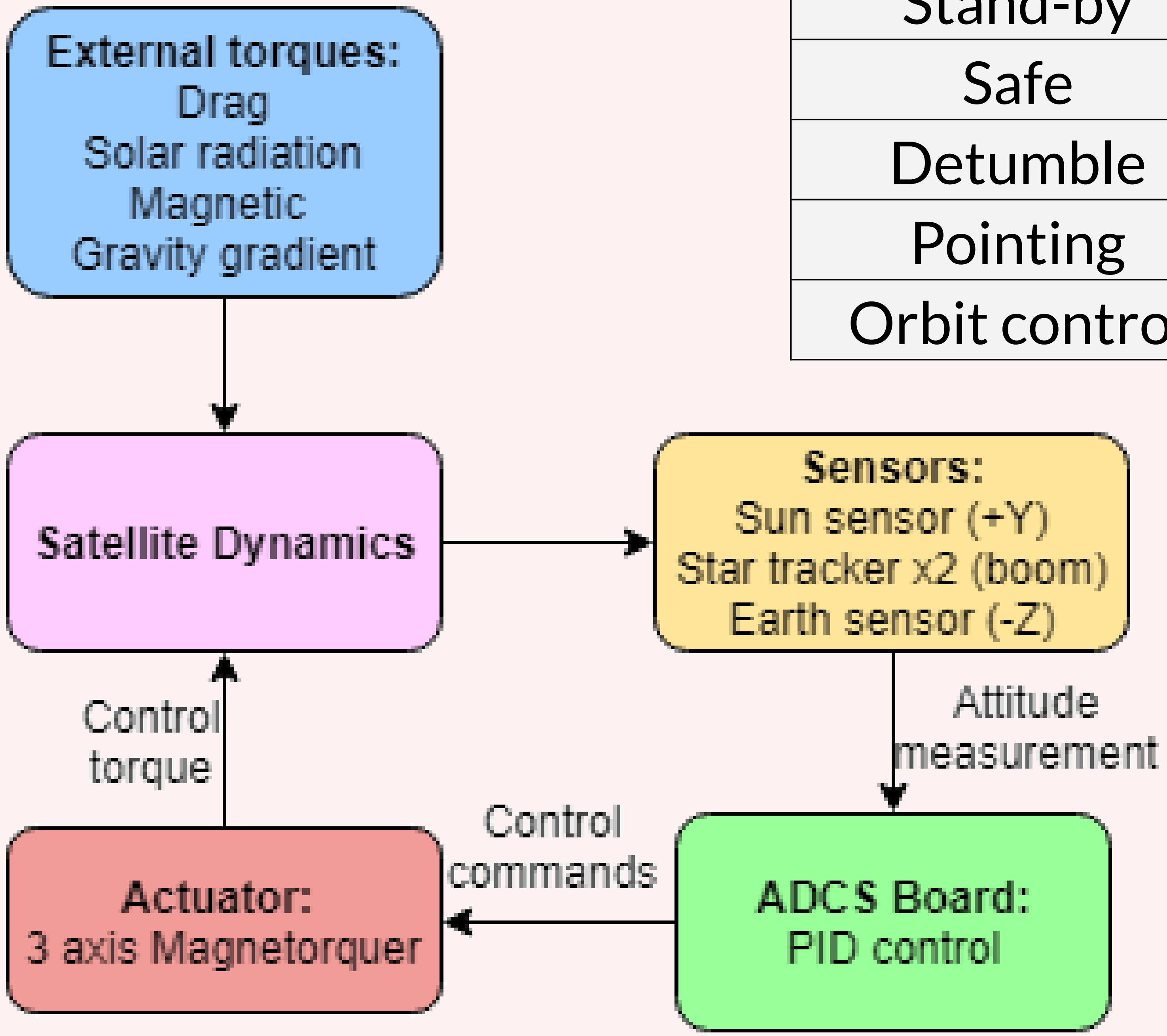
Pointing accuracy 5°
Pointing stability 1°

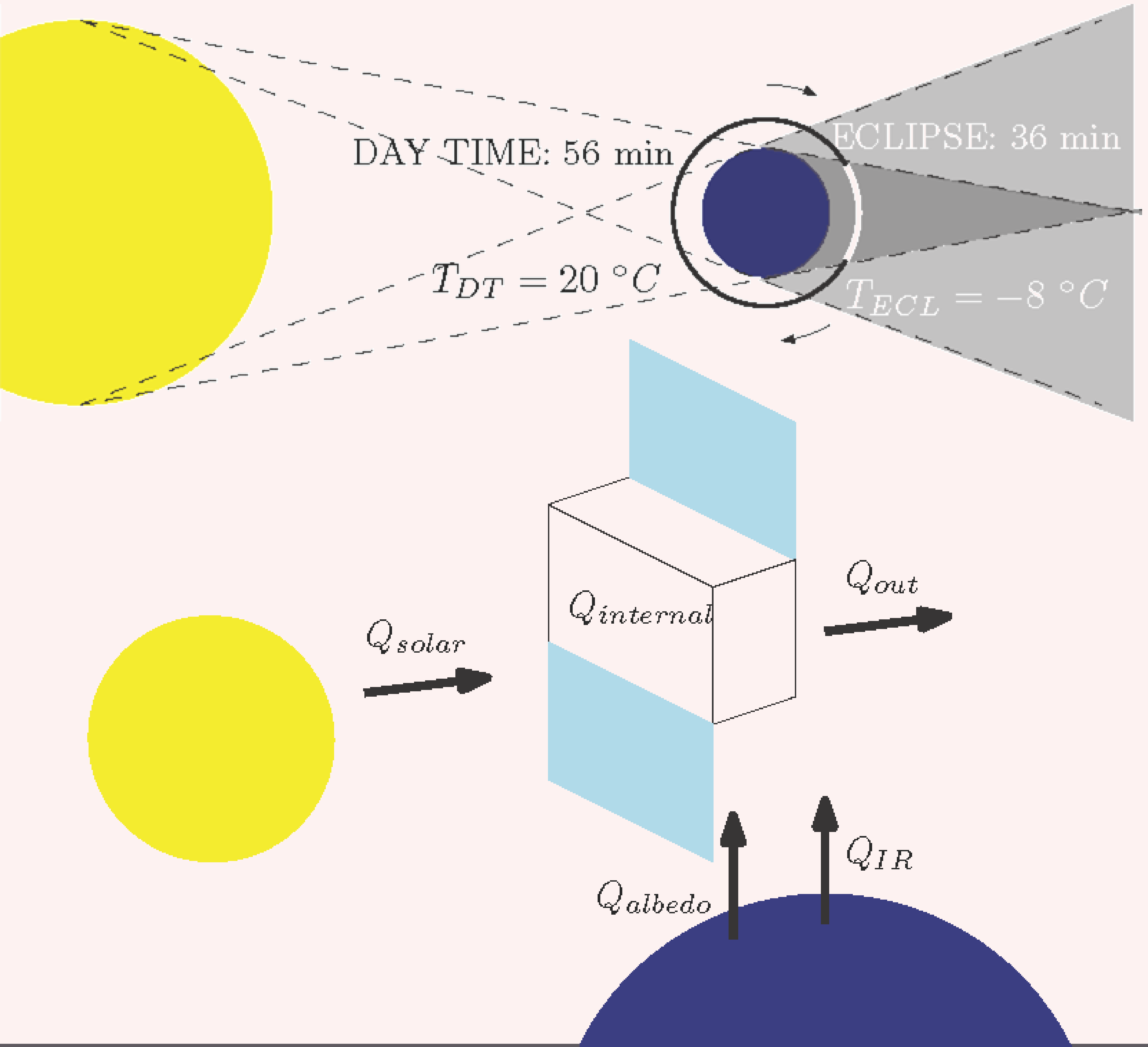
Attitude knowledge 1 arcsecond
-> 2 star trackers
1.5 arcsecond

Earth pointing (Antenna)
-> Earth sensor

Solution

ADCS Modes
Stand-by
Safe
Detumble
Pointing
Orbit control





THERMAL CONTROL SYSTEM

Temperature requirements: 0°C to 40°C

Heat inputs	
Q_solar (W/m^2)	1371
Q_albedo (W/m^2)	261
Q_infrared(W/m^2)	210
Q_internal (W)	7.6
Hot case (°C)	20
Cold case (°C)	– 8

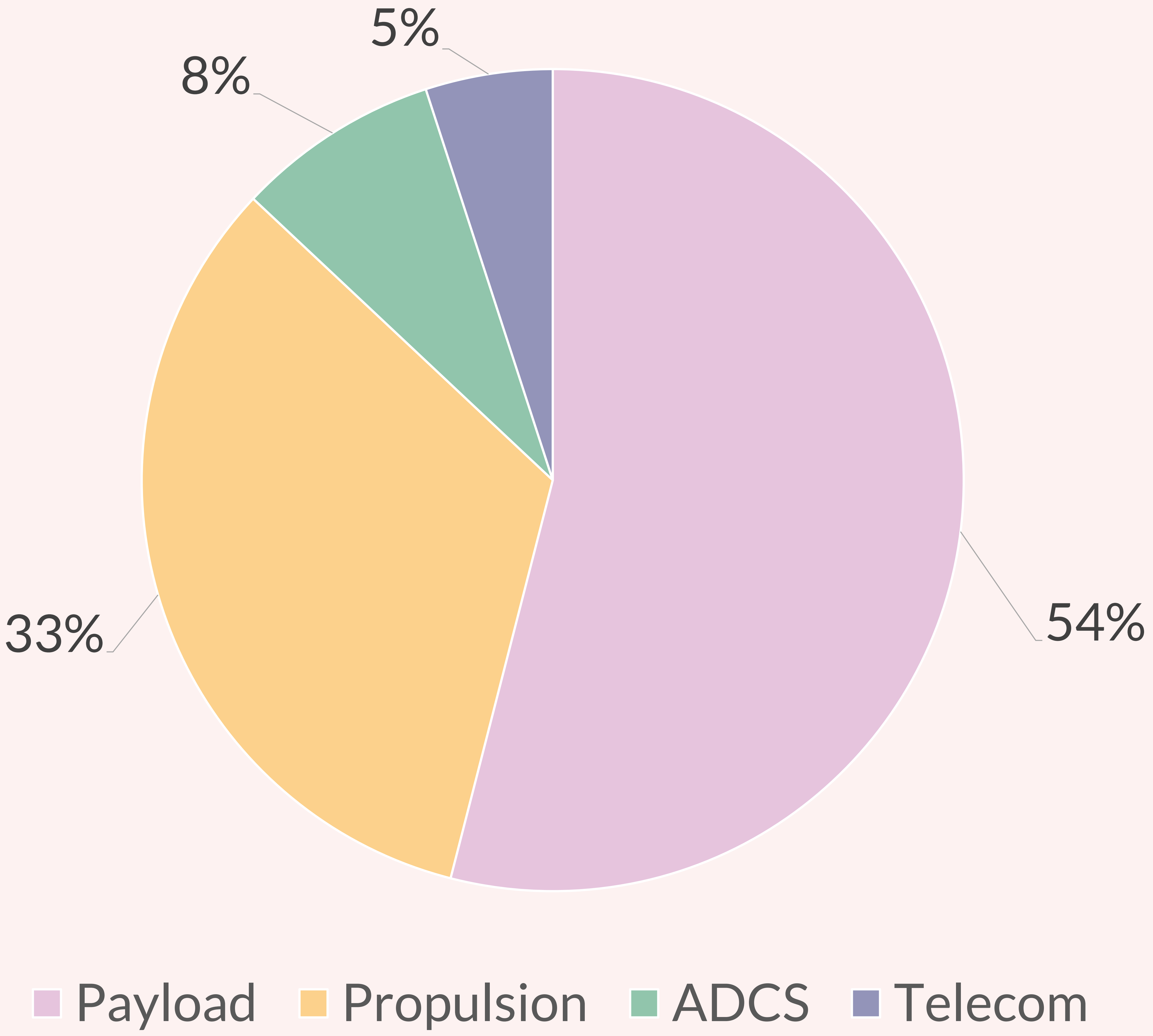
Passive thermal system -> Requires no power

Materials	Emissivity	Absorptivity
Sun facing	High	Low
Space facing	Low	High

SCENARIO POWER BUDGET

Total: 12.83 W

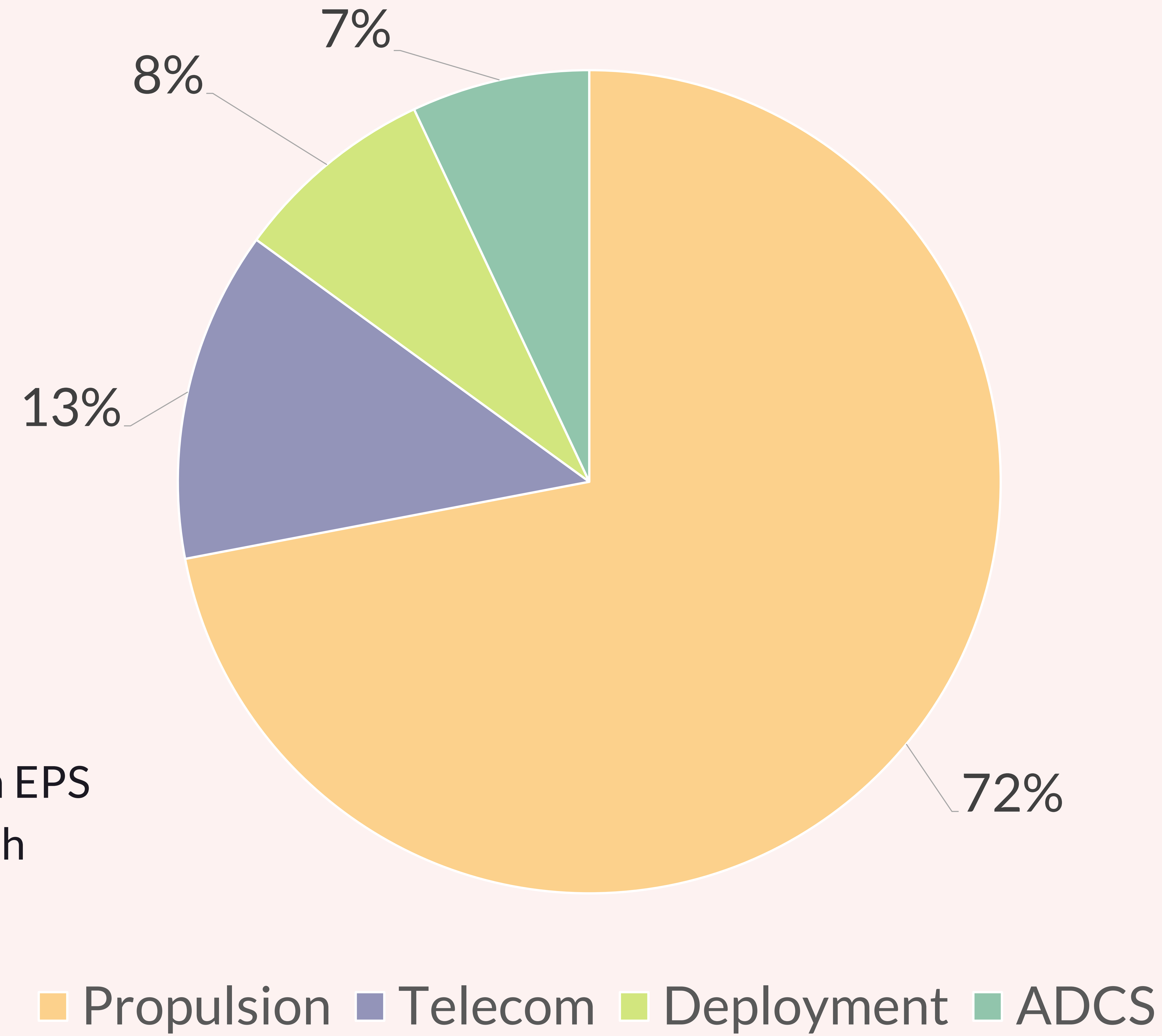
- Solar panel area: 0.17m^2
- Silicon cells:
  - 22% efficiency
  - 3.75% performance degradation
- 20% margin



LEOP POWER BUDGET & COMMISSIONING

TOTAL: 22.56 W

- On battery at the beginning of LEOP
- 51.12 Wh in science mode
- 2 VES16 batteries and 22.5 Wh from EPS
- Solar panel deployed 15h after launch



COST & RISK

LAUNCHER

Rocket	k€/satellite	k€/constellation
Soyuz	195	780
Vega	250	1000
Falcon 9	27	108
SpaceFlight (broker)	545	2180
Electron	480	1920
PSLV	315	1260

Falcon 9 SSO-service

Payload Cost Analysis

Payload Development Cost

Fluxgate Magnetometer:

Development time estimated: ~2y

Person-power: ~2-3 person-year

Total cost estimated: **~500 k€**

Scalar Magnetometer:

Development time estimated: ~1y

Person-power: ~2-3 person-year

Total cost estimated: **~250 k€**

Instrument Cost

GNSS receiver:

Price: **~27 k€**

Star tracker:

Total cost estimated: **~100 k€**

Overall Payload Cost

8 satellites

2.6 M€

CUBESAT

Spacecraft Bus

- 8 CubeSats: ~450 k€/Sat
- Development time estimated: ~2y
- Person-power: ~3 person-year
- **Total cost estimated for 8: ~4.6 M€**

AIV/AIT/Magnetic Cleanliness

- 8 CubeSats: ~50 k€/Sat
- Person-power: ~1 person-year
- **Total cost estimated for 8: 500 k€**

Payload Price: 8 x payload **~2,6 M€**

Launchers Price: 2 x 110 k€ **~220 k€**

LIFETIME OPERATION

Ground Segment

- Operational lifetime: ~3y
- Person-power: ~1 person-year (automation)
- **Price: 300 k€**

Science Data Analysis

- Operational lifetime: ~3y
- Person-power: ~3 person-year
- **Price: ~900 k€**

Overall Cost (8 satellites)

9 M€ (+ 20% = 10.7 M€)

+ 2 satellites = 10.5 M€ (+20% = 12.5 M€)

RISK FOR THE PROPULSION SYSTEM

The propulsion system is required for:
Orbit & Constellation acquisition while the Launch and Early Operation Phase (LEOP)
Orbit station keeping
Failure → Formation can´t be maintained & deorbiting within 1 years
→ continuous measurement of the magnetic field
Mitigation → providing a new satellite within 1 year or use 5 satellites (single redundancy)

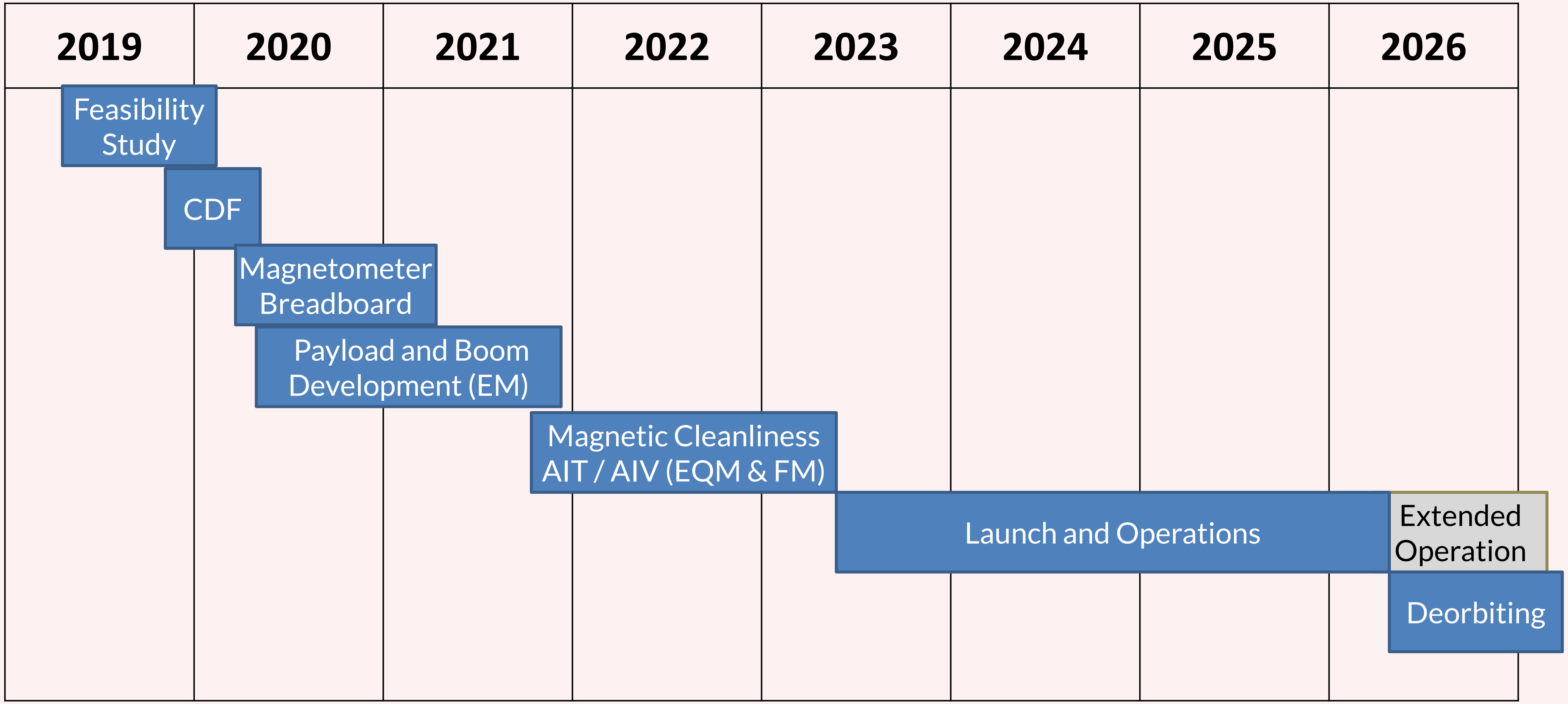
Severity	5	low	medium	high	very high	very high
	4	low	low	medium	high	very high
	3	very low	low	low	medium	high
	2	very low	very low	low	low	medium
	1	very low	very low	very low	low	low
		A (remote)	B (unlikely)	C (likely)	D (highly likely)	E (near certain)
		Probability				

RISK ASSESSMENT

PROPULSION → More satellites: 1 spare per constellation
BOOM → More testing and validation
PAYLOAD Sensitivity at instrument as achieved
→ Magnetic cleanliness/testing

Severity	5		PROPULSION	BOOM		
	4	SOLAR PANELS		PAYLOAD SENSITIVITY		
	3			ADCS POINTING KNOWLEDGE		
	2	POWER RF				
	1					
		A (remote)	B (unlikely)	C (likely)	D (highly likely)	E (near certain)
		Probability				

RUBIKS FUTURE ROADMAP



CONCLUSION

CONCLUSION

- We propose a combined magnetic and gravity mission to resolve the composition and dynamics of the mantle, and to better constrain outer core dynamics
- 4 x 6U per formation
- Orbits: Cartwheel-Helix formation 2 different orbital planes
- 2 launches
- Master/Slave configuration
- Cost: 10,000,000 €
- Several free science applications (GNSS TEC, neutral winds, ionosphere)

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TEAM RED

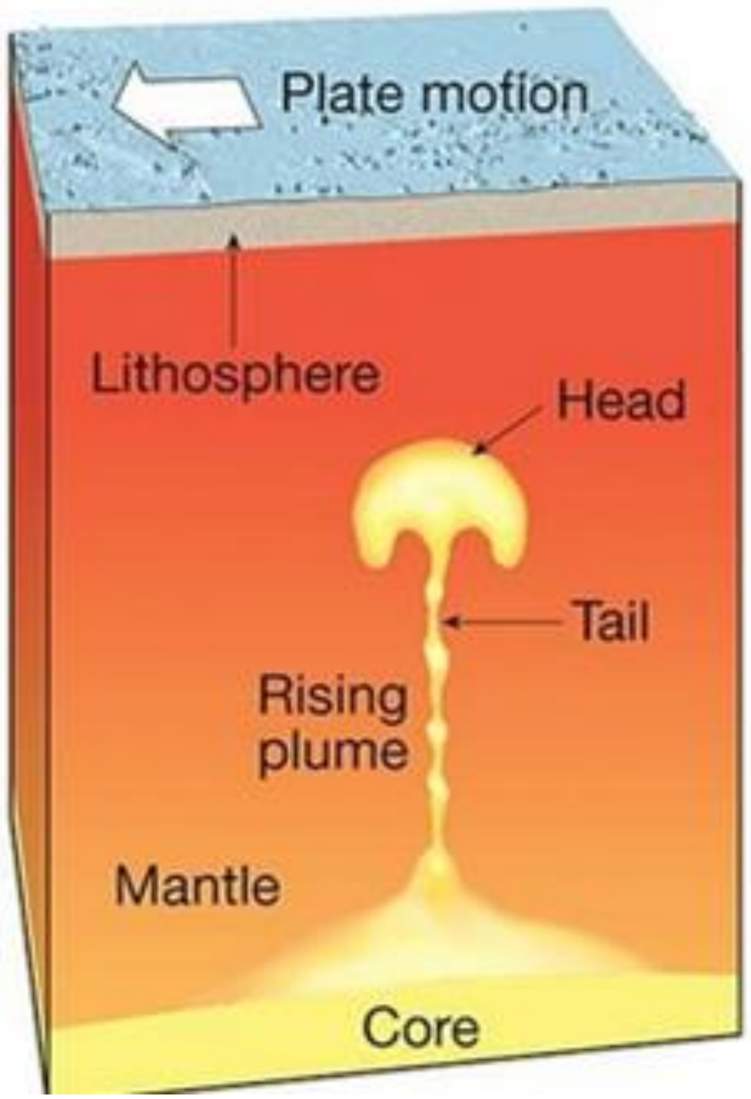
Q&A

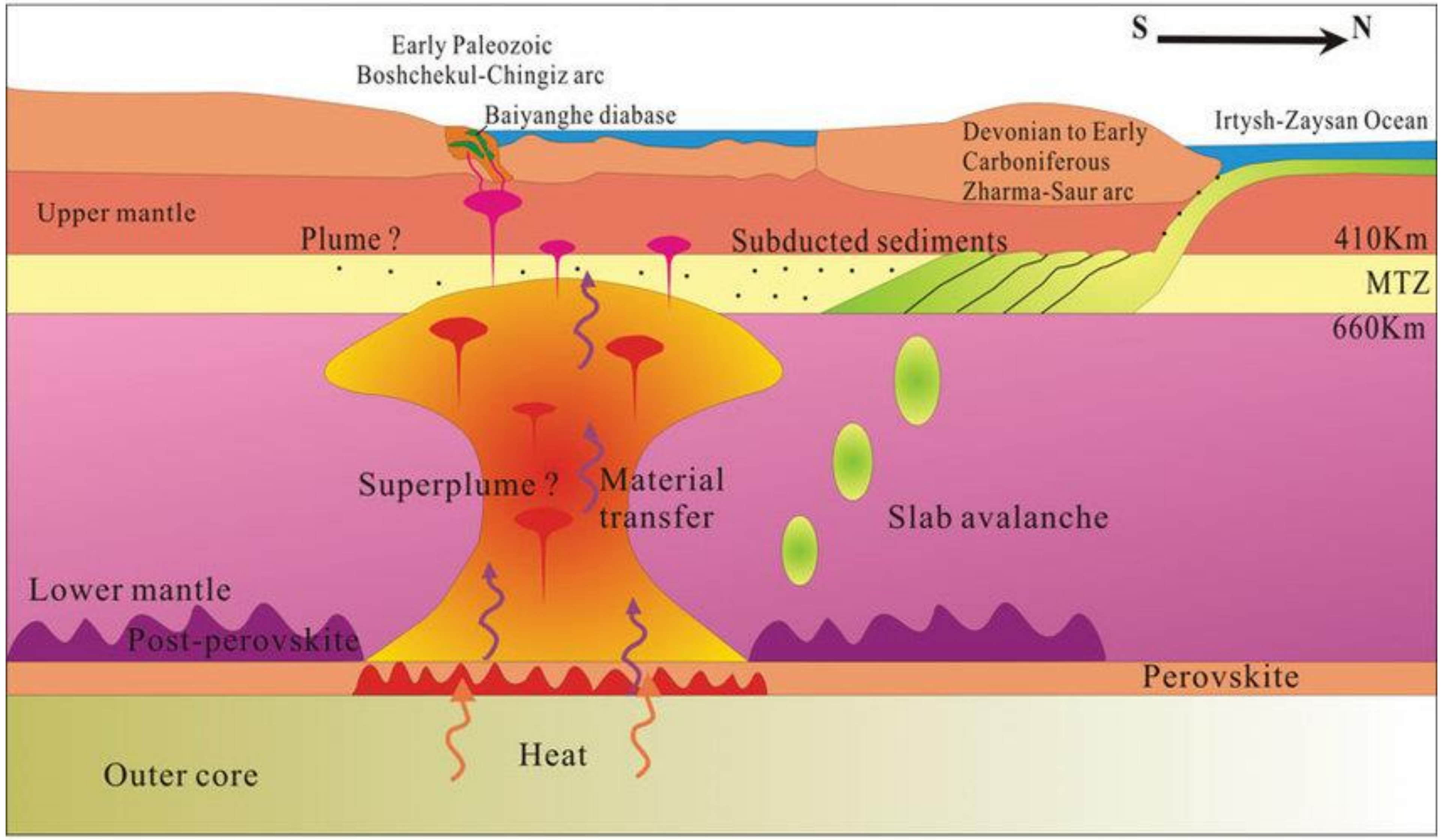
Alpbach Summer School 2019

RADIO COMMUNICATIONS

- 1 ESA ground station in Kiruna with a 15m S-band antenna. A large antenna releases power constraints for satellite bus, offering large antenna gain.
- More than 1 visibility windows of more than 5 minutes per day for master to ground station link, enough to send all the data measured per day ✓
- Maximum angular speed to track satellite : 5°/s > 4.5°/s (angular speed at 400km) ✓

What is the origin, shape and size of **mantle plumes**?



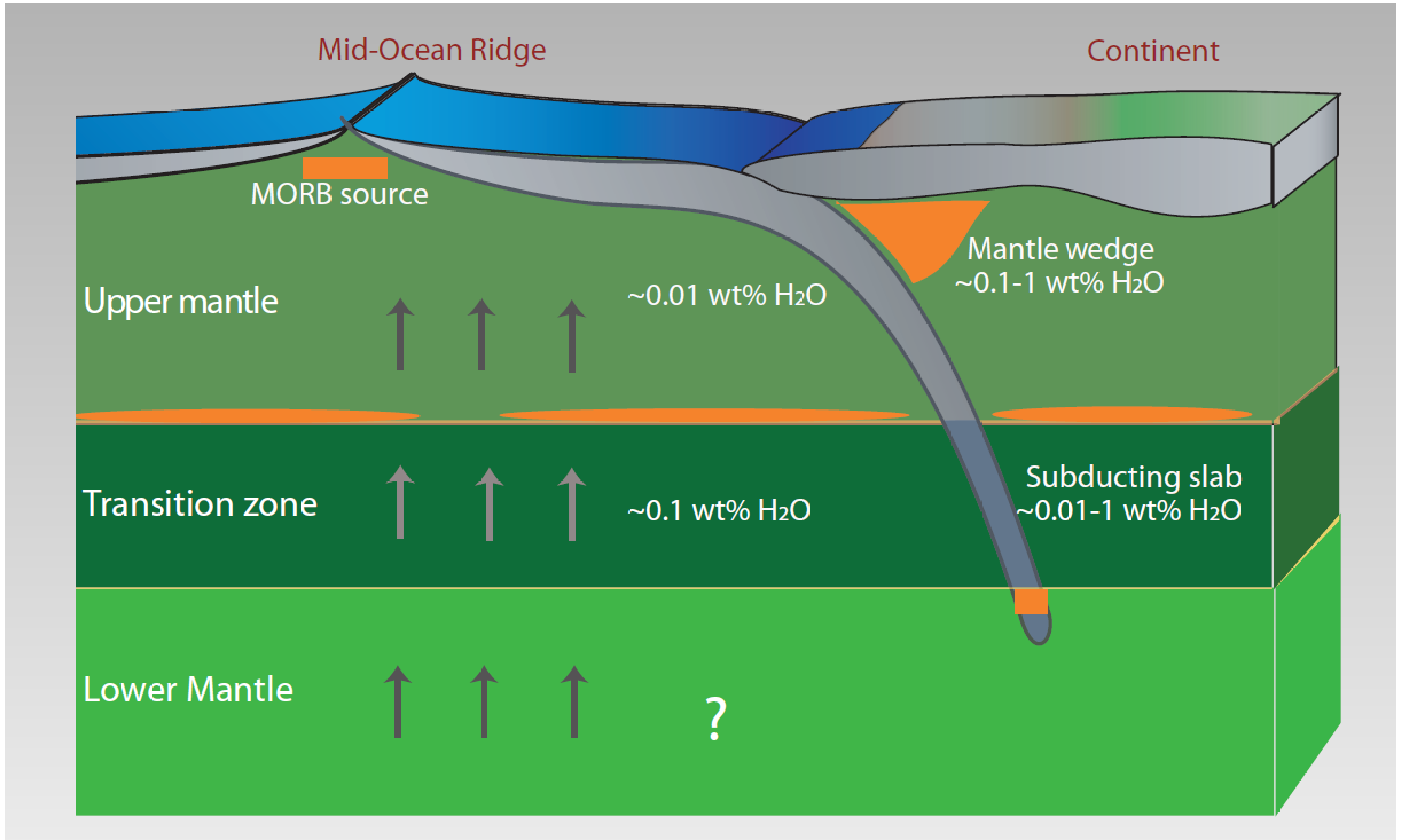


Source: UPSC

Miao *et al*, 2018

Other open questions

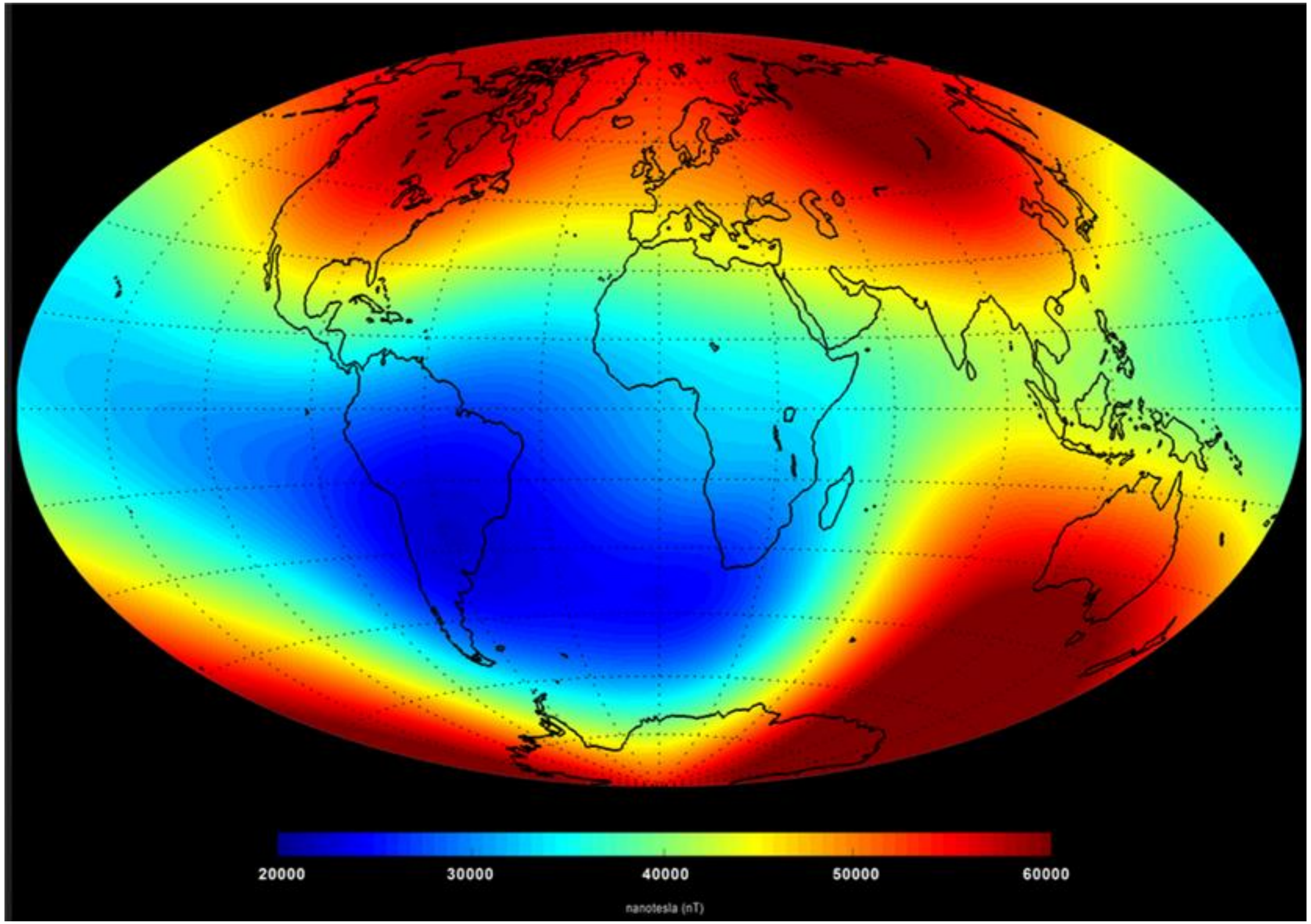
Where is water stored in the mantle? What is the source of the water?



Khan *et al.*

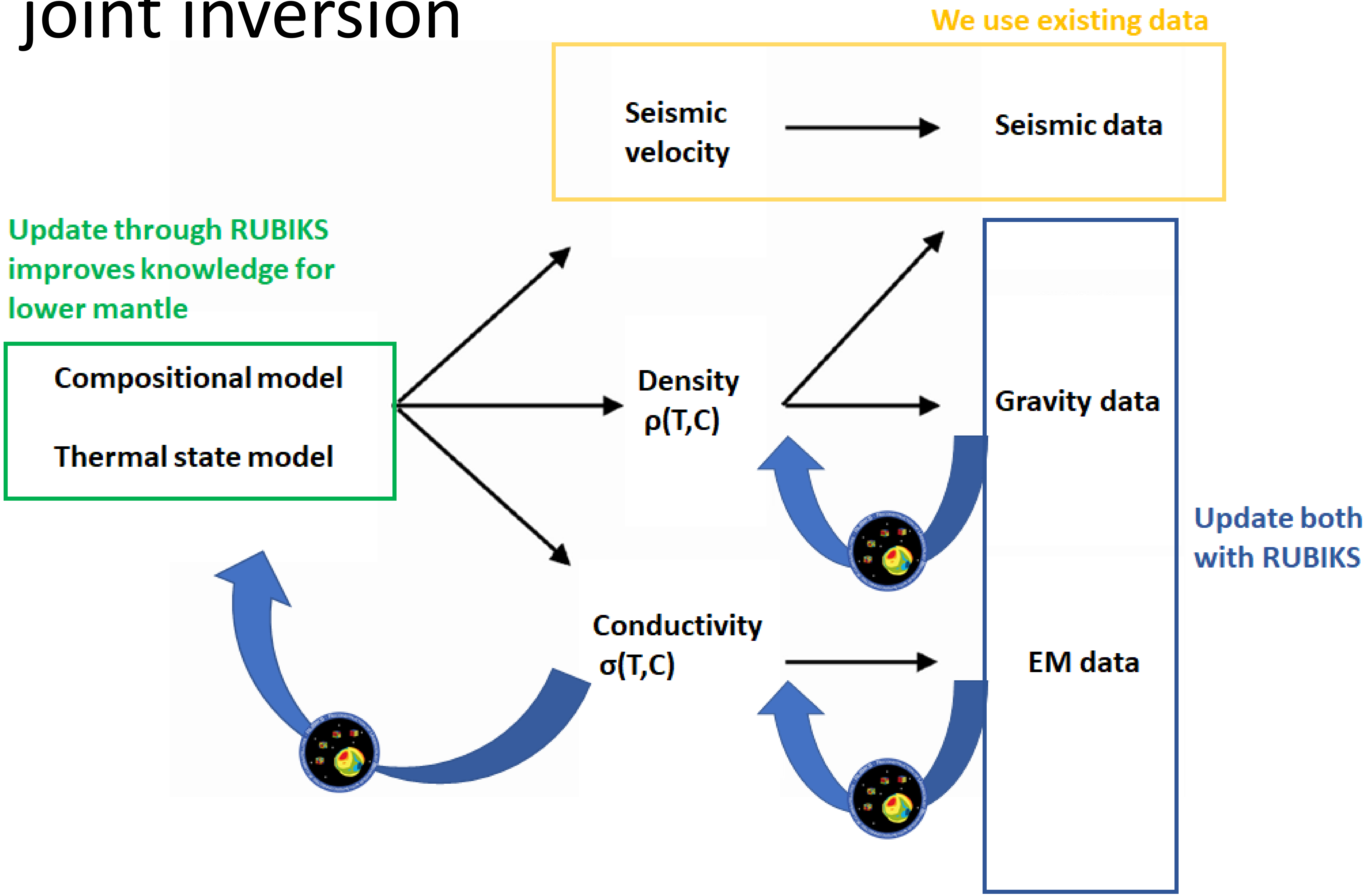
Other open questions

Could the South Atlantic anomaly originate from the lower mantle response?

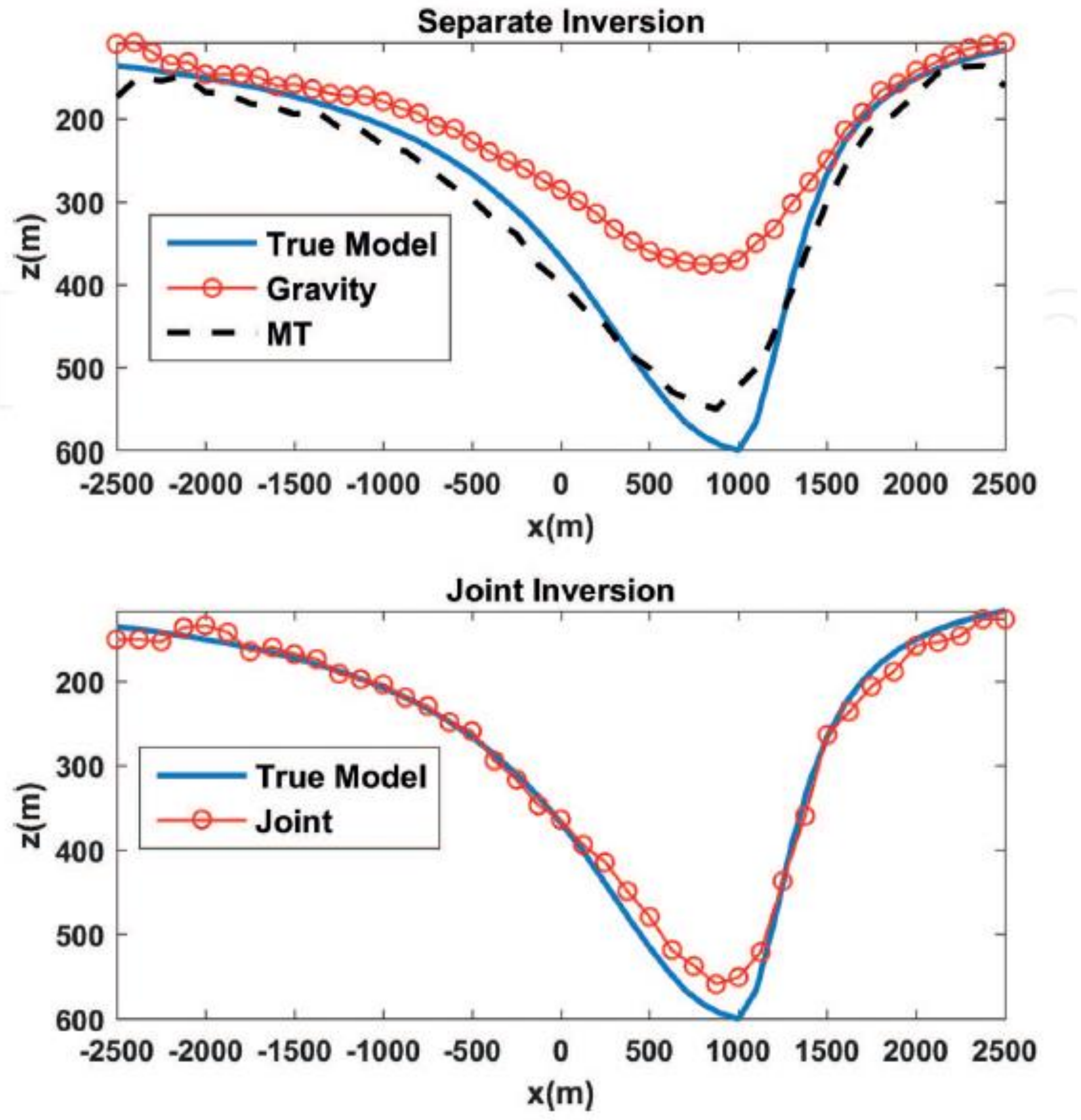


SWARM
January 1 - June 30 2014

3D joint inversion

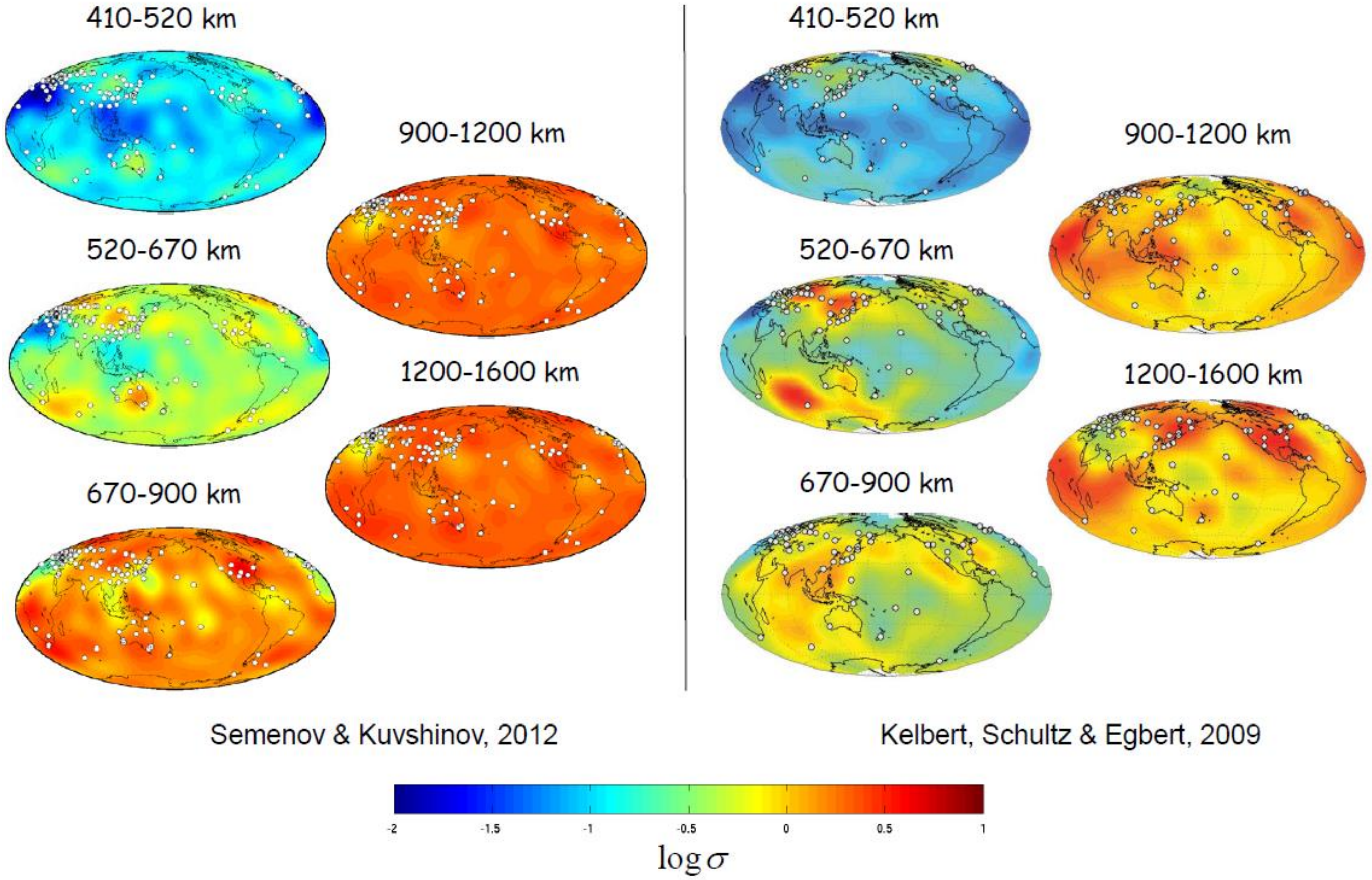


Improvement to true model



Cai et al. (2017)

State of Art: 3D conductivity models



SWARM formation does not allow to decrease uncertainties

→ full magnetic tensor information not possible

SR0: Conductivity and density sampling at same points in time and space for the lower mantle d=1000-2900 km

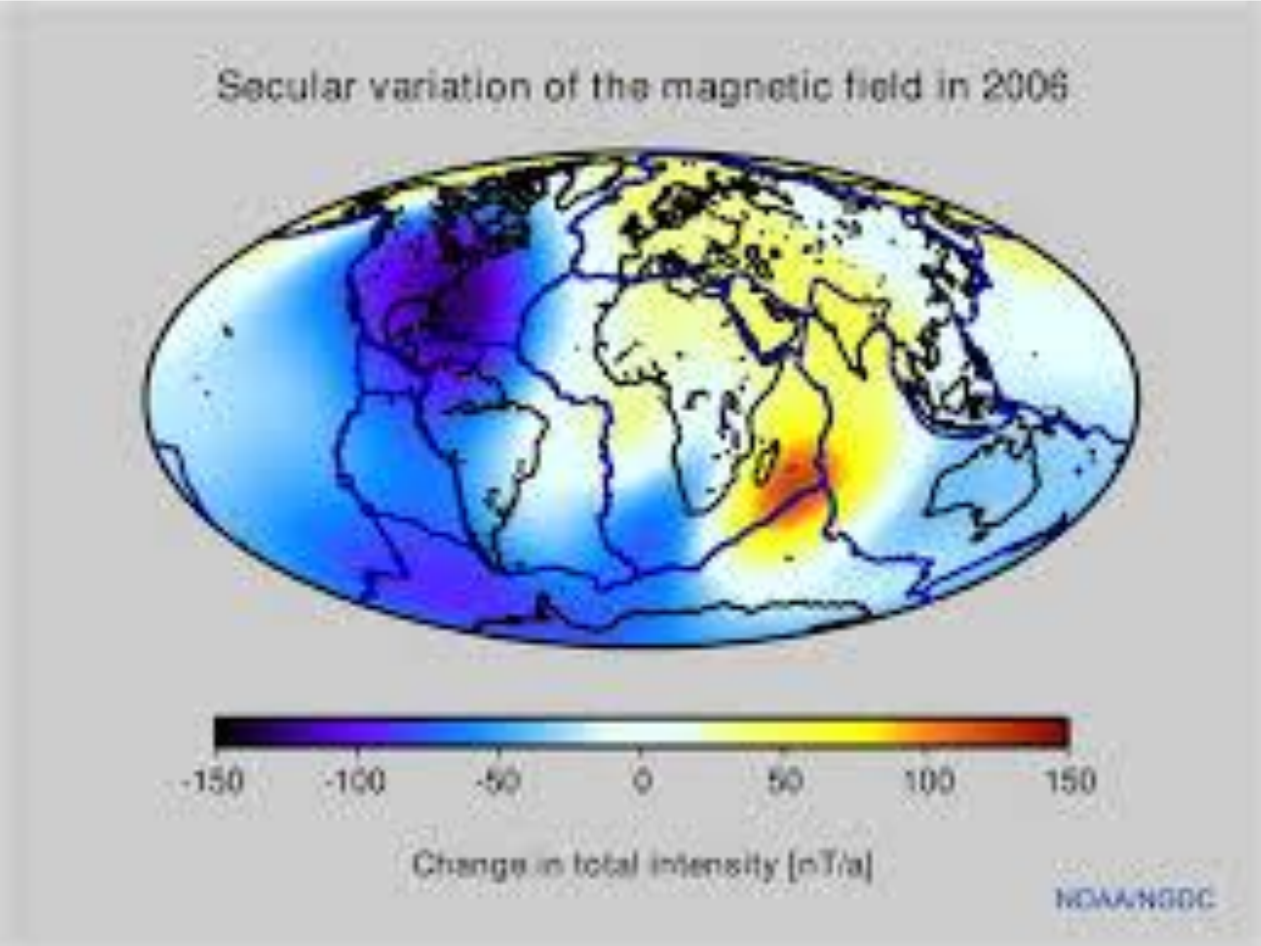
SR1: Measure temporal magnetic field variations – 3D EM sounding for d=100-2900 km

SR2: Measure temporal gravity field variations – 3D density anomalies in lower mantle d=1000-2900 km

SR1.1: Clearly separate between external and internal field components	**SR1.1.1:** Measure primary B-fields produced by external currents	**SR1.1.2:** High temporal resolution to separate different source signals with overlapping period ranges to allo spherical harmonics modelling	**SR1.1.2A:** Measure Solar Quiet variations d/o 12 P=4-24 h
			SR1.1.2B: Measure Ring Current d/o4 P=3-180 days
			SR1.1.2C: Measure Field aligned currents (locally) P=2-4 h Cancel out as noise!
SR1.2: Sensitivity to induced B-field at orbit altitude reliable conductivity and fluid velocity data	**SR1.2.1:** Improving dynamic core field data (secular variations)		**SR1.2.2:** Quiet night conditions (22pm -5am LT, Kp<3+. DST<5)
	SR1.2.2: Separate induction response in mantle contribution and ocean current		**SR1.2.3A:** Measure ocean current B-field d/o 12 P=12.47 h
			SR1.2.3B: Measure mantle induced B-field (Amplitude <0.5 nT)

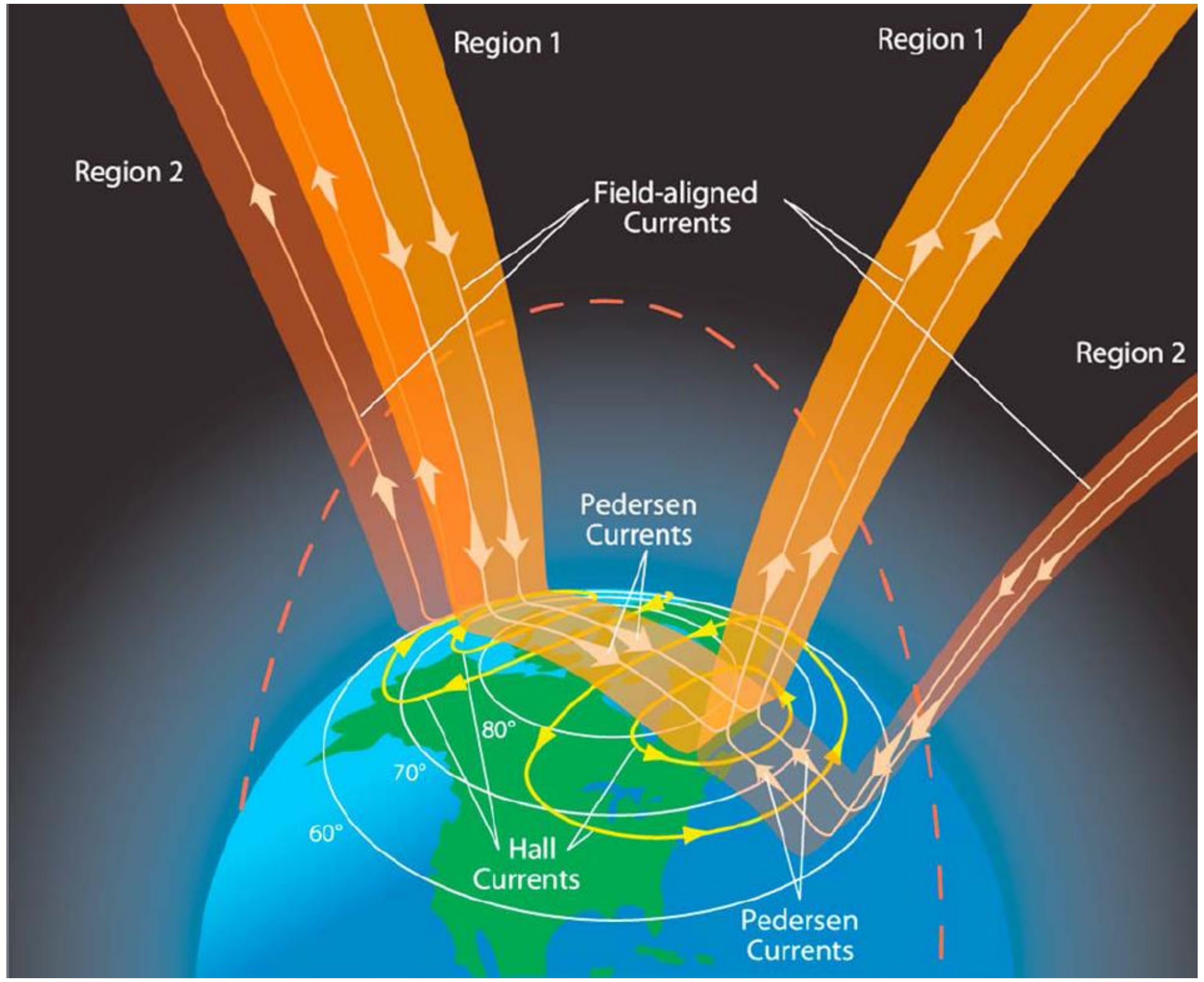
Core Field

- Strongest field, slow time variation (60.000 nT)
- Reference model: Chaos-6 d/o 16 in dipole coordinates (1.2 months resolution)
- Spatial resolution: 22.5° Lon, 11.25° Lat
- Daily resolution necessary
- Estimation needs quiet night time conditions (22 LT to 5 LT)
- Error in Position at the measurement Point needs to smaller than 10 m (Test using IGRF-12: 0.1 nT error)

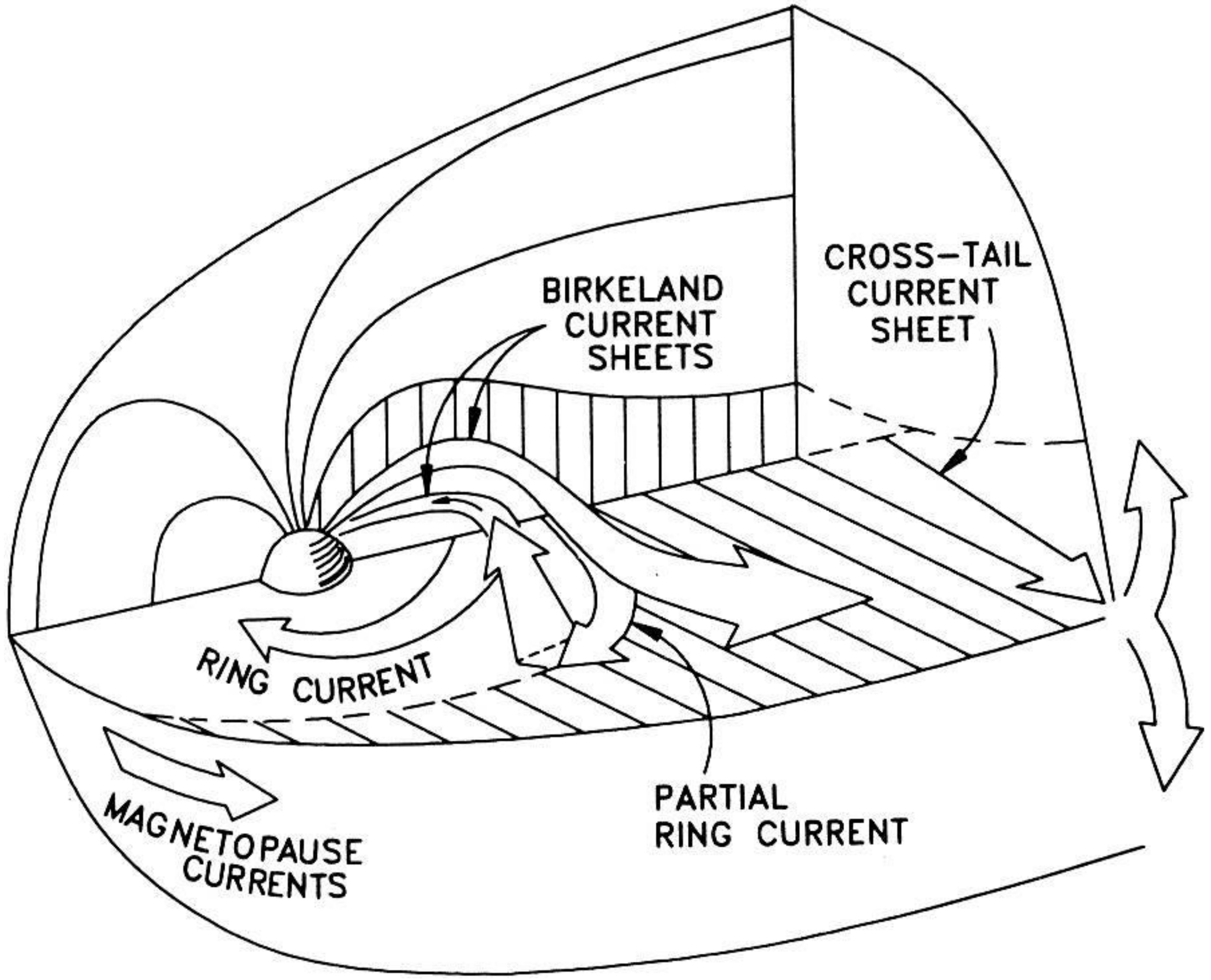


Field aligned currents

- Source: Polar regions (65° N to 75° N)
- Signal strength: up to few hundred nT
- Fixed in mLT/mLat
- Small scale at 400 km (10 km - 400 km)
- Most important: horizontal component
- Temporal resolution 1-2 hours



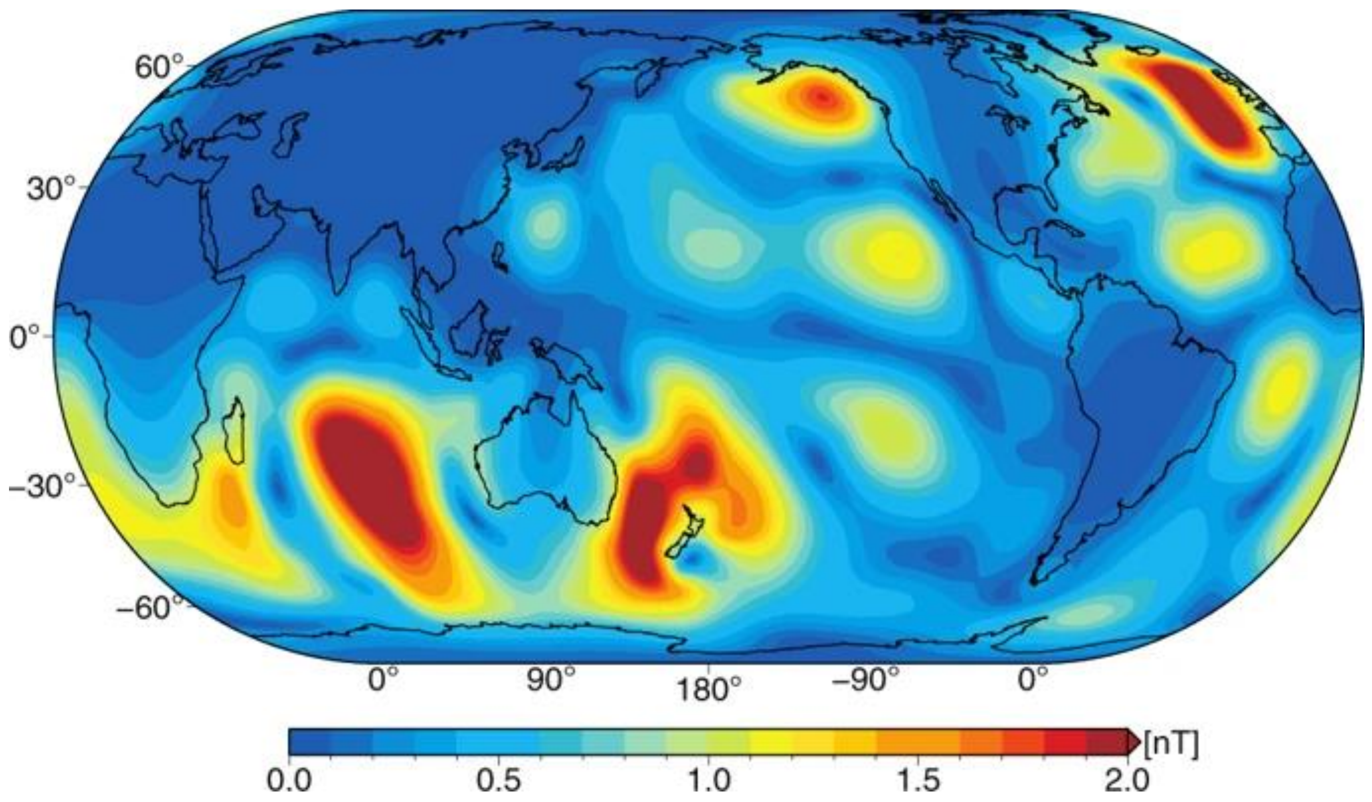
Ring current



- Large scale (2-6 earth radii)
- Signal strength at 400 km:
  - <5 nT (quiet)
  - up to 600 nT (geomagnetic storm)
- Spherical harmonics with degree and order 4 (80° Lon, 40° Lat in dipole coordinates)
- Periods for EM-Sounding: 3 d -180 d +, depth (400 km- 1600 km +)

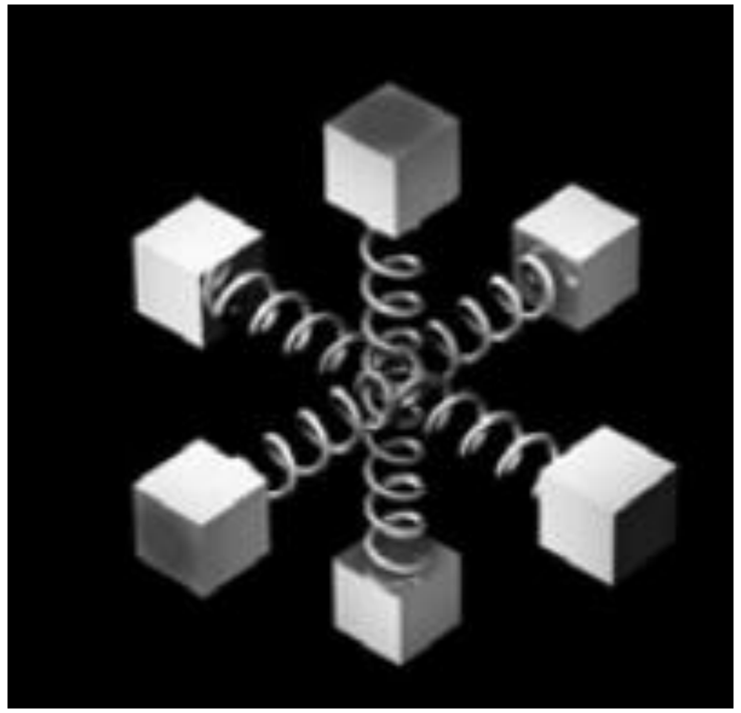
Ocean currents and Lithosphere

- Ocean:
    - Period 12.47h (6h resolution)
    - Signal strength 2 nT at Satellite altitude (Irrgang, 2019)
    - Resolution d/o 10 (Error below 0.1 nT)
- Crustal Field:
    - Static, use superior model (LCS-1 (Olsen *et al.*) d/o 160) to remove influence

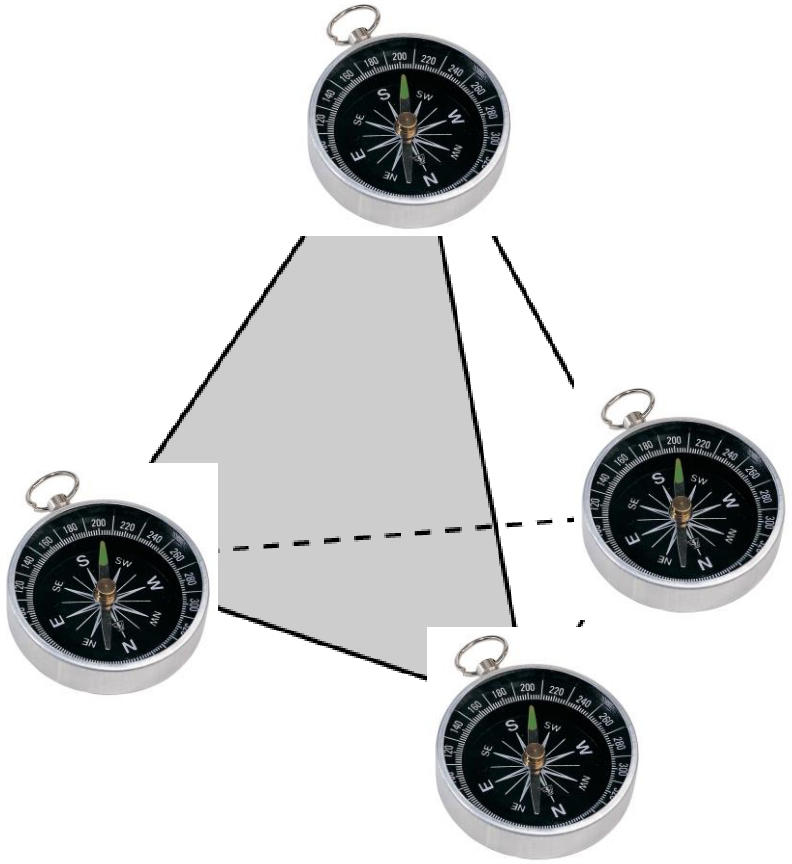


Measurement Principle

- Gradiometer principle for both the magnetic field and the gravity field simultaneously.
- Virtually improves the spatial coverage.
- Obtain the full gradient Tensor in three dimensions at one measurement epoch:



$$grad\vec{B} = \begin{pmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{pmatrix}$$



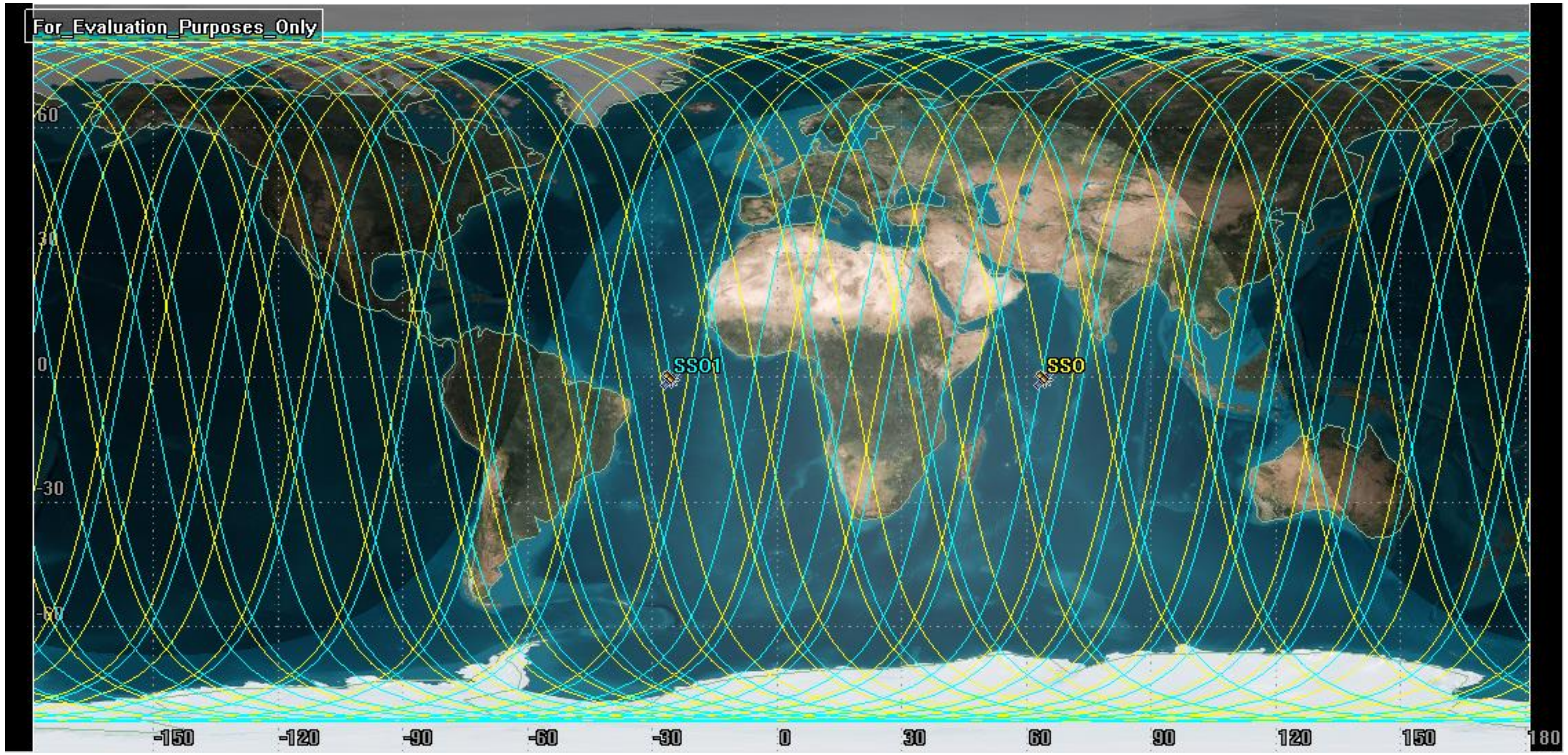
2 constellations, 2 orbital planes

Requirement (3)

- Spatial resolution 20°
- Revisit time 36 h (earth-fixed)

Evaluation ✓

- Analysis time of 36h
- Resolution of 8.0° (Minimum)



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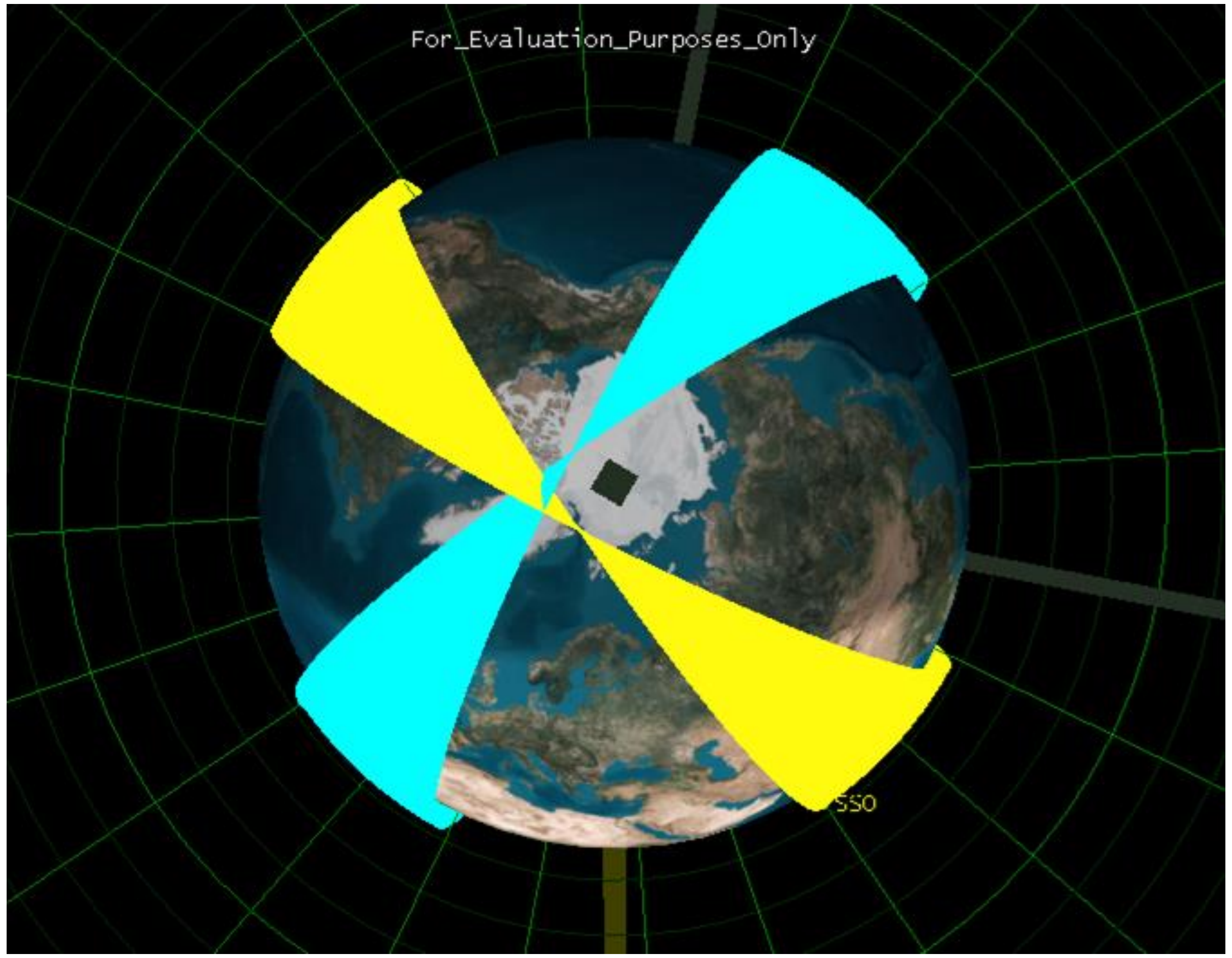
Keplerian Orbital Elements

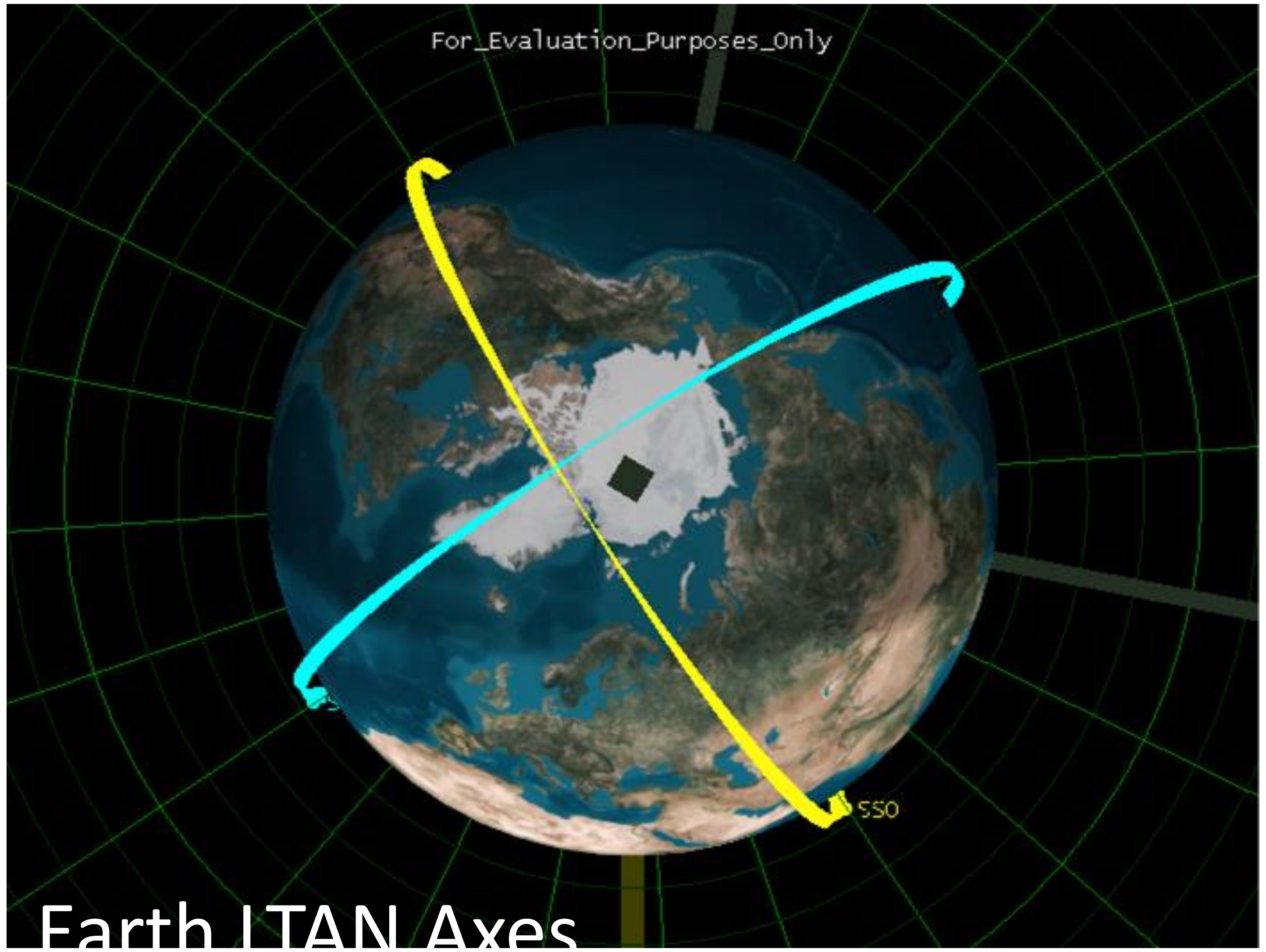
Orbit Parameter	S1 / S5	S2 / S6	S3 / S7	S4 / S8
a[km]	6768	6768	6768	6768
e[-]	0.00453319	0.00453319	0.00453319	0.0001
i[deg]	97.0054	97.0054	97.0054	97.0054
Ω[deg]	0 / 90	0.2 / 90.2	0.1 / 90.1	1.4 / 91.4
ω[deg]	45	ω(1)+120	ω(1)+240	ω(1)-90
M[deg]	360-ω(1)	M(1)+240	M(1)+120	360-ω(4)

Mission lifetime for 3 years

Simulations were only performed for the J2-Perturbations

DRAG perturbations require the use of active attitude control and propulsion





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Annex: Radio Communications

Requirements :	Resolution	Range	Number bits to code data	Frequency acquisition	Data per day
GPS data	1-3cm	-	-	0.1 Hz	80 Mbits
Flux gate magnetometer	0.2nT	± 50000 nT	19 bits x 3 axis	1 Hz	5 Mbits
Coupled dark state magnetometer	0.2nT	20000-100000 nT	19 bits	1 Hz (for calibration, used 5 min every 20 min)	0.4 Mbits
2 Star trackers	1,5 arcsecond	+/-360°	21 bits x 3 axis x 2 star trackers	1 Hz	11 Mbits
House keeping data	-	-	-	-	10 kbits

Total per satellite : 96 Mbits generated per day per satellite
Total per formation of 4 satellites : 380 Mbits per day

Annex: Radio Communications

UPDATED

Hardware :

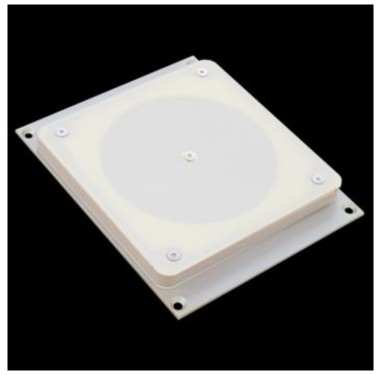
- 2 S-band antennas on opposite side of the satellites
- One S band transmitter 1W output RF power
- One S band receiver
- QPSK modulation
- One switch to select the antenna with best signal over noise ratio

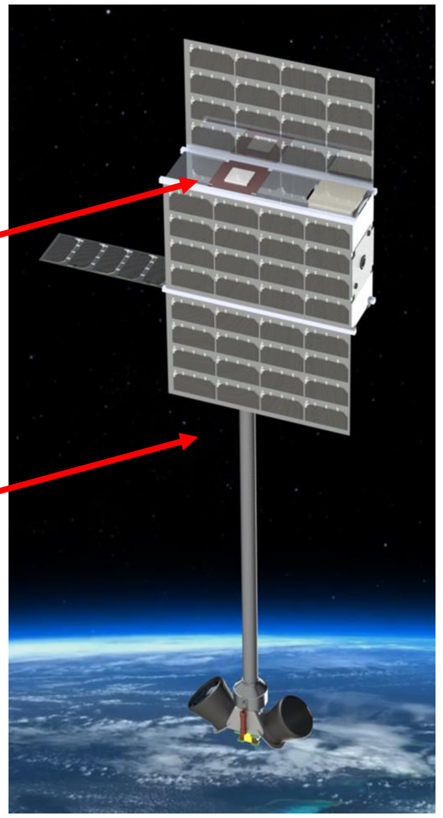
Frequency assignment :

- 2x15kHz per slave satellite for return and forward link
- 0,72MHz bandwidth for downlink to the ground station

Master to ground station link: 5 minutes communication per day with datarate of 1.3Mbps

Slaves to master: 50 minutes communication per day with datarate 30kbps





2 S-band antennas per satellite

Annex: ISIS On Board Computer

- Operating Systems: FreeRTOS, KobOS Linux
- Processor: 400MHz 32-bit ARM9 processor
- TRL Status: 9
- Pins: I^2C, SPI, UART, GPIO, ADC: 8 channel 10 bit, PWM
- Library offers: Checksumming, Watchdog kicking, Timekeeping

ADCS Modes

Subsystems	Power (mW)	Operation Modes							
		Launch		Detumbling / Comissioning		Science Acquisition (Eclipse Time)		Science Downlink (Daylight Time)	
		Duty Cycle [%]	Ave. Power [mWh]	Duty Cycle [%]	Ave. Power [mWh]	Duty Cycle [%]	Ave. Power [mWh]	Duty Cycle [%]	Ave. Power [mWh]
Magnetorquer	350	0	0	100	350	0	0	10	35
Star tracker 1	600	0	0	100	600	100	600	100	600
Sun sensor	23	0	0	100	23	100	23	100	23
Earth sensor	40	0	0	100	40	100	40	100	40
TOTAL			**0**		**1013**		**663**		**698**

GNSS receiver

$\alpha = 10\ krad\ Si$ Total dose radiation(FOTON)

$\beta = 1\ krad/y$ Radiation over 1y in LEO

$t = 3\ y$ Lifetime of the mission

$e^{-\frac{\beta}{alpha}t} = 0.74$

options:

	Type		
	COTS	Software Defined	Radiation Hardened
Example	OEM	FOTON	BlackJack
Size [cm]	8.2 x 12.5 x 1.3	8.3 x 9.6 x 3.8	19 x 13.3 x 10
Weight [g]	75	350	4500
Power [W]	2.1	4.8	25
Cost [k$]	10	30	200
Total Dose Radiation [krad Si]	10	10	100
Reprogrammability	Through API	Yes	Partial
On-board Orbit Determination	Not Native	Yes	Yes
Carrier tracking sensitivity	Medium	High	High

Actual Startracker

TERMA T1 startracker

Scientific Requirements	Observational Requirements	Instrument requirements			Mission requirements		Orbit requirements	
	OR0.1: magnetic and gravity measurements should not interfer	**I0.1** Magnetometer **I0.2** Gravity instruments			**MR0.1.1:** satellites act as (free-)falling masses		Cartwheel Helix Tetrahedral	
					MR0.1.2: Magnetic boom Cleanliness < 0.2 nT			
SR1.1.2A: Measure Solar Quiet variations d/o 12 P=4-24 h	**OR1.1.2A:** Temporal resolution (model) Δt = 2h						2 orbital planes	
SR1.1.2B: Measure Ring Current d/o4 P=3-180 days	**OR1.1.2B:** Temporal resolution (model) Δt = 1.5 days				**MR1.1** B- field vector measurements	**MR1.1.2B** 3 years to account for seasonal variations		
SR1.1.2C: Measure Field aligned currents (locally) P=2-4 h Cancel out as noise!	**OR1.1.2B**: Measurement Update Δt = 1-2 h	**IR1.1:** Fluxgate magnetometer						
	OR1.2.2A: daily model corrections d/o 16	**IR1.2:** Scalar magnetometer for calibration	**IR1.4:** Max. Error in Attitude Knowledge 1 Arc s	**IR1.2.2:** Positioning accuracy Δxp = 10m	**MR1.2** Full magnetic gradient Tensor measurements in low and mid latitudes 4 satellites, tetrahedral formation		Full tensor needed in equatorial regions at Polar regions x-y plane enough	No dusk or dawn orbit. Avoid local times between 17 LT and 21 LT or 5-7 LT
	OR1.2.2B: Spatial resolution 22.5° Lon							
SR1.2.3A: Measure ocean current B-field d/o 12 P=12.47 h	**OR1.2.3A**: Temporal resolution (model) Δt = 6h	**IR1.3:** 2 startrackers						
SR1.2.3B: Measure mantle induced B-field (Amplitude <0.5 nT)	**OR1.2.3B:** Given by solar quit and ring current variations (cf. OR1.1.2B)			**IR1.2.3B:** Sensitivity for resolving frequencies 0.2 nT				
SR2.1: Modelling with d/o 5	**OR2.1** Observe large-scale anomalies >7200 km	**IR2.1** dual frequency GNSS receiver with 0.1Hz sampling			**MR2.1:** Full gravimetric tensor satisfied by MR1.2	**MR2.2:** Satellite separation 100 200 km	**OR2.1** separation only few hundred km (<200 km) to allow GNSS double Baseline differencing	
	OR2.3 Signal sensitivity 100 mGal (Total strength 10 Gal)							
	OR2.1 Semi-diurnal sampling							