

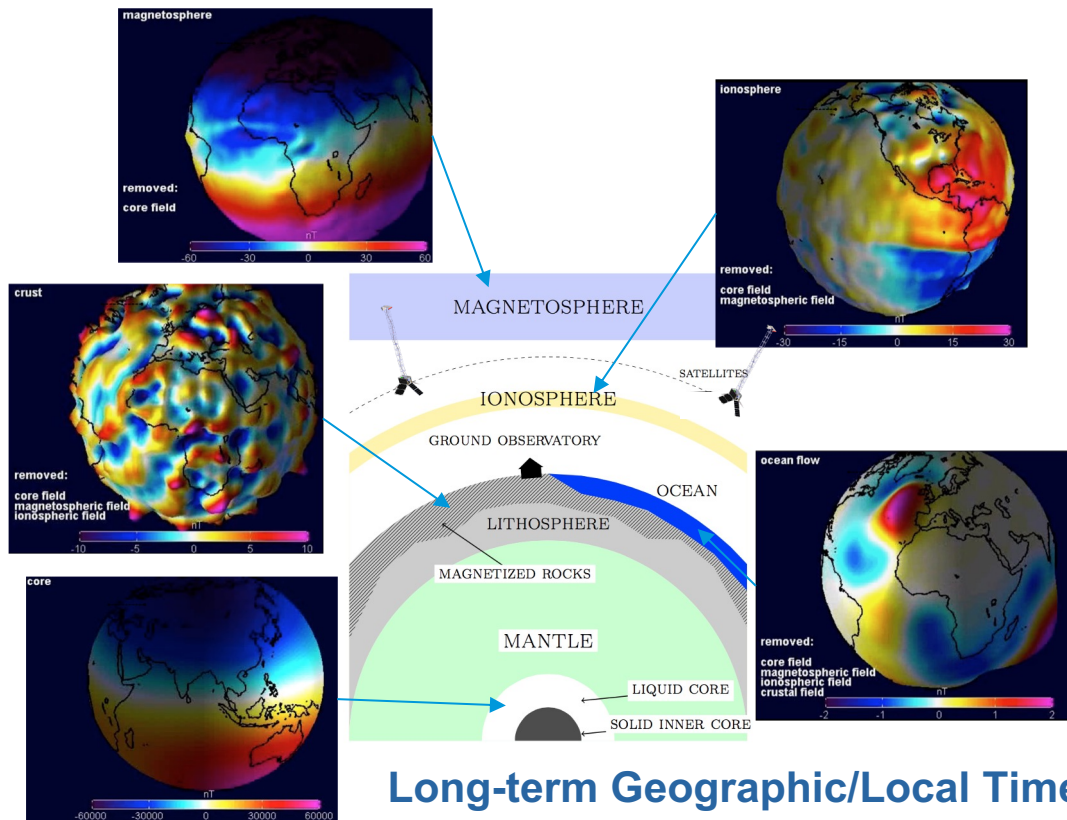
The ESA Scout NanoMagSat mission and beyond, towards improved permanent geomagnetic field and ionospheric environment monitoring and modeling

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Symposium A04, 01/09/2025, Lisbon, Portugal

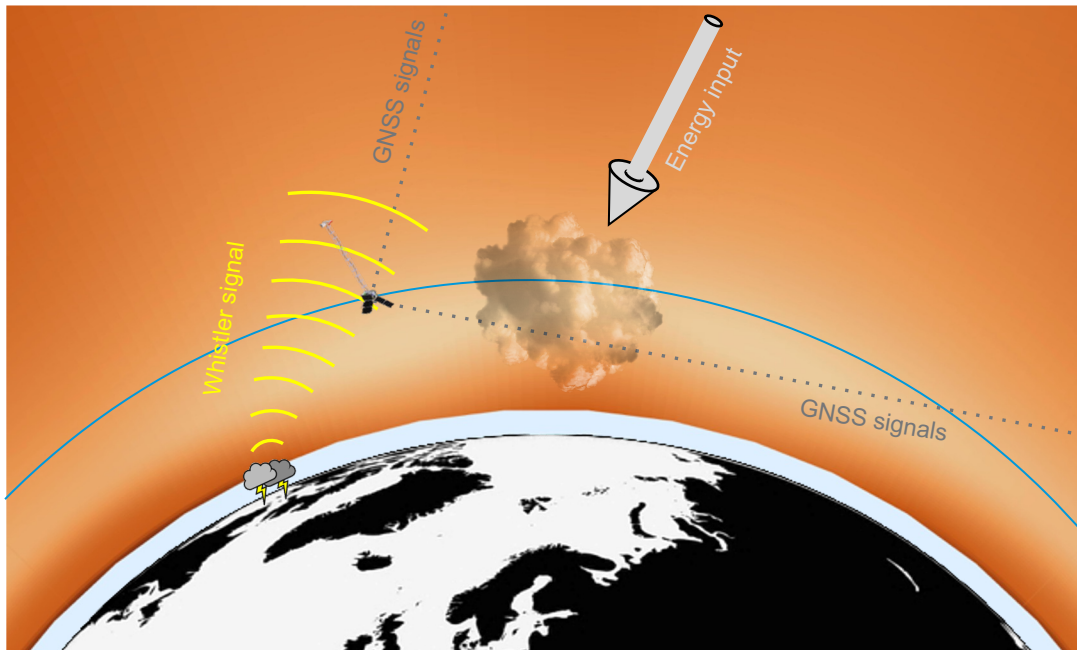
Earth's magnetic fields: much progress, but more needed



- We still miss knowledge of **fast planetary changes in core, ionospheric and magnetospheric fields**
- also crucial for improving **recovery of crustal and oceanic signals**
- To investigate **fast core dynamics, solar-terrestrial interactions, crust and deep Earth properties** and possible signatures of **climate change**

Long-term Geographic/Local Time fast-coverage with accurate 1 Hz magnetic absolute vector data much needed !

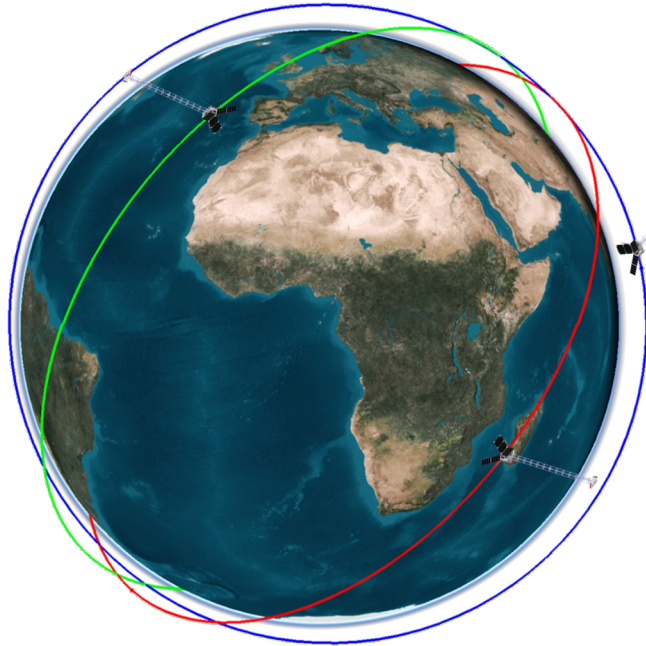
Ionospheric environment: small-scale dynamics and ELF signals are still poorly known



- Need to further investigate **ionospheric dynamics at all scales**
- Need to monitor **in situ meter to km scale dynamics and energy input**
- Need to improve **sensing the ionosphere below the satellites**
- Need to better monitor **ELF (Hz to kHz) signals**
- To investigate **Space weather** phenomena that affect radio and GNSS signals, and improve **science and operational ionospheric models**

Requires innovative compact payload

NanoMagSat mission concept



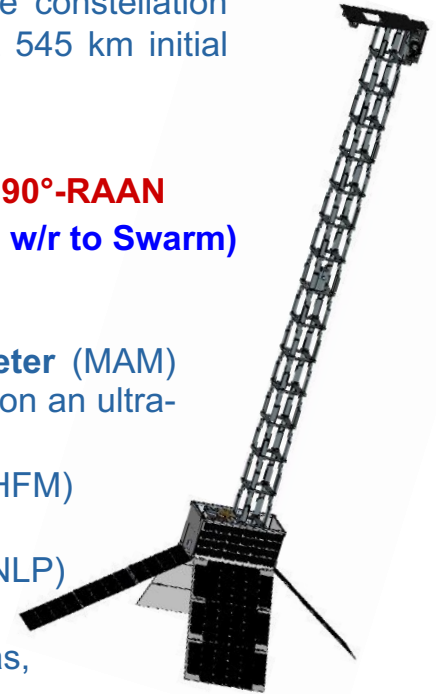
Innovative orbital configuration

A 3-year minimum (targeting 5+ years) lifetime constellation composed of 3x16U Cubesats (about 34kg) at 545 km initial altitude, no propulsion, gravity stabilized

- **1 satellite at 60° inclination**
- **1 satellite at 60° inclination offset by 90°-RAAN**
- **1 satellite in near-polar orbit (phased w/r to Swarm)**

State of the art compact payloads

- A **Miniaturized Absolute Magnetometer (MAM)** with a set of **two Star Cameras (STR)** on an ultra-stable optical bench at tip of boom
- A **High Frequency Magnetometer (HFM)** at mid-boom
- A **multi-Needle Langmuir Probe (m-NLP)** on the ram face
- **2 dual-frequency GNSS** (3 antennas, ram, wake, top)



Initiating a **low-cost scalable collaborative constellation solution for very long-term observations** (extending to space the Intermagnet network of magnetic observatories)

NanoMagSat Level 2 data requirements

1 Hz product synchronized to 1 ms

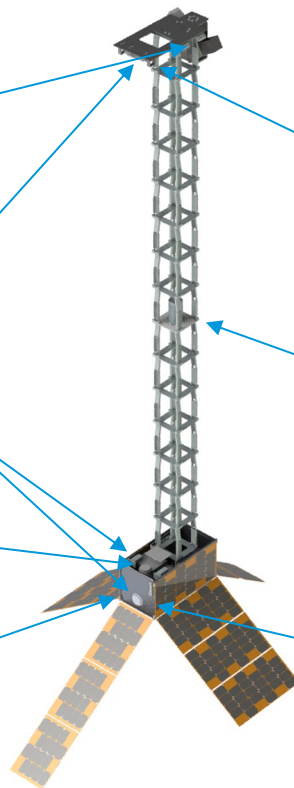
Attitude (STR) : $\sigma < 4$ (12) arcseconds

B vector (MAM frame) : $\sigma < 0.6$ nT, $\mu < 1$ nT
B vector (NEC frame) : $\sigma < 1.4$ (3) nT, $\mu < 1$ nT
B scalar (MAM) : $\sigma < 0.2$ nT, $\mu < 1$ nT

GNSS products (TEC, IP, SCI):
Single frequency pseudorange: $\sigma < 1.5$ m
Single frequency carrier phase : $\sigma < 5$ cm
C/N0 : $\sigma < 1$ dBW

POD (r, θ , ϕ): within 2m (radius), 10m (else)

Electron density & temperature (m-NLP):
Ne: $\sigma < 10^8$ m⁻³ for 10^{10} m⁻³ to 10^{12} m⁻³ range
Te: $\sigma < 500$ K for 500 K to 1000 K range



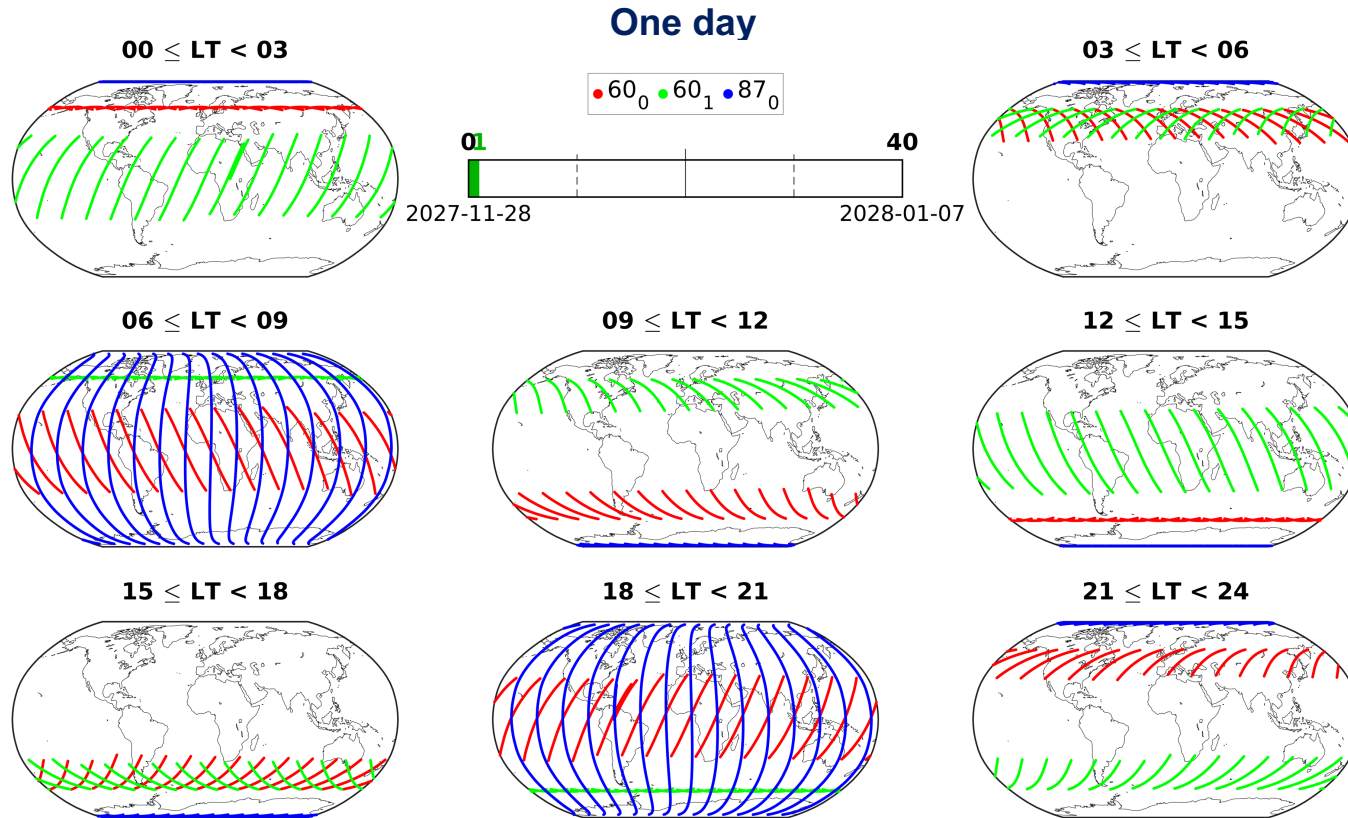
2 kHz product synchronized to 0.5 ms

B scalar (MAM):
Noise below 1 pT/ $\sqrt{\text{Hz}}$ over 20-800 Hz

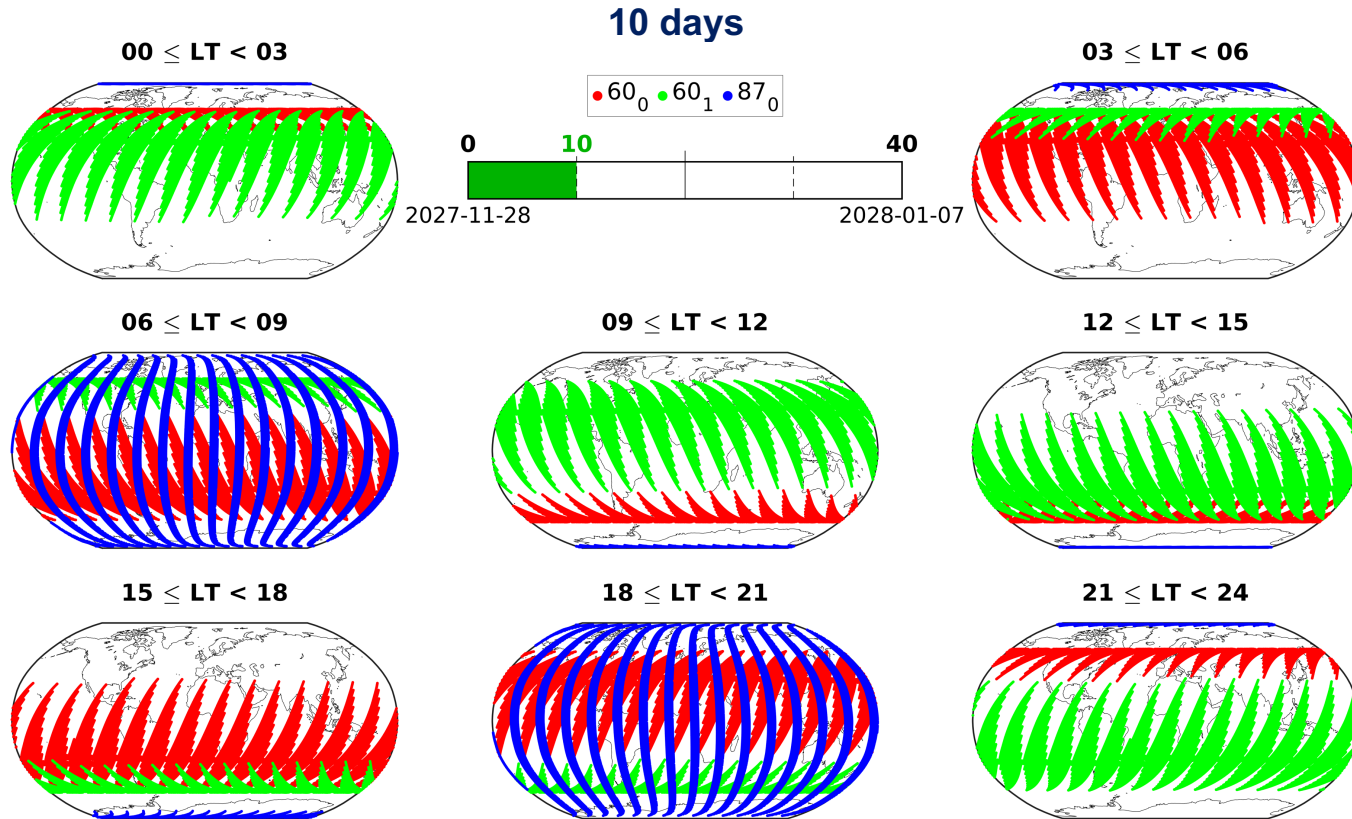
B vector (HFM frame):
Noise below 1 pT/ $\sqrt{\text{Hz}}$ over 20-800 Hz
Noise decreasing from 2.7 nT/ $\sqrt{\text{Hz}}$ at 1 Hz to 85 pT/ $\sqrt{\text{Hz}}$ at 10 Hz to 30 pT/ $\sqrt{\text{Hz}}$ at 20 Hz
B vector (NEC frame):
Same as above

Electron density (m-NLP):
Ne: $\sigma < 10^8$ m⁻³ for 10^{10} m⁻³ to 10^{12} m⁻³ range

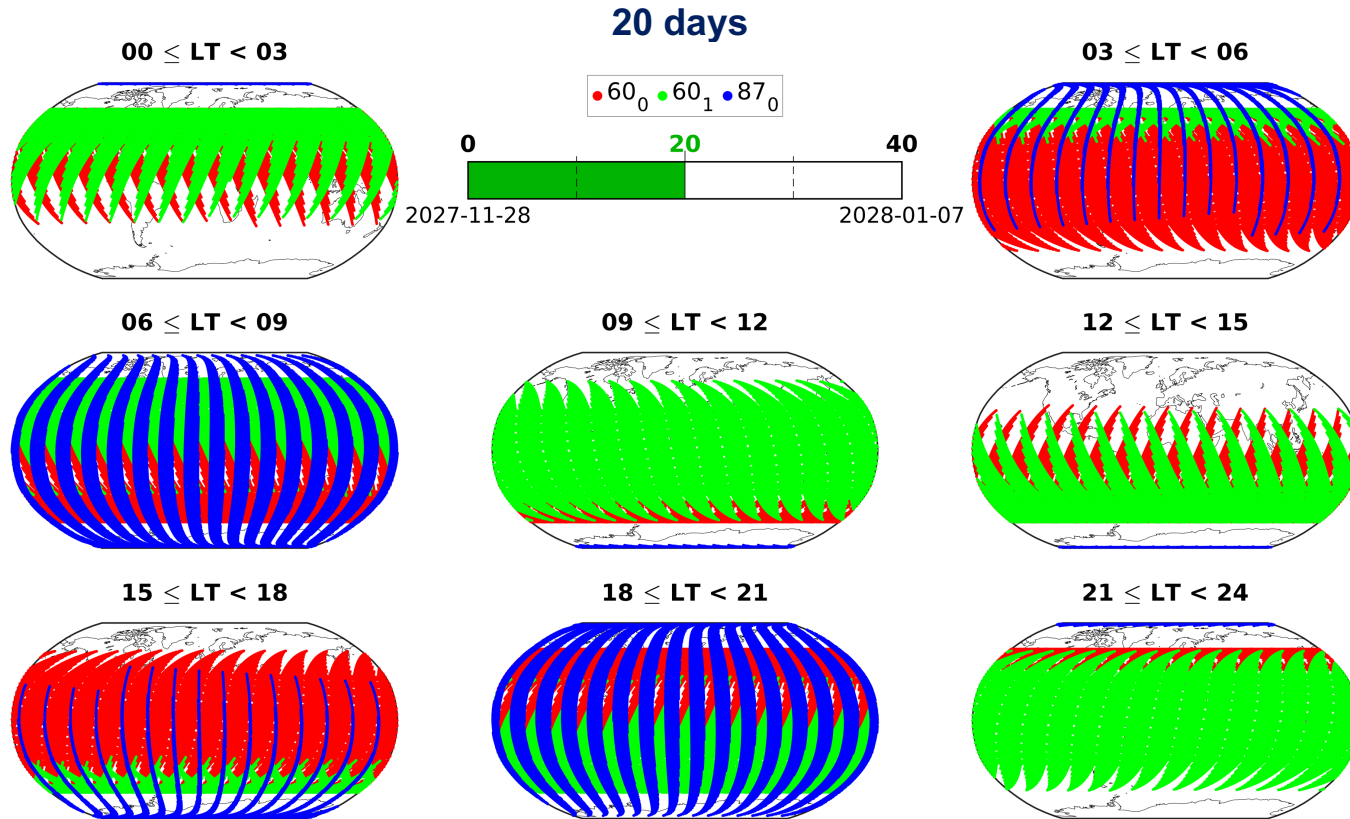
NanoMagSat Geographic/Local Time coverage



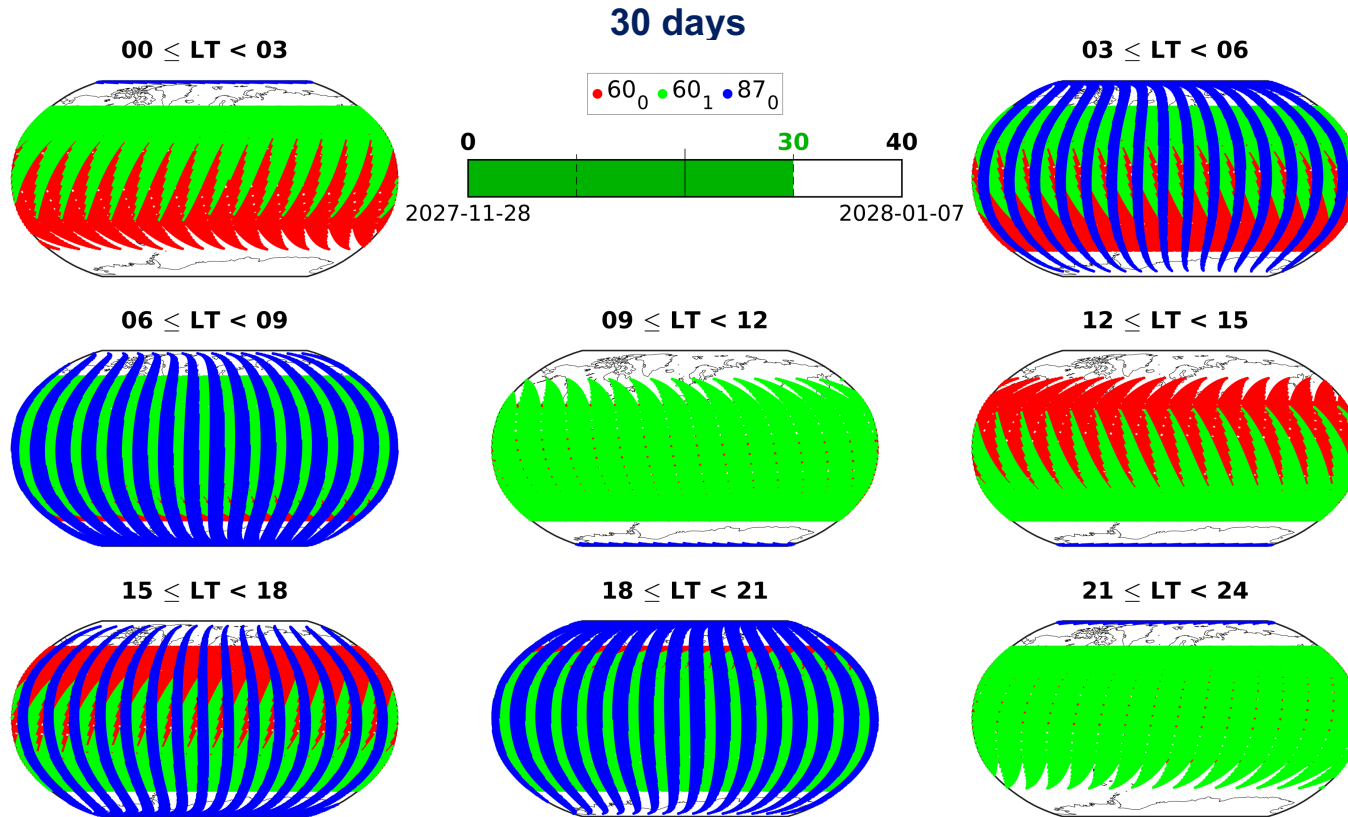
NanoMagSat Geographic/Local Time coverage



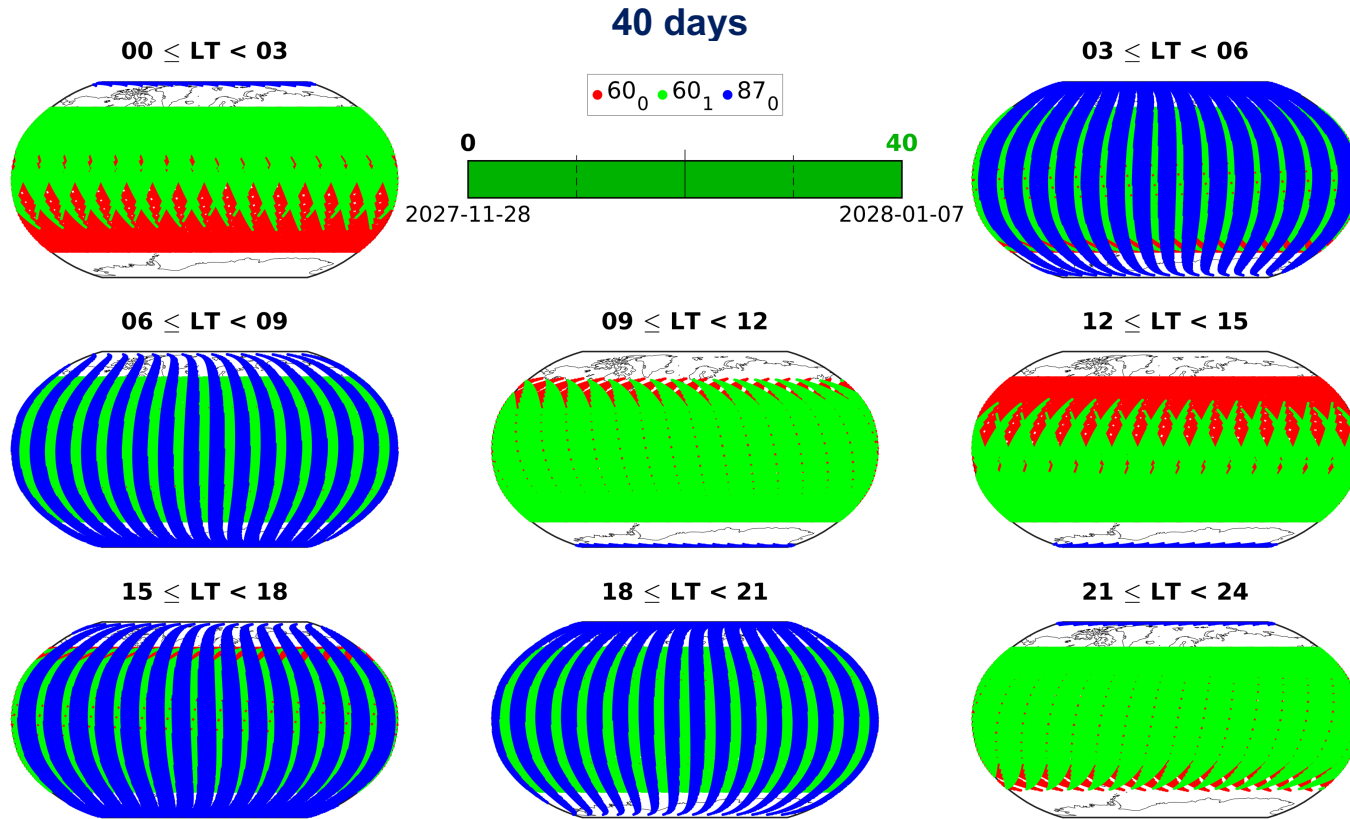
NanoMagSat Geographic/Local Time coverage



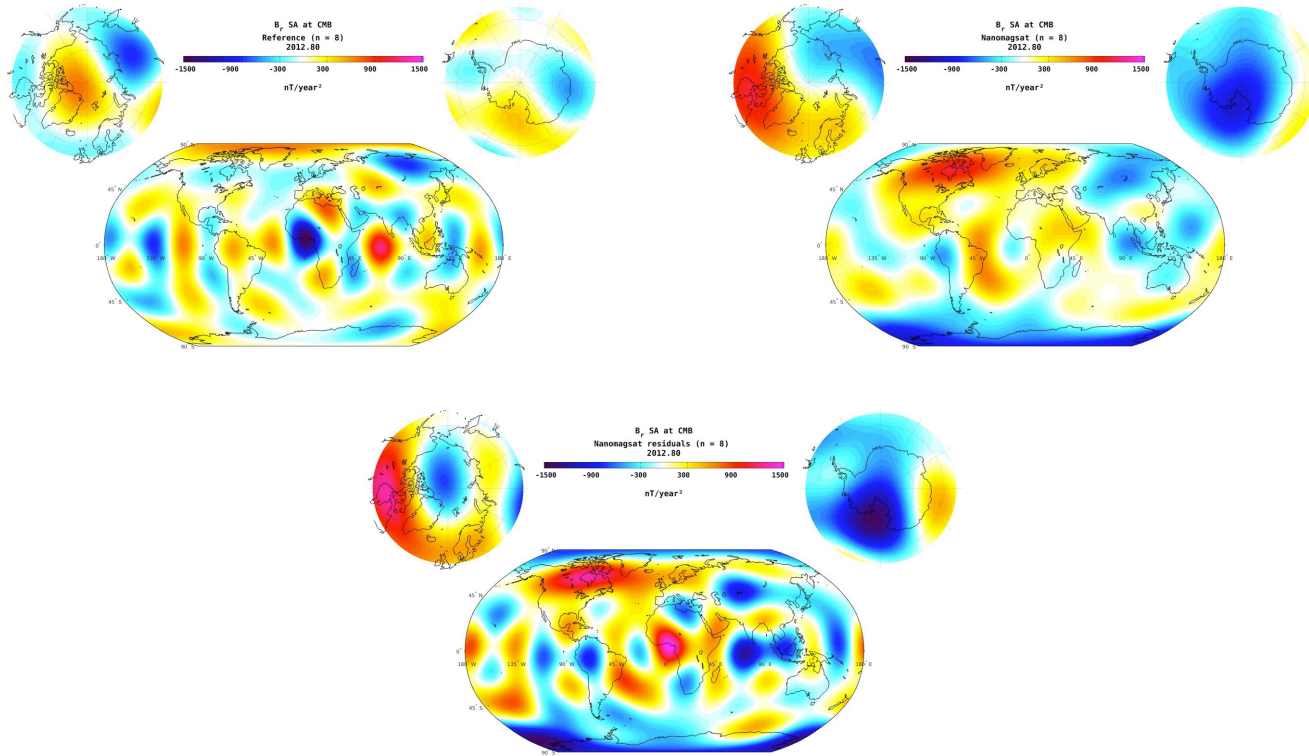
NanoMagSat Geographic/Local Time coverage



NanoMagSat Geographic/Local Time coverage

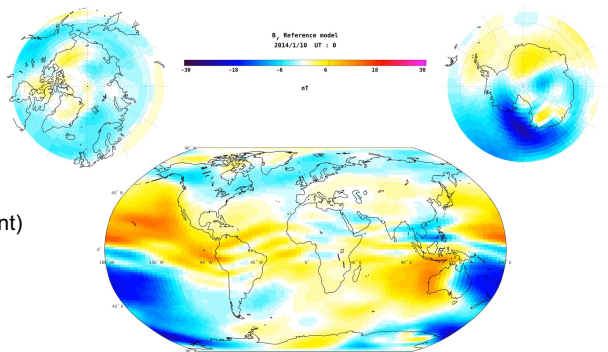


Improving planetary fields recovery: fast core field signals

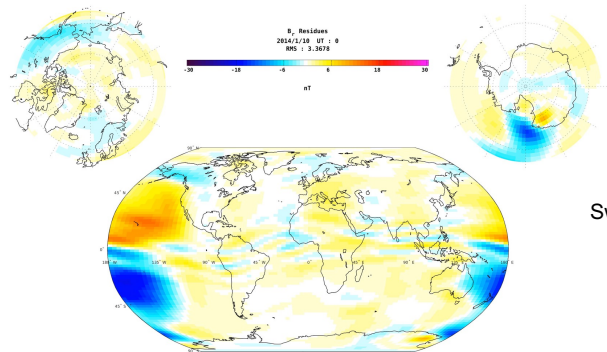


- **Recovery of fast signals** predicted from numerical simulations (J. Aubert) in the second time derivative of the core field at the core surface up to SH degree 8
- E2E simulation by P. Alken, G. Hulot and R. Duchêne, based on methodology of Alken et al., EPS, 2020.

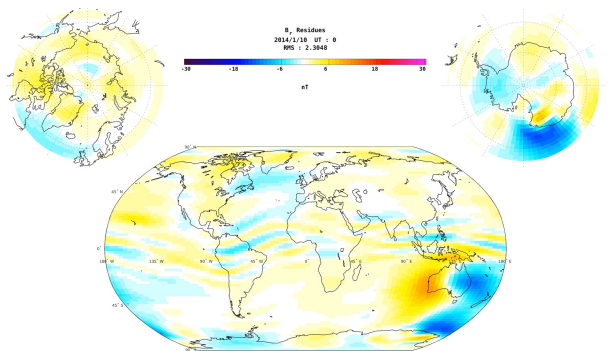
Improving planetary fields recovery: Day-to-day variability of the low/mid latitude Sq ionospheric field



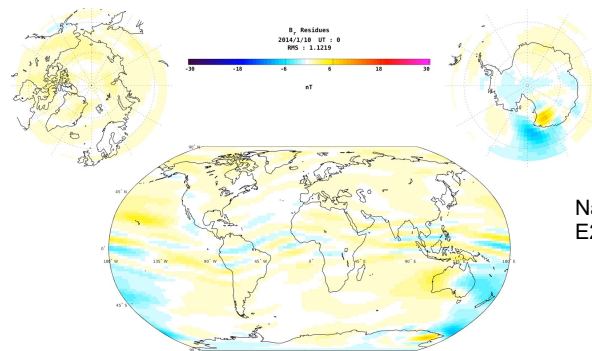
DIFI-4 prediction at 400km (Br component)



Swarm E2E residuals



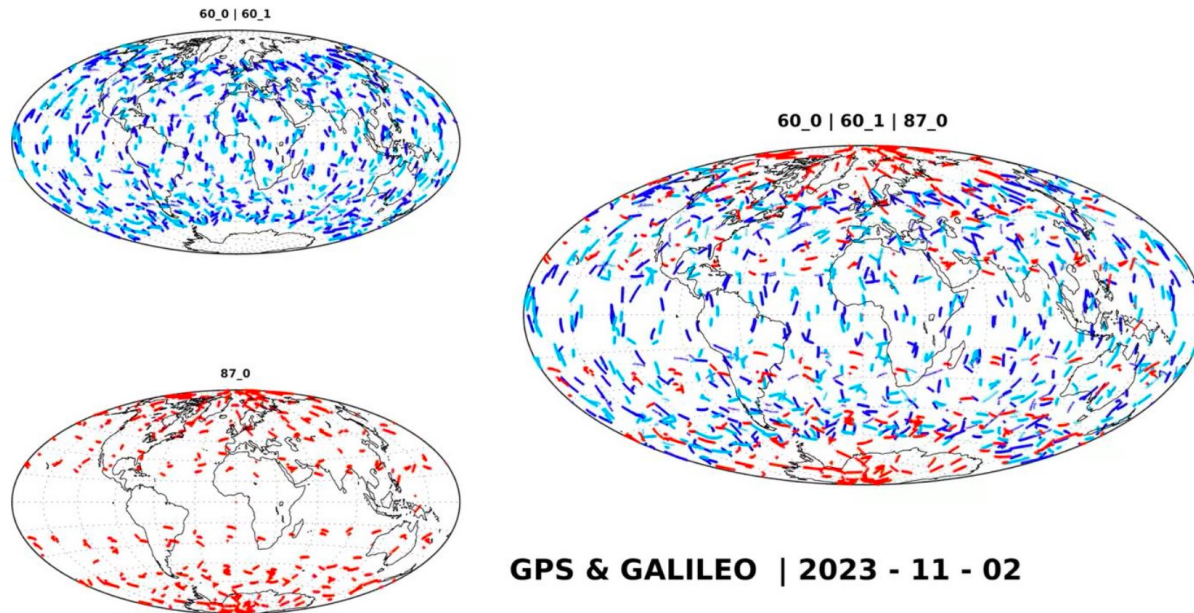
NanoMagSat E2E residuals



NanoMagSat + Swarm E2E residuals

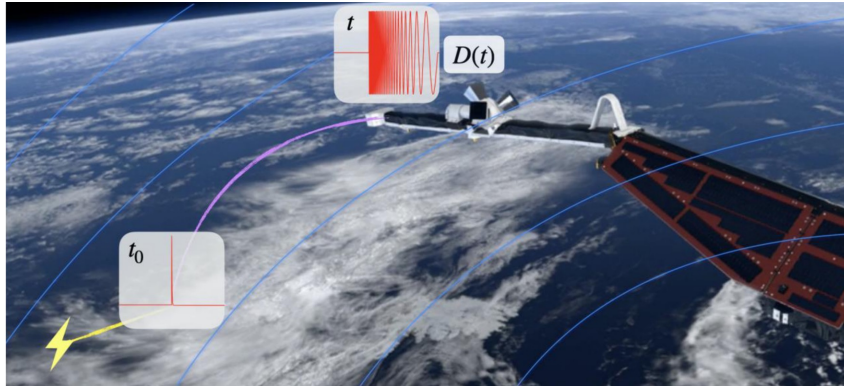
- E2E Recovery of DIFI-4 version of Sq climatological model of Chulliat et al., EPS, 2016, only using one day of data at a time.
- **Swarm fails, NanoMagSat does much better at large scales, combined constellations do even better**

Improving sensing the ionosphere below the satellites: acquiring nearby ionospheric Radio Occultation profiles

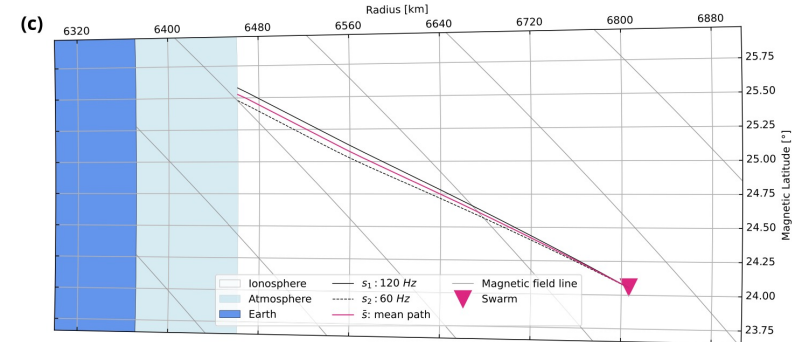
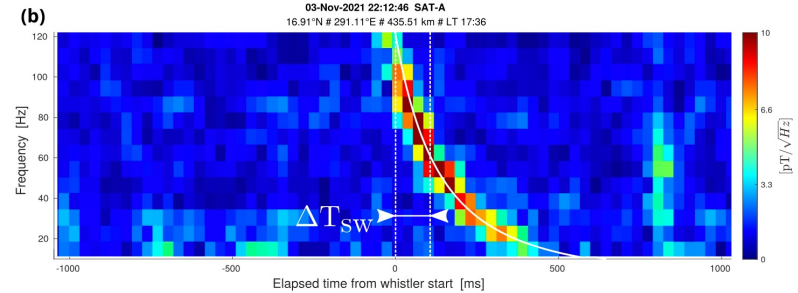


- Shown are day-by-day occultation tangent points with GPS and Galileo satellites, starting at altitudes of 90 km (up to NanoMagSat satellites), when traces are less than 1000 km long (i.e. sampling the ionosphere close to the NanoMagSat satellites).
- 60° inclined orbits (close to the 55°/ 56° GPS/Galileo inclined orbits) are very favorable.

Improving sensing the ionosphere below the satellites: Using lightning-induced whistlers to recover TREC



$$\text{TREC}(s_{sw}) = \int_0^{s_{sw}} \sqrt{N} ds$$

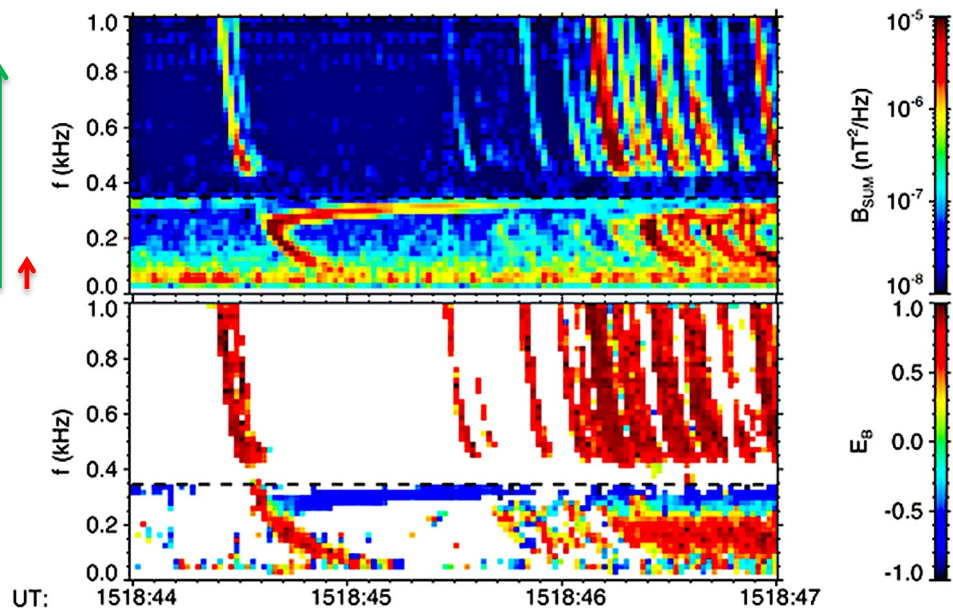


- Swarm has shown that the Total Root Electron Content (TREC) could be recovered from 250 Hz magnetic data
- See Jenner et al. (2024), Total Root Electron Content: A New Metric for the Ionosphere Below Low Earth Orbiting Satellites, GRL, 51, e2024GL110559, doi: 10.1029/2024GL110559

Improving investigations of low altitude Extremely Low Frequency (ELF) signals

MAM and HFM
800 Hz bandwidth

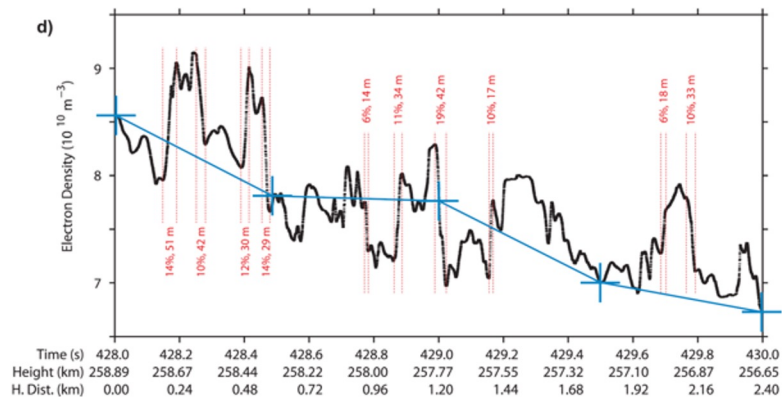
Swarm ASM
120 Hz bandwidth



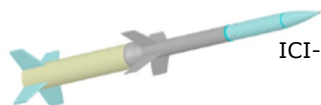
3s of **Demeter** (2004-2010) observations at ~ 700 km altitude (Shklyar et al, Space Physics, 2012)

- Although no electric data will be available, **full scalar and vector magnetic data at 2 kHz (waveforms and not only spectral data) will be provided.**

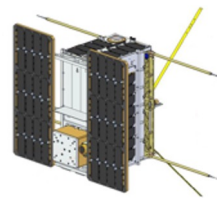
Allowing investigations of in-situ small scale plasma variability



Moen, J., et al. (2008), doi:10.1029/2012GL051407



ICI-2 sounding Rocket



NorSat-1 nano-satellite



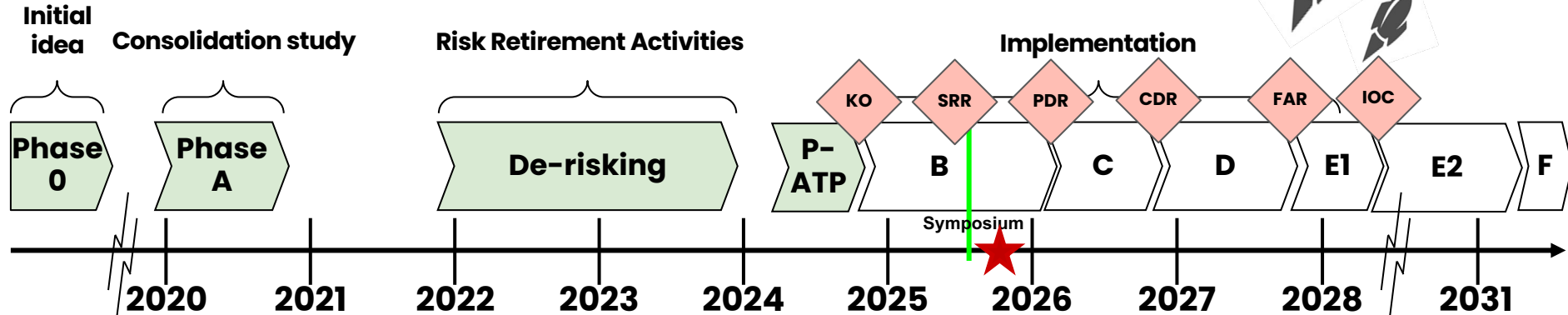
BRI-II nano-satellite

- **NanoMagSat will allow first joint measurements of electron density and magnetic signals at high frequencies (2 kHz) to access meter to km scale plasma variability and associated electrical currents using the multi-Needle Langmuir Probe (m-NLP), only flown so far on sounding rockets, and the NorSat-1 and BRIK-II nano-satellites, and the High Frequency Magnetometer (HFM), which both NorSat-1 and BRIK-II failed to have.**

Programmatic status and next steps

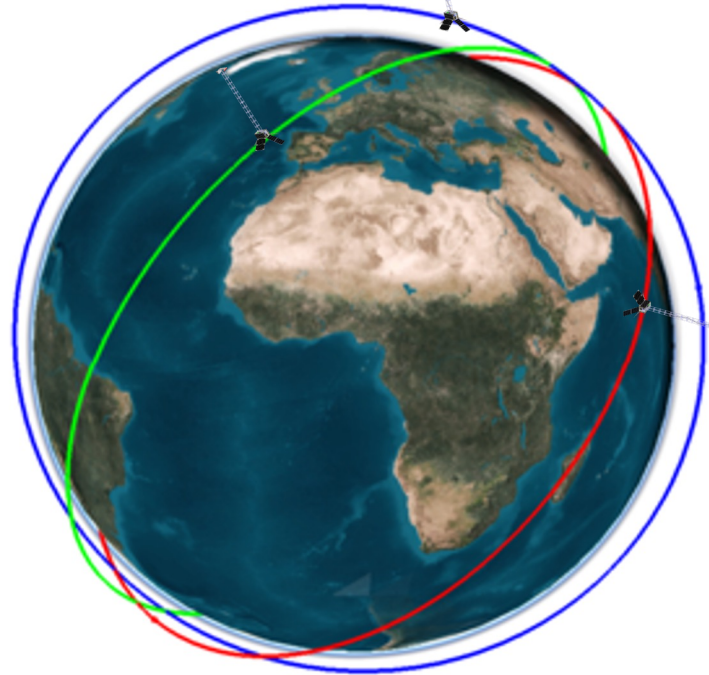


esa SCOUT Programme

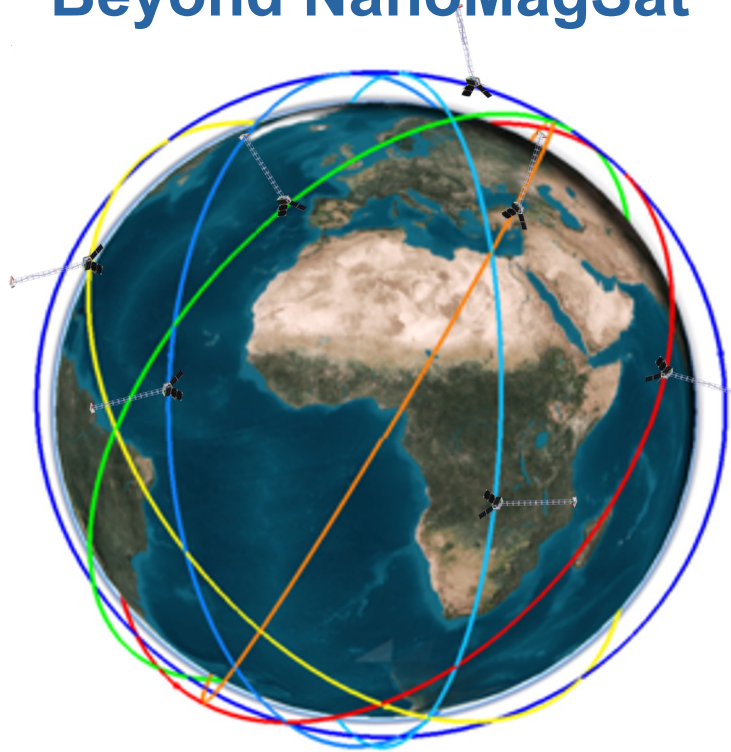


- Project currently in Phase B, System Requirements Review (SRR) passed on July 17, 2025
- **First satellite to be launched end of 2027, full constellation in place in 2028, minimum of 3 years of constellation operation (hopefully with Swarm, MSS, CSES,... still in operation)**
- Simulated Level 2 data soon to be released to the science community for testing.
- **First dedicated NanoMagSat symposium to be held jointly with 15th Swarm Data Quality Workshop Oslo, Norway (6-10 October 2025), Remote attendance: <https://swarmdisc.org/dqw-2025/information/>**
- **For more information, contact G. Hulot: gh@ipgp.fr**

Beyond NanoMagSat

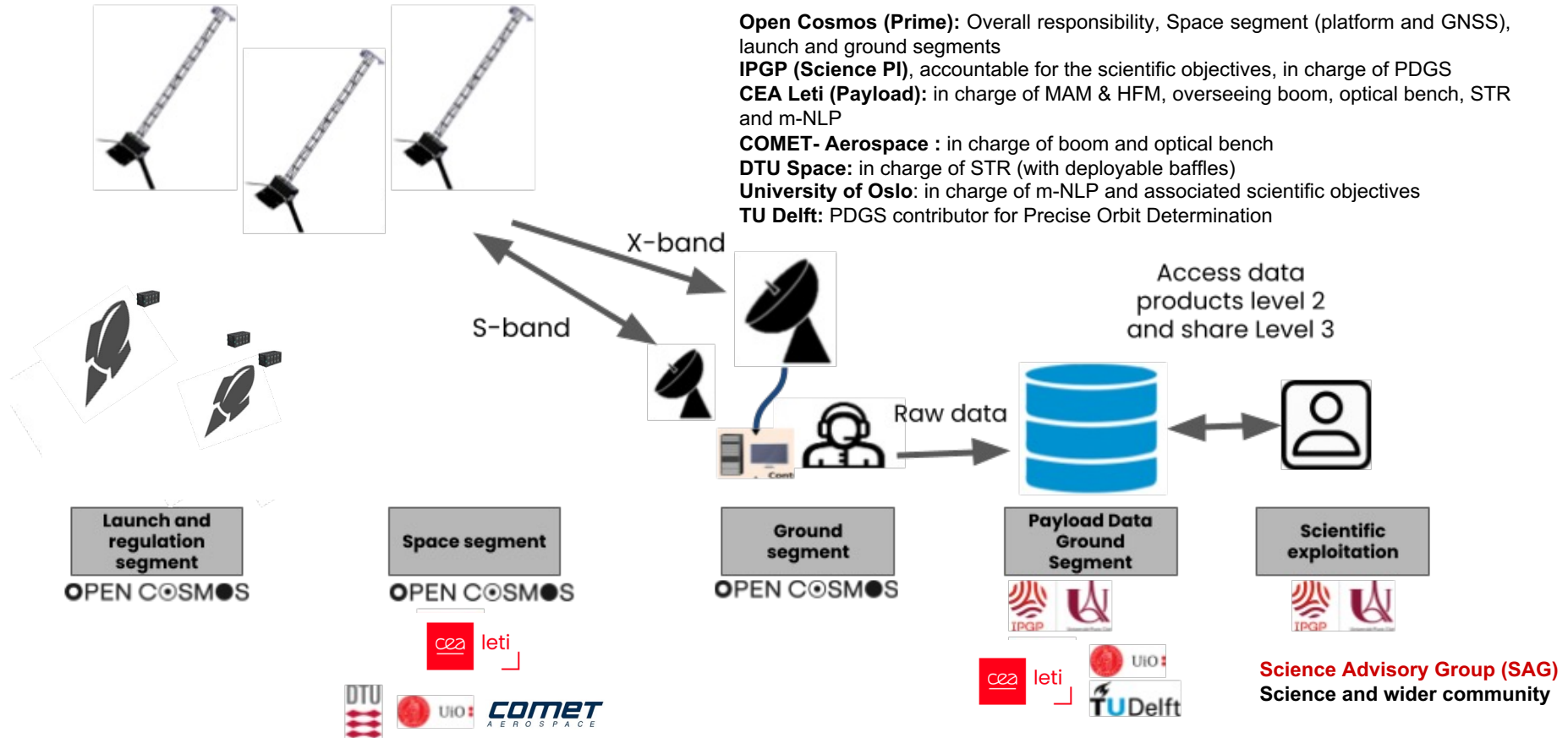


Beyond NanoMagSat



Setting up a low-cost scalable collaborative constellation solution for very long-term observations (extending to space the Intermagnet network of magnetic observatories)

Consortium and Mission architecture



Open Cosmos (Prime): Overall responsibility, Space segment (platform and GNSS), launch and ground segments
IPGP (Science PI), accountable for the scientific objectives, in charge of PDGS
CEA Leti (Payload): in charge of MAM & HFM, overseeing boom, optical bench, STR and m-NLP
COMET- Aerospace : in charge of boom and optical bench
DTU Space: in charge of STR (with deployable baffles)
University of Oslo: in charge of m-NLP and associated scientific objectives
TU Delft: PDGS contributor for Precise Orbit Determination