living planet symposium BONN 23–27 May 2022

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NanoMagSat, an optimal New Space low-Earth orbiting nanosatellite constellation to investigate Earth's magnetic field and ionospheric environment

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Session B7.01: Scout - ESA NewSpace Science Missions

25/05/2022

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19 institutions from 12 ESA member states + USA

NanoMagSat programmatic status

- **Submitted to the first ESA Scout** call in August 2019
- **One of the four missions selected for a Consolidation Study** in November 2019
- Consolidation study leading to a **full report to ESA in August 2020**
- **Presentation to ACEO in October 2020, very highly evaluated**:

"ACEO confirms the scientific relevance of the NanoMagSat concept"

"ACEO confirms the uniqueness of the NanoMagSat concept"

"unique opportunity for demonstrating long-term magnetic field monitoring, as a continuation of the Swarm mission"

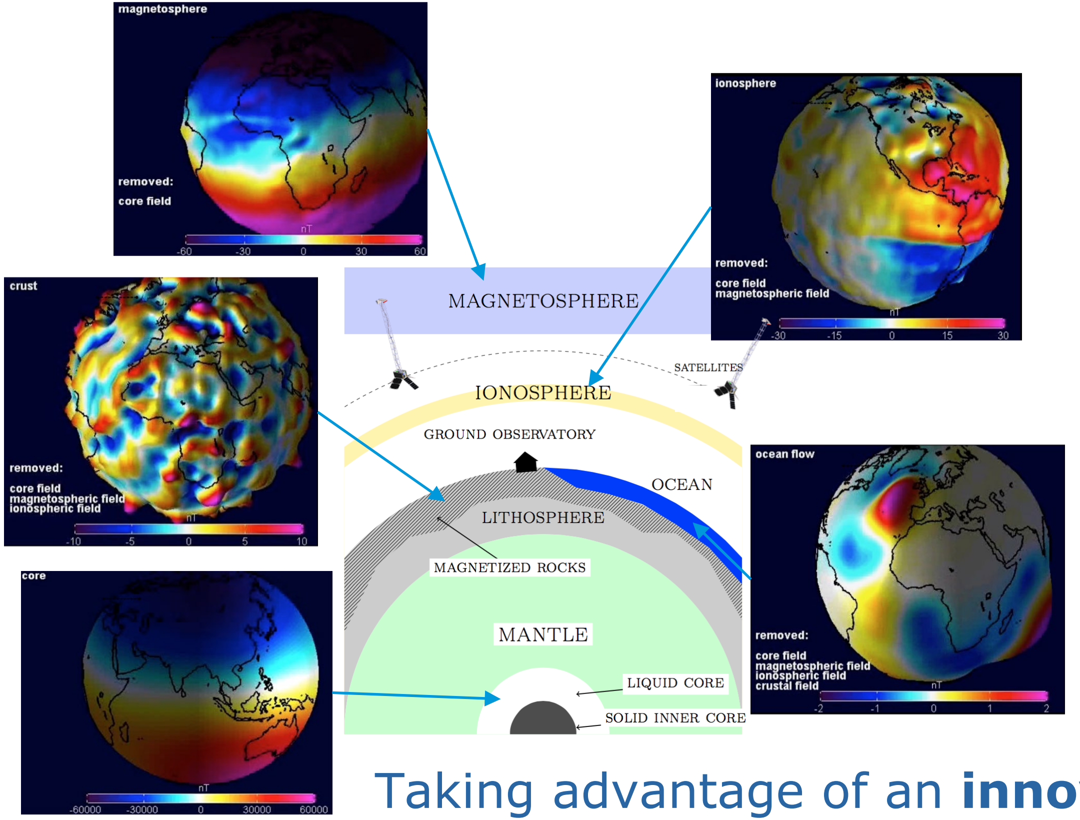
- But not selected on ground of high risks of not meeting costs and schedule criteria
- **18 months ESA funded Risk Retirements Activities kicked off in January 2022**, with **already good progress**, see **presentations on technical progress tomorrow (26/05/22)**:

-> **session B7.03, 14:45 J.M. Léger et al.**, "NanoMagSat magnetometry payload"

-> **session B7.03, 15:55, F. Deconink et al.** "NanoMagSat: a cost-effective 3x16U satellite constellation for fast recovery of the Earth magnetic field and the ionospheric environment"

-> **Poster 53, L. Clausen et al.** "The multi-needle Langmuir Probe on board NanoMagSat"

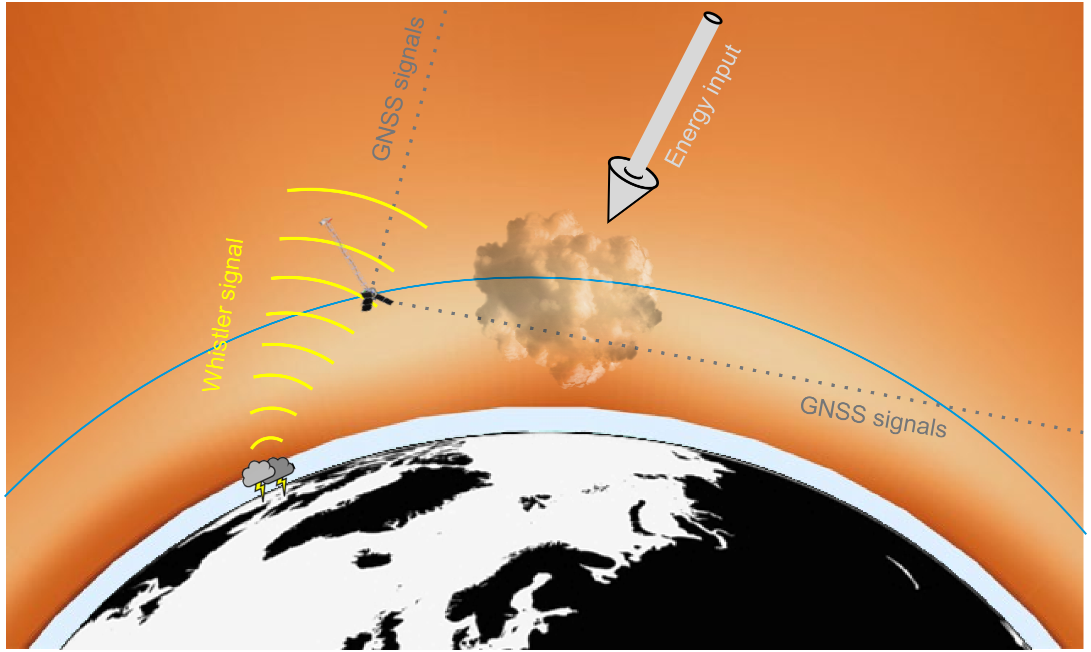
First family of objectives: Earth's magnetic field



- Targeting **recovery of fast planetary changes** in **core**, **ionospheric** and **magnetospheric** fields, also 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

Taking advantage of an **innovative constellation**

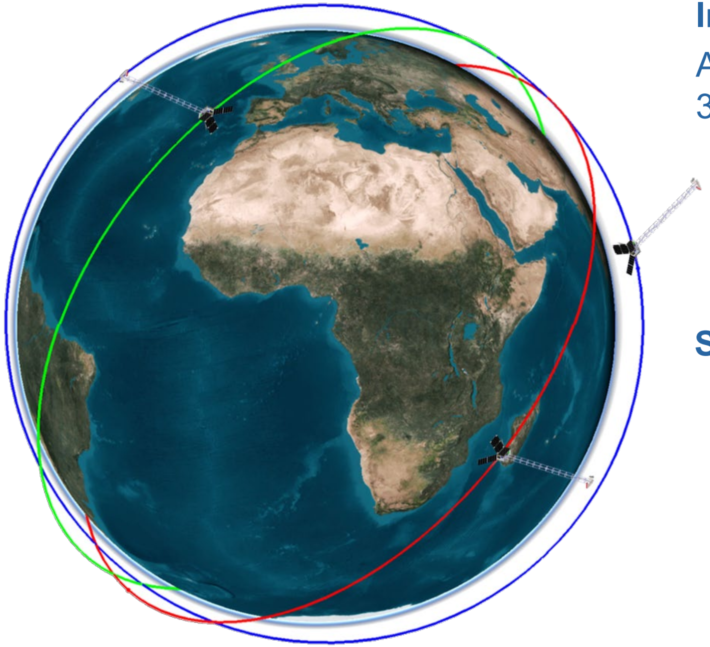
Second family of objectives: Ionospheric environment



- Targeting **ionospheric plasma density dynamics**
- Combining standard **GNSS techniques**
- With **new ways of sensing the ionosphere below the satellites and monitoring in situ meter to km scale dynamics and energy input**
- To investigate **Space weather** phenomena that affect radio and GNSS signals, and improve **science and operational ionospheric models**

Taking advantage of an **innovative compact payload**

NanoMagSat mission concept



Innovative orbital configuration

A 3-year minimum lifetime constellation composed of 3x16U Cubesats at 575 km initial altitude

- **1 satellite at 60° inclination**
- **1 satellite at 60° inclination offset by 90°-RAAN**
- **1 satellite in near-polar orbit**

State of the art compact payloads

- A **Miniaturized Absolute Magnetometer** (MAM) with a set of **two Star Cameras** (STR)
- A **High Frequency Magnetometer** (HFM)
- A **multi-Needle Langmuir Probe** (m-NLP)
- 2 **dual-frequency GNSS**

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

NanoMagSat magnetic & ionospheric environment data

1 Hz data synchronized to 1 ms

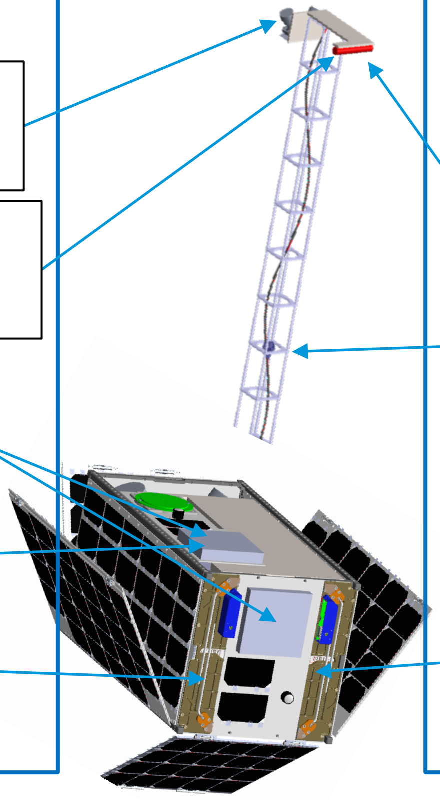
Attitude (STR) : σ < 5 arcseconds
High Energy Proton Flux (>60 MeV)

B vector (MAM) : σ < 0.8 nT
B vector (NEC frame) : σ < 1 nT
B scalar (MAM) : σ < 0.2 nT

GNSS products (TEC, IP, SCI):
standard requirements

POD (r, θ, φ) within 8 m

Electron temperature (m-NLP)



2 kHz data synchronized to 1 μs

B scalar (MAM)
Noise below 1 pT/√Hz over DC-800 Hz

B vector (HFM)
B vector (NEC frame)
Noise below 0.25 pT/√Hz over 1-800 Hz

Electron density (m-NLP)
1 σ <1% for n_e>10^{10} m^{-3}
1 σ <10% for 10^9<n_e<10^{10} m^{-3}

Identified NanoMagSat high level Science targets

Constellation

Primary objectives:

- **Earth's Main Field** (Core Field CF Product)
  ⟶ MHD processes in the core, improving predictability
- **Ionospheric Field** (Solar Quiet Field SQF Product)
  ⟶ Investigating thermospheric - ionospheric and magnetospheric - ionospheric interactions
- **Magnetospheric Field** (Fast Magnetic Field FMF Product)
  ⟶ Investigating Solar-Terrestrial interactions, recovering solid Earth electrical conductivity properties

Secondary objectives:

- Improving mapping of **Lithospheric Field** (LF Product)
  ⟶ With applications to tectonics, geology and natural resources
- **Oceanic Lunar Tide Field signals** (OLTF Product)
  ⟶ Recovering solid Earth electrical conductivity properties, and monitoring global heat content of oceans
- **Global Ocean Circulation variability** (Under consideration)
  ⟶ Monitoring dynamics of large scale ocean currents

Single satellite

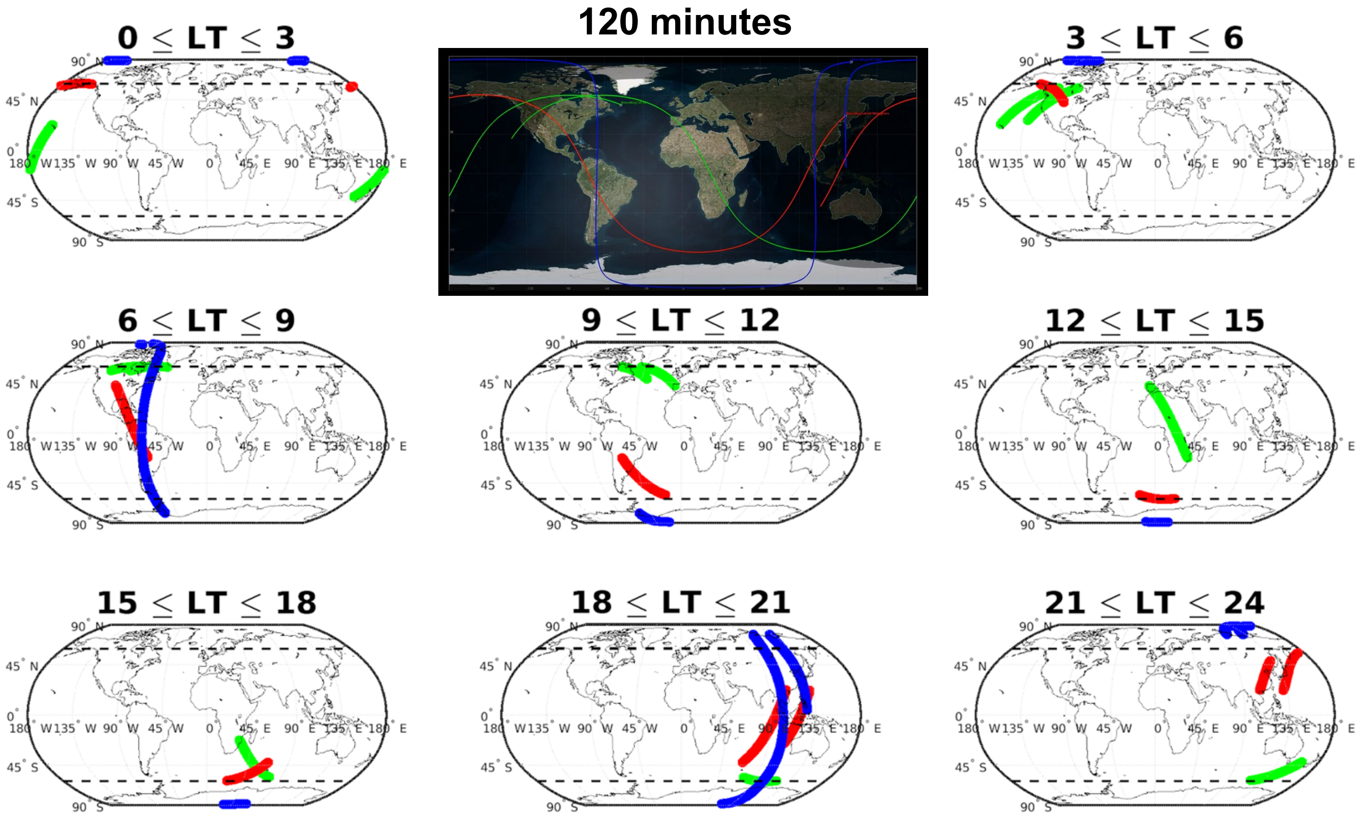
Primary objectives:

- **ELF magnetic and Whistler Signals** (WS Product)
  ⟶ Large-scale ionospheric plasma variability
- **Ionospheric meter-scale plasma density structures** (MSPDS Product)
  ⟶ Small-scale ionospheric plasma variability

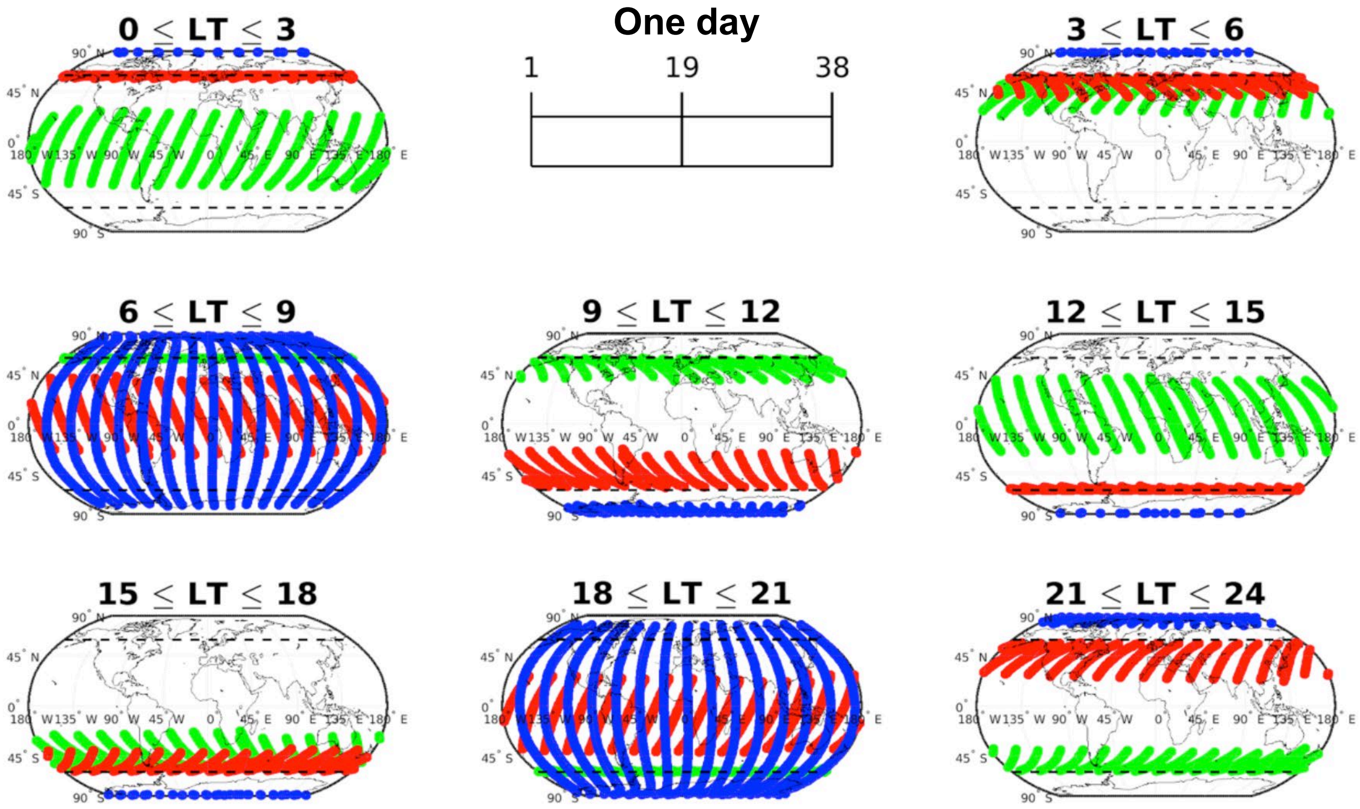
Secondary objectives:

- Monitoring ionospheric **high latitude and equatorial local currents** (FAC and EEF Products)
  ⟶ Investigating thermospheric - ionospheric and magnetospheric - ionospheric interactions
- Monitoring ionospheric **Total Electron Content** (TEC Product)
- Producing **occultation Ionospheric Profiles** (IP Product)
- Characterising **ionospheric scintillations** along GNSS radio links (SCI product)
  ⟶ Ionospheric plasma variability
- **High Energy proton flux** (Under consideration)
  ⟶ Radiation environment monitoring

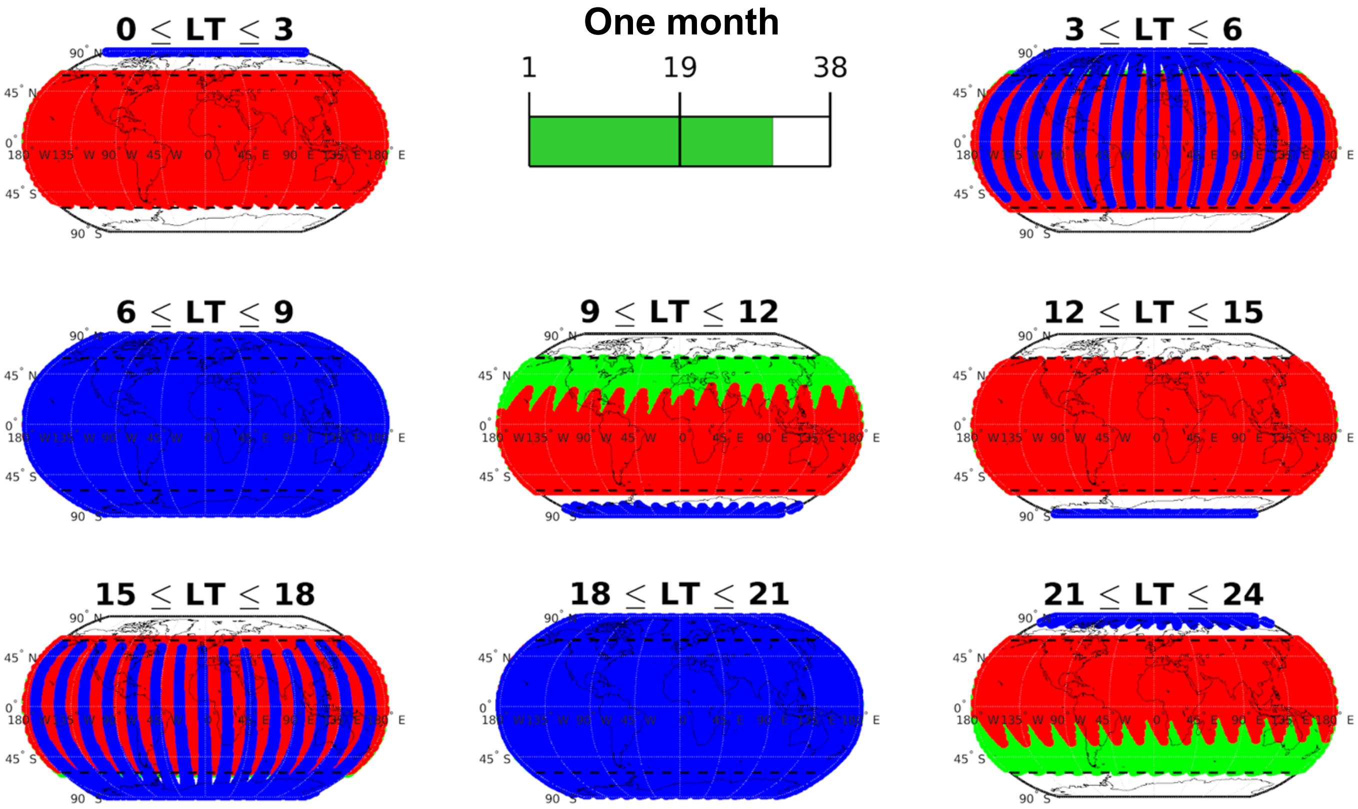
NanoMagSat Geographic/Local Time coverage



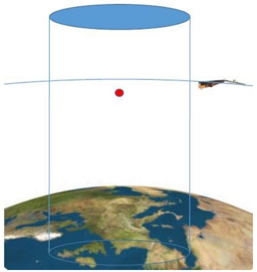
NanoMagSat Geographic/Local Time coverage

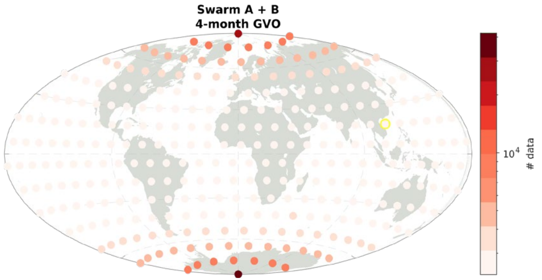


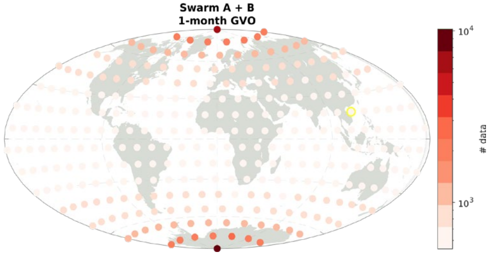
NanoMagSat Geographic/Local Time coverage

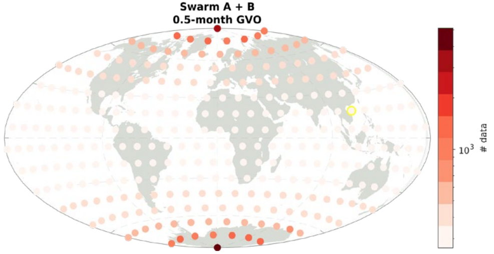


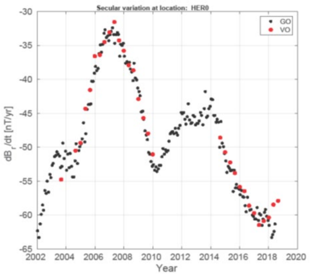
Will lead to much improved series of Geomagnetic Virtual Observatory (GVO) data for Core Field investigations

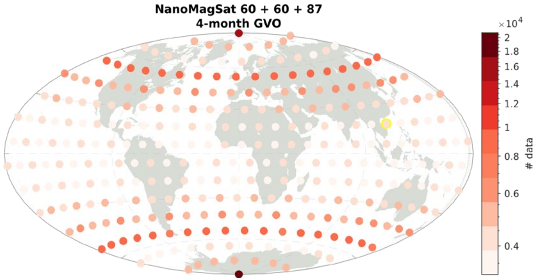


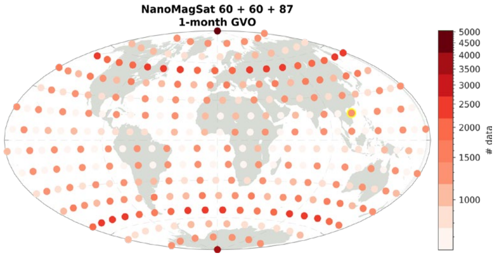


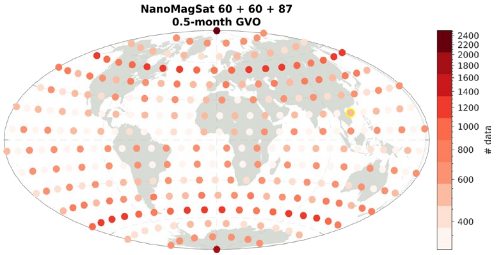






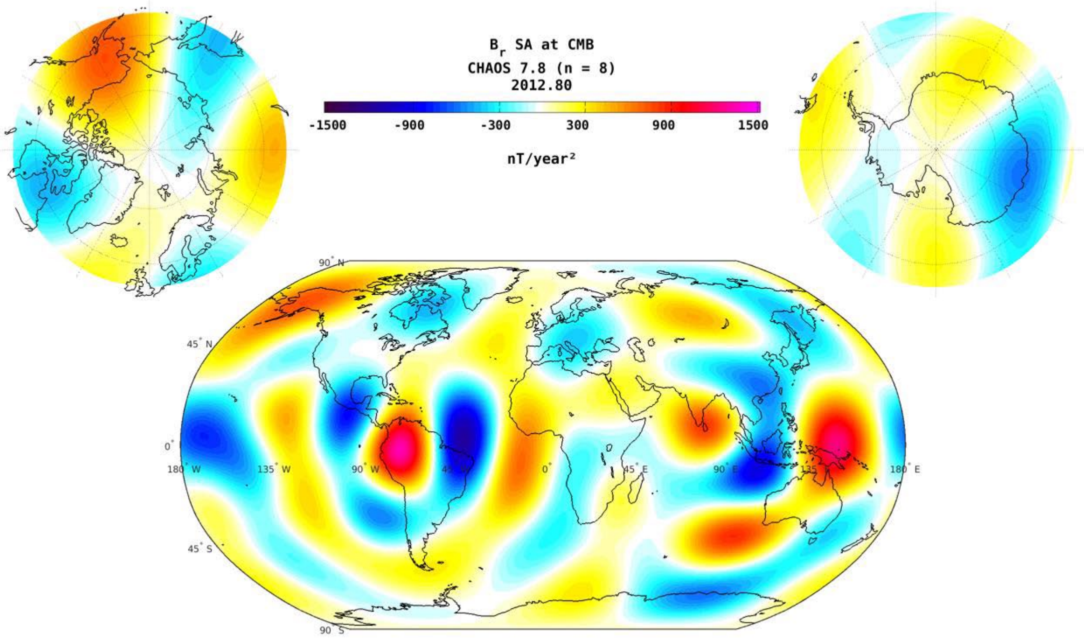






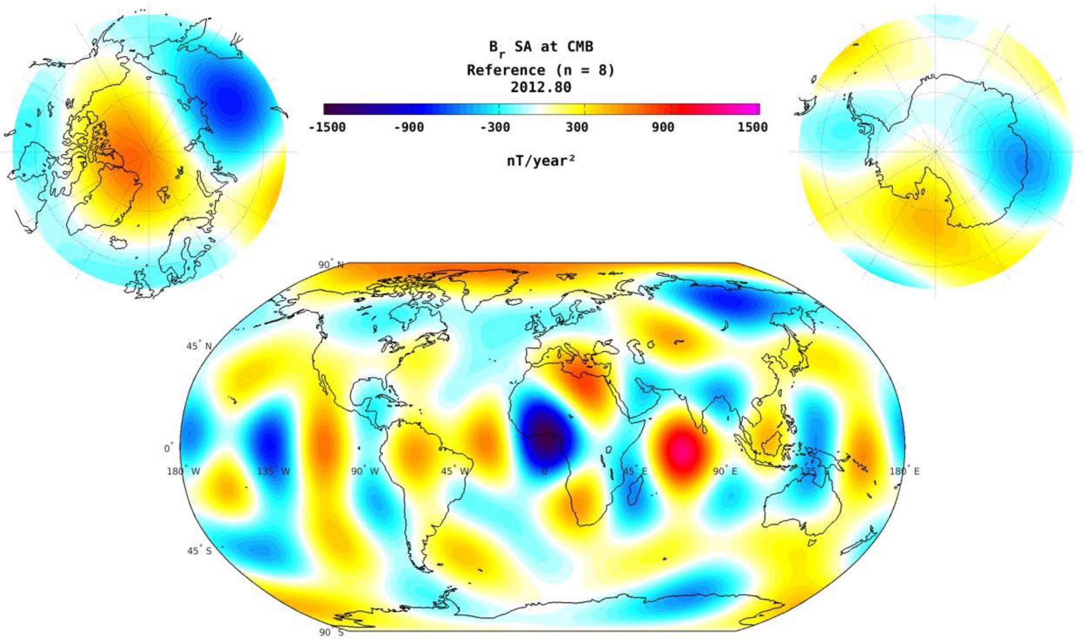
High-quality full LT GVO could then be created on a 3-weekly basis, substantially increasing the current time resolution of 17 weeks based on Swarm.
(see **Poster 550 on Thursday 26/05/2022 by Brown et al.,** ***Geomagnetic Virtual Observatories for investigating sub-annual core field variation***).

Core Field Secular Acceleration currently recovered by Swarm



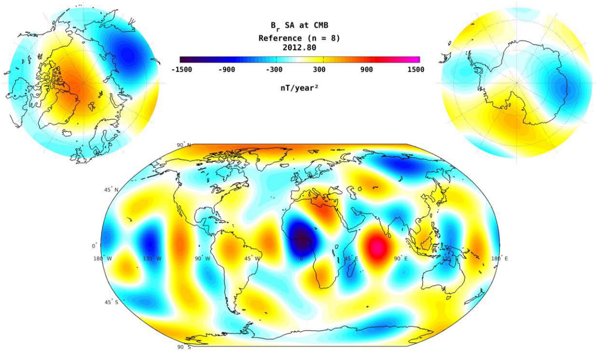
Radial component of the second time derivative of the core field at the core surface up to SH degree 8 between 2012.8 and 2015.8 (3 years), as modelled by the CHAOS 7.8 model (Finlay et al., EPS, 2020)

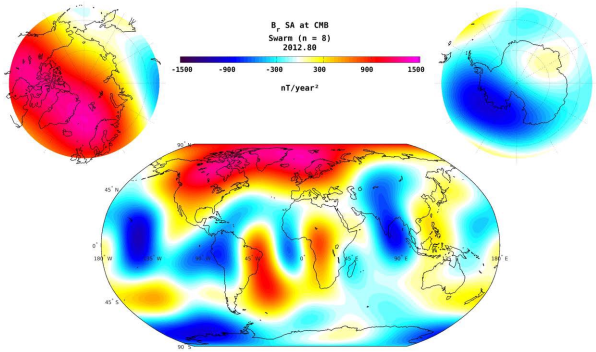
Additional faster Secular Acceleration dynamics predicted by dynamo simulations

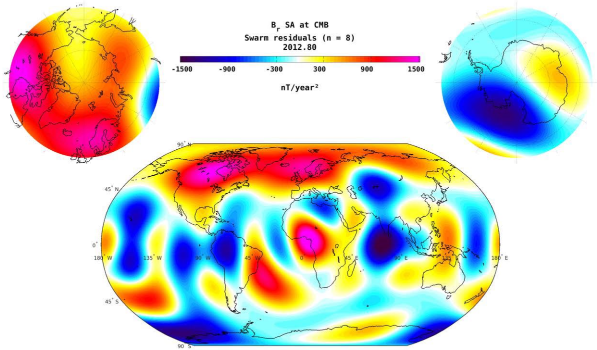


Radial component of additional faster signal predicted in the second time derivative of the core field at the core surface up to SH degree 8, simulated between 2012.8 and 2015.8 (3 years), using dynamo runs by J. Aubert, IPGP (based on Aubert, GJI, 2015; Aubert et al., JFM 2017; Aubert and Gillet, GJI 2021).

This signal can hardly be recovered by Swarm

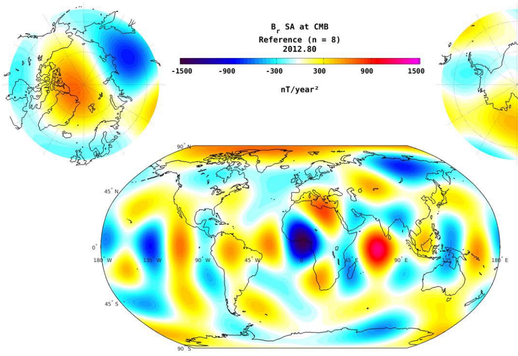


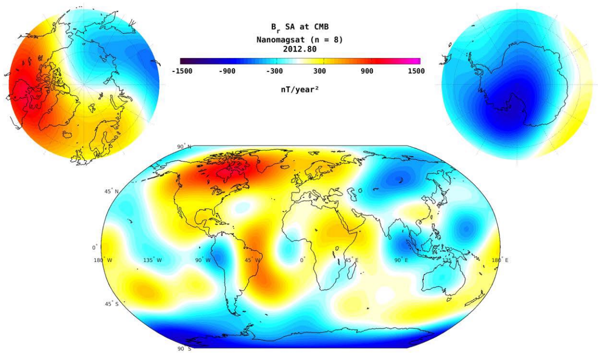


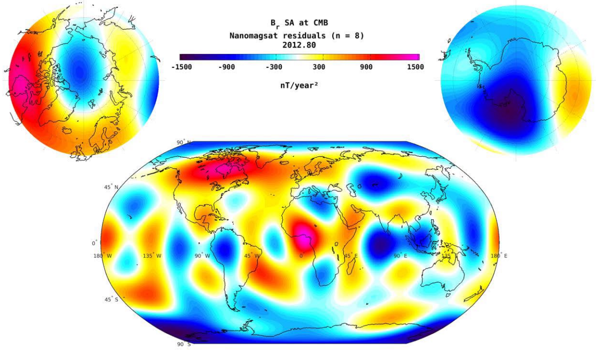


Radial component of the additional faster signal predicted in the second time derivative of the core field at the core surface up to SH degree 8 (upper left), recovered by Swarm (upper right) and residuals (bottom). Model recovery based on methodology of Alken et al., EPS, 2020.

NanoMagSat can !

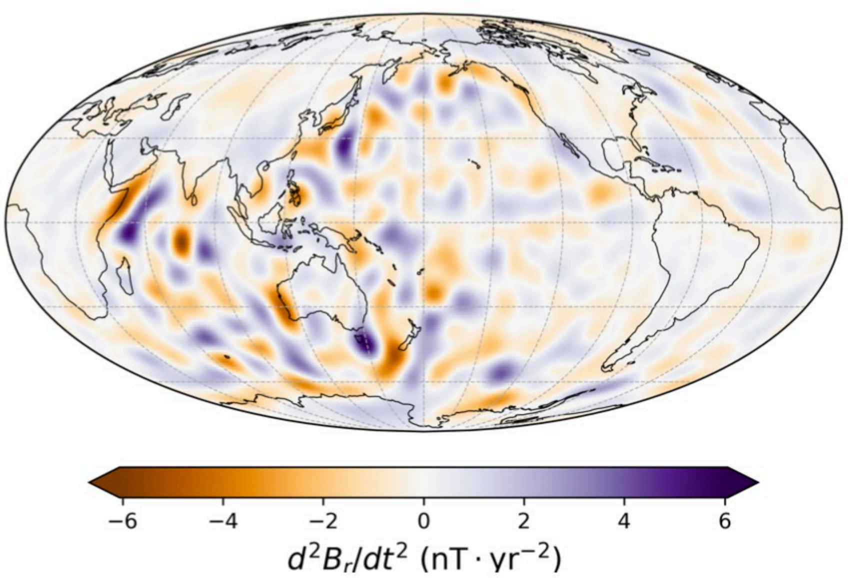




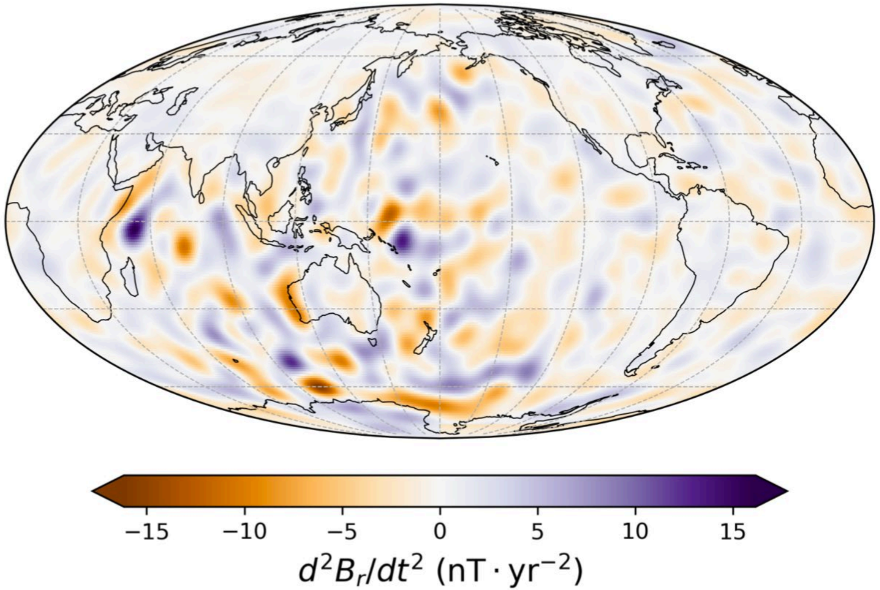


Radial component of the additional faster signal predicted in the second time derivative of the core field at the core surface up to SH degree 8 (upper left), recovered by NanoMagSat (upper right) and residuals (bottom). Model recovery based on methodology of Alken et al., EPS, 2020.

NanoMagSat could also help recover magnetic signals produced by global ocean circulation



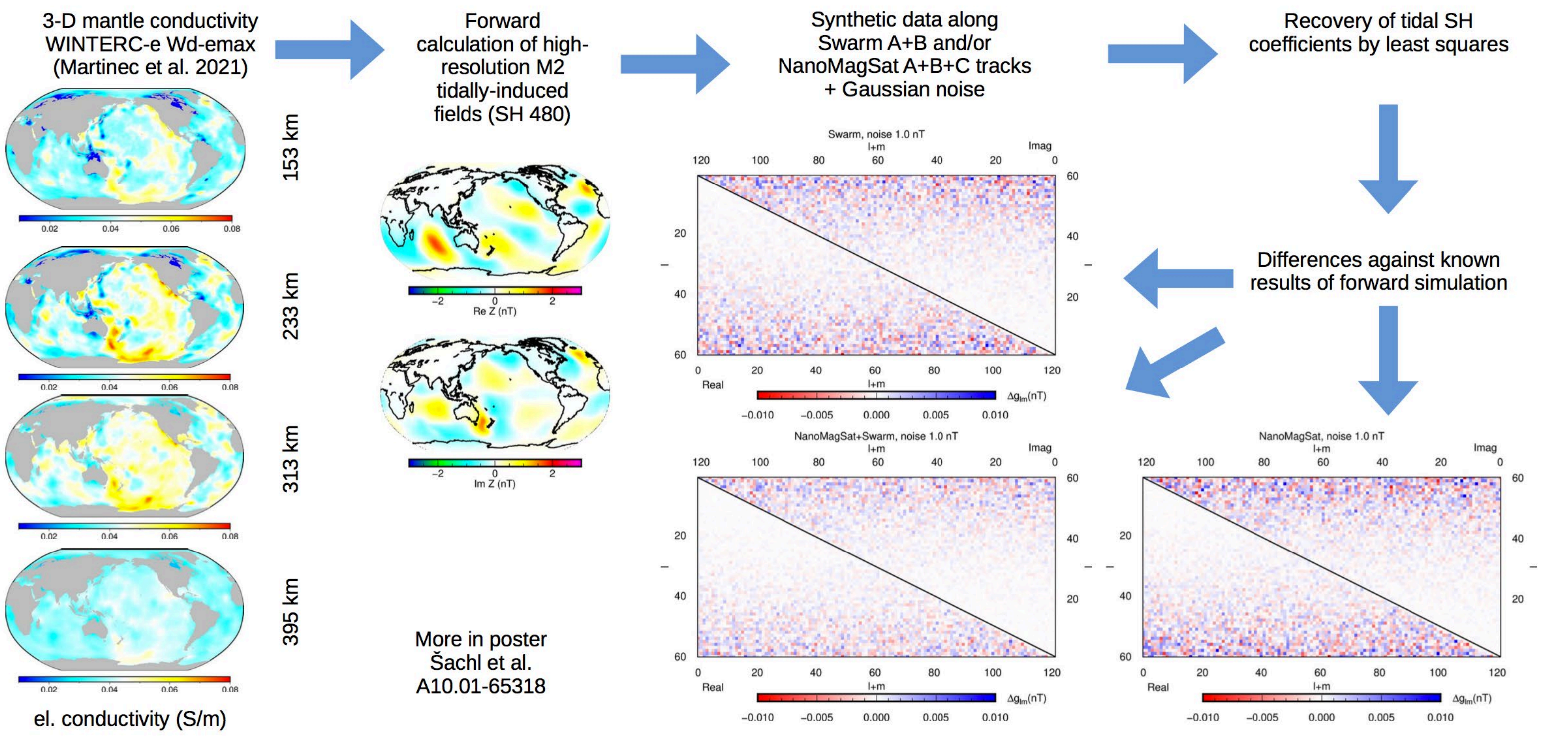
Simulated Secular Acceleration between degrees 9-30 at Earth’s surface



Recovered Secular Acceleration between degrees 9-30 at Earth’s surface

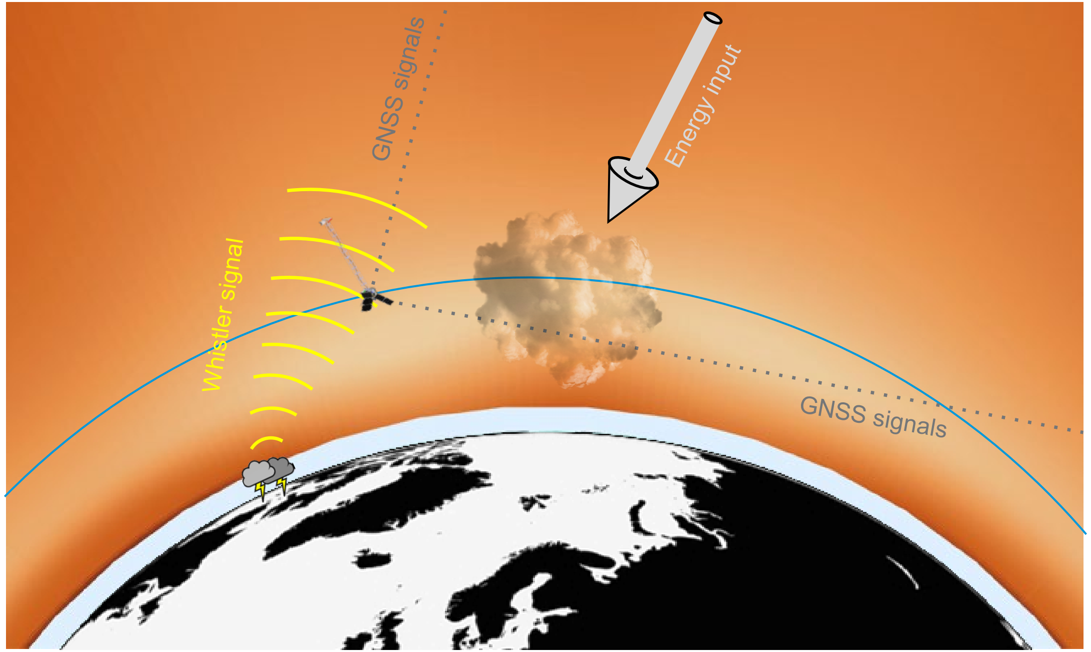
Average Secular Acceleration of the field over 6 months is likely dominated by that produced by Ocean water circulation (and not by the core dynamo) beyond SH degree 8, which Swarm can potentially recover, even better so with NanoMagSat (**see Poster 548 on Thursday 26/05/22, by Finlay et al., “*Signatures of the global ocean circulation in geomagnetic secular variation and acceleration*”**)

NanoMagSat will also recover magnetic signals produced by M2 tides



NanoMagSat does as well as Swarm (**as shown on Poster 475 on Thursday 26/05/22, by Sachl et al., "*Validation and interpretation of the 3-D upper-mantle electrical conductivity reconstructed from the satellite-observed tidal magnetic fields*"**)

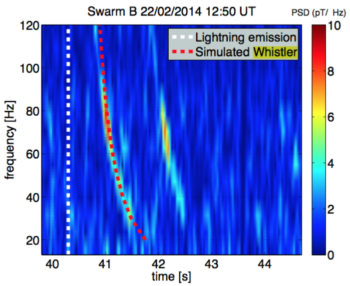
What about Ionospheric environment ?

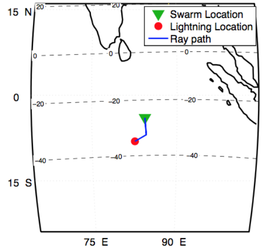


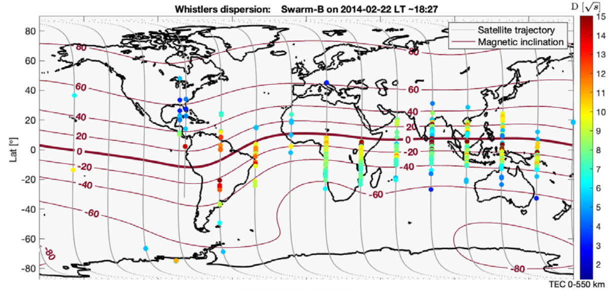
- Targeting **ionospheric plasma density dynamics**
- Combining standard **GNSS techniques**
- With **new ways of sensing the ionosphere below the satellites and monitoring in situ meter to km scale dynamics and energy input**
- To investigate **Space weather** phenomena that affect radio and GNSS signals, and improve **science and operational ionospheric models**

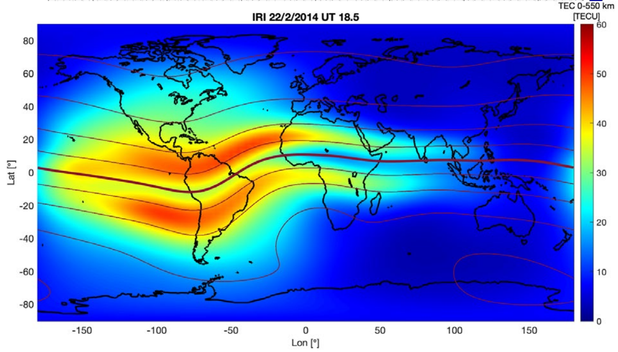
Taking advantage of an **innovative compact payload**

Monitoring the ionosphere below NanoMagSat will be possible

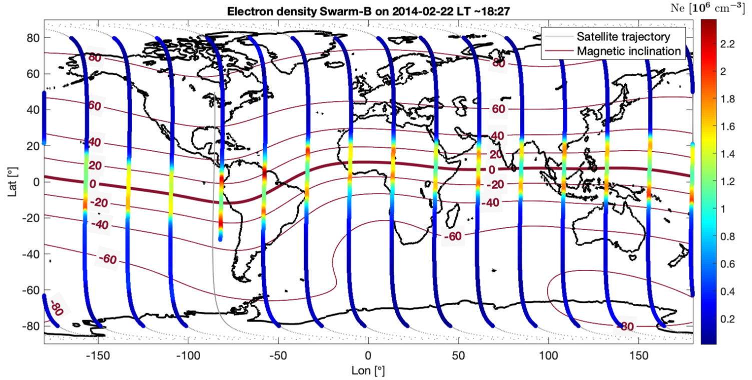








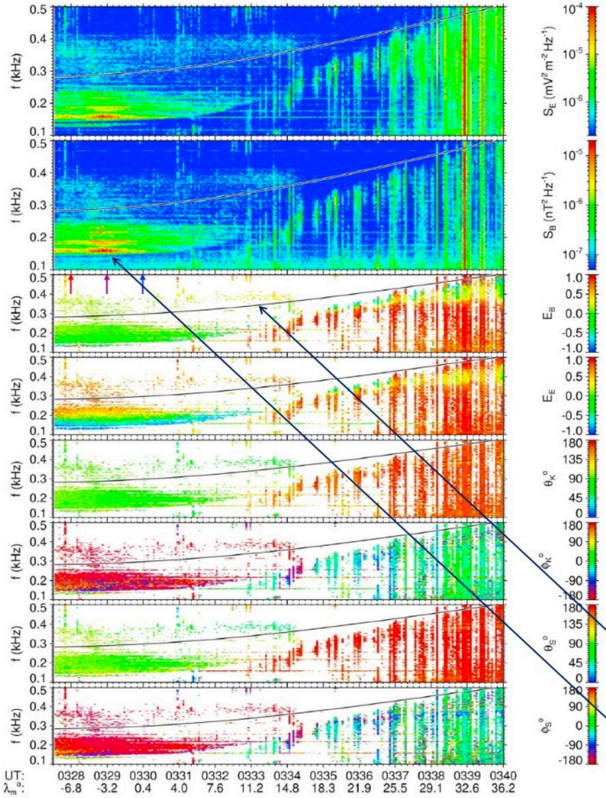
Principle illustrated using Swarm B ASM (250 Hz magnetic scalar Burst mode, left) and 1 Hz Langmuir Probe data (below) on 22/02/2014



IRI model prediction on 22/02/14

- **Take advantage of ELF Whistlers produced by lightning**, **detected by the MAM (scalar) and HFM (vector) magnetometers (2 kHz)**
- These propagate through the ionosphere with a dispersion that **allows sensing the ionospheric plasma below the satellites**
- **Complementing local m-NLP measurements**
- **Providing information in regions not covered by ionosonde or GNSS techniques**
- **See talk on Thursday 26/05/22 (Session A6.02, 14:15), P. Coïsson et al., "*Whistler in ELF detected from LEO: lightning detection and ionospheric monitoring using Swarm satellites and the future NanoMagSat mission*"**

Investigating ELF waves coming from above will also be possible (as shown by Demeter)



DEMETER spacecraft on 12 April 2005

Propagation of equatorial noise to low altitudes

Power-spectral densities of electric field components (not available on NanoMagSat).

Sum of the power-spectral densities of three orthogonal magnetic field components (available on NanoMagSat).

Ellipticity of the magnetic field polarization with a sign corresponding to the sense of polarization (available on NanoMagSat).

Ellipticity of the electric field polarization (not available on NanoMagSat).

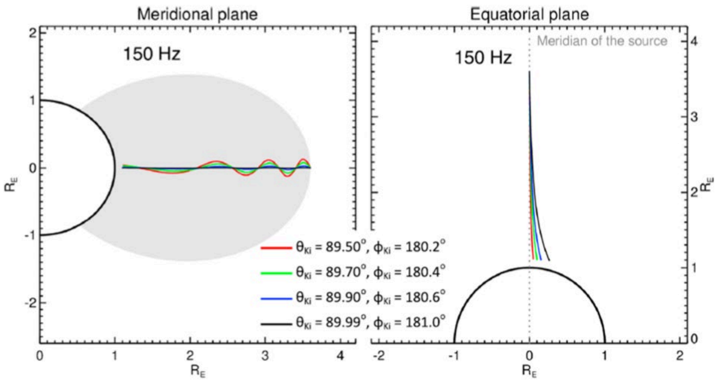
Angle between the wave vector and the background magnetic field (available on NanoMagSat with 180° ambiguity).

Azimuth of the wave vector with respect to the outward direction, positive eastward (available on NanoMagSat with 180° ambiguity).

Poynting vector direction (not available on NanoMagSat).

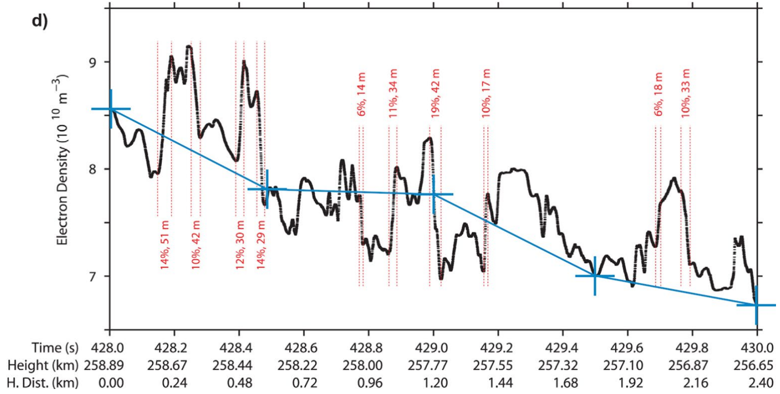
$$f_{L=0} = f_{H^+} \frac{1 + P_O(R_{OH} - 1)}{R_{OH}}$$

Santolik et al., Geophys. Res. Lett., 2016

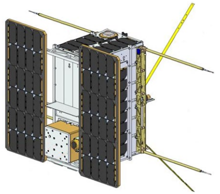


See Poster 527, Thursday 26/05/22, by O. Santolik et al., “*Coupling of electromagnetic waves between the magnetosphere and the topside ionosphere: new proposed science targets for the NanoMagSat mission*”.

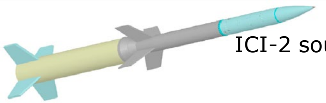
As well as investigating in-situ small scale plasma variability



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



NorSat-1 nano-satellite



ICI-2 sounding Rocket

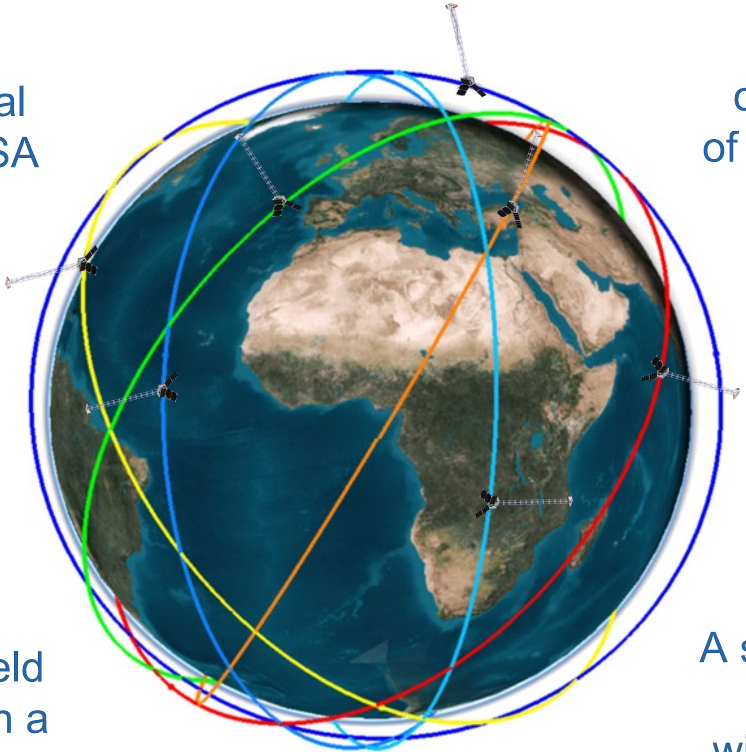
- **First joint measurements of electron density and magnetic signals at high frequencies** (2 kHz) **to access meter to km scale plasma variability and associated electrical currents** using the **multi-Needle Langmuir Probe** (m-NLP), only flown so far on sounding rockets and the NorSat-1 nano-satellite, and the **High Frequency Magnetometer** (HFM), which NorSat-1 fails to have
- **See poster 53 on Thursday 26/05/22, by L. Clausen "*The multi-needle Langmuir Probe on board NanoMagSat*"**

More examples of the benefit of NanoMagSat for ionospheric studies at this meeting

- **Talk this afternoon at 15:40 in session A6.01 by B. Heilig "*LEO observations of conjugated magnetospheric-ionospheric phenomena for improved plasmapause monitoring*"**
- **Poster 539 on Thursday 26/05/22 by M. Dunlop et al., "*Coordination of ground based and in orbit multipoint measurements: comparison of magnetospheric and ground currents*"**

NanoMagSat

A mission for a wide scientific community and 50+ institutional users, strongly aligned with ESA EO Science Strategy



A mission ensuring continuity in the monitoring of Earth’s magnetic field and ionospheric environment (long-term Science).

A nanosatellite constellation to investigate Earth’s magnetic field and ionospheric environment in a unique way.

A stepping stone for a space network of observatories with international scalability.