NANOMAGSAT STATUS: A 3X16U LOW-EARTH-ORBIT CONSTELLATION TO MONITOR THE EARTH MAGNETIC FIELD AND THE IONOSPHERIC ENVIRONMENT

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PAPER

NanoMagSat is a mission concept to deploy and operate a new Low-Earth orbiting constellation concept of three identical 16U nanosatellites, using two inclined (~ 60°) and one polar orbit, for investigating the Earth's magnetic field and ionospheric environment.

The constellation is designed to provide fast coverage of all local times (LT) at all latitudes, with special emphasis within ± 60°. NanoMagSat measurements will improve identification and investigation of fast planetary magnetic signals as well as the ionospheric environment, all of which requires such fast LT/geographic coverage to disentangle signals that are sensitive to the local time (Sun position).

Each satellite will carry a payload suite combining: an absolute scalar and self-calibrated vector magnetometer collocated with two star trackers on an optical bench at the tip of a deployable boom ; a High Frequency Magnetometer at mid-boom; a multi-needle Langmuir probe and two GNSS receivers for precise orbit determination, TEC recovery and ionospheric radio occultation. The key challenges of the mission are the launch availability, the miniaturisation of the magnetometers and the magnetic cleanliness of the satellite. The latter drives the need for a 3m deployable boom and specific development of some of the platform subsystems and related accommodation.

1 NANOMAGSAT BACKGROUND AND PURPOSE

1.1 Monitoring and investigating the Earth's magnetic field

1.1.1 Need for a long-term and well-designed observation strategy

The Earth's magnetic field is the complex result of a great variety of geophysical sources. Electrical currents with widely varying characteristics are ubiquitous. They can be found within the Earth's core (and solid inner-core), mantle, lithosphere, oceans and above the neutral atmosphere in the ionosphere and magnetosphere (see Figure 1.). In addition, most rocks within the Earth's uppermost layers are magnetized. Length and time scales involved extend from planetary to meter scales, and from millions of years (the Earth's magnetic field is almost as old as the Earth itself) to less than a second [1]. All sources simultaneously contribute to the magnetic field observed anywhere on Earth and in the near-Earth environment, and each observation contains information about all sources simultaneously. This has two important consequences: one is that no signal from a single source can easily be extracted from any observation without considering the contributions from all other sources. The other is that no source can be investigated from observations without appropriate spatio-temporal coverage of the observations. Hence the now well-identified need to simultaneously carry on long-term observations from ground and space, with the best possible spatio-temporal coverage. Previous missions already helped reveal a lot about these sources, but a lot of questions remain open and new questions have arisen.

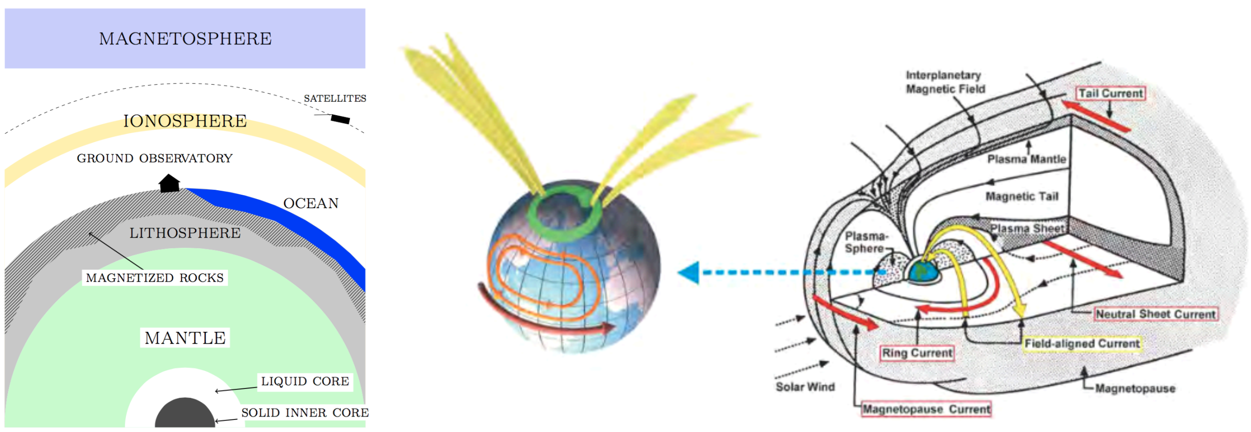

Figure 1.: Sources of the Earth's magnetic field - Left panel: electrical currents associated with the geodynamo acting within the liquid core (white) with a solid inner core (black) and producing the main field; induced electrical currents flowing within the mantle (green), lithosphere and crust (grey), electrical currents within the ocean due to the motion (including those associated with oceanic tides) of the electrically conducting seawater within the main field (navy blue); currents flowing within the electrically conducting ionosphere (yellow), currents due to charged particles circulating within the magnetosphere (light purple), and magnetized rocks in the upper layers of the Earth (shaded grey). Right panel: Details of the ionospheric and magnetospheric current systems, the field-aligned currents connecting the two (also regions of high space weather risks) being shown in yellow.

1.1.2 Historical development

The Earth's magnetic field has been known to man for centuries [3]. It was soon recognized scientifically as one of the most fascinating natural phenomena, as well as a very useful tool for many applications such as sea and ground navigation still applicable today. This dual motivation, and the permanently changing nature of this field, quickly led to its systematic observation and a large body of data was collected over the centuries, thanks to the patient work of hundreds of individuals across the world.

The 19th century marked a turn with the setting up of permanent magnetic observatories, many of which are still operating within the framework of the international INTERMAGNET program, initiated at the end of the 1980s and which currently counts 154 affiliated observatories (http://www.intermagnet.org). The advent of space technology in the 1960s quickly led to near-continuous observations of the Earth magnetic field since 1999 (see figure 2.), one of the main goals being to fill the gaps left by ground observatories.

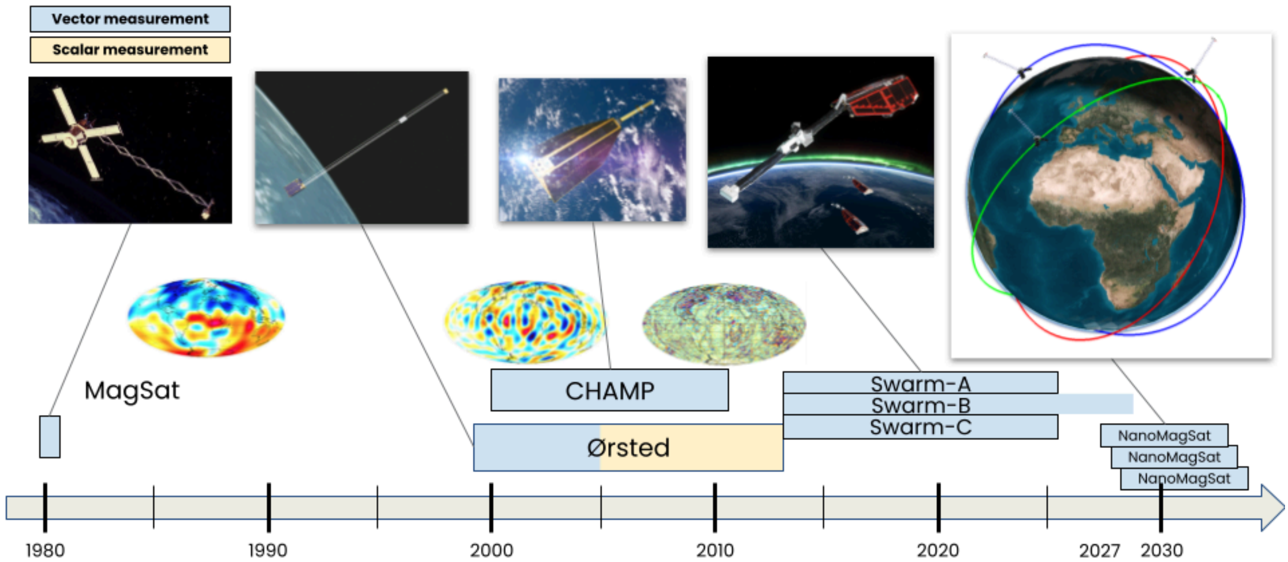

Figure 2.: The launch of the US MAGSAT satellite in 1979 proved the feasibility of acquiring accurately calibrated (using absolute measurements) and oriented (using vector measurements and star cameras to recover coordinates in a useful Earth reference frame) measurements. These efforts successfully led to a series of LEO satellites, including the Danish satellite Oersted (launched in 1999, providing useful data until July 2010), the German satellite CHAMP (2000-2010), and the still operating ESA Earth Explorer three LEO satellite mission Swarm

The scientific success of these previous missions is considerable [4]. We owe them much of what we currently know of the various sources of the field. But we now also know that substantially longer equally accurate observations with even better spatio-temporal coverage are still needed to better understand the physics underlying these signals.

1.2 NanoMagSat timeliness and purpose

Building on the Swarm experience, NanoMagSat intends to provide a rapid prototype of a low-cost nano-satellite constellation to permanently monitor the Earth's magnetic field and ionospheric environment with unprecedented spatial and temporal resolution.

By doing so, it will maintain the European leadership in this domain and aims to demonstrate the feasibility of long-term monitoring of the field and the ionospheric environment using low-cost nanosatellite constellations through international collaboration.

Inheriting from Swarm, but also providing new data thanks to its innovative payload, NanoMagSat will provide 1 Hz absolute vector oriented magnetic measurements, 2 kHz vector and scalar magnetic data, 2 kHz electron density data, 1 Hz electron temperature, as well as 1 Hz total electron content (TEC) and ionospheric radio-occultation profiles, with a latency of 2 weeks.

1.2.1 Maintaining and improving spatio-temporal coverage

The NanoMagSat mission is a 3-year lifetime constellation to prolong and improve the coverage currently provided by Swarm.

Regarding the spatio-temporal coverage, the on-going 3-satellite Swarm mission currently provides a 24h local time coverage about every 5 months [5]. This is due to the orbital configuration of the satellites having polar orbits (1 satellite at 87.30° and 2 satellites at 87.75°, orbiting next to each other [2]) leading to slow precession of Local Time of the Ascending Node (LTAN) and therefore Local Solar Time (LST).

NanoMagSat aims at improving this spatio-temporal coverage. Over a spatial-LST mesh of cells of size ±6° long., lat. X ±1.5h LST the target is to provide a 24h local time coverage about every 2 months for latitudes below 60° and 5 months for latitudes above 60°. An illustrative comparison on the expected scientific impact of such an improved revisit can be seen in Figure 3.

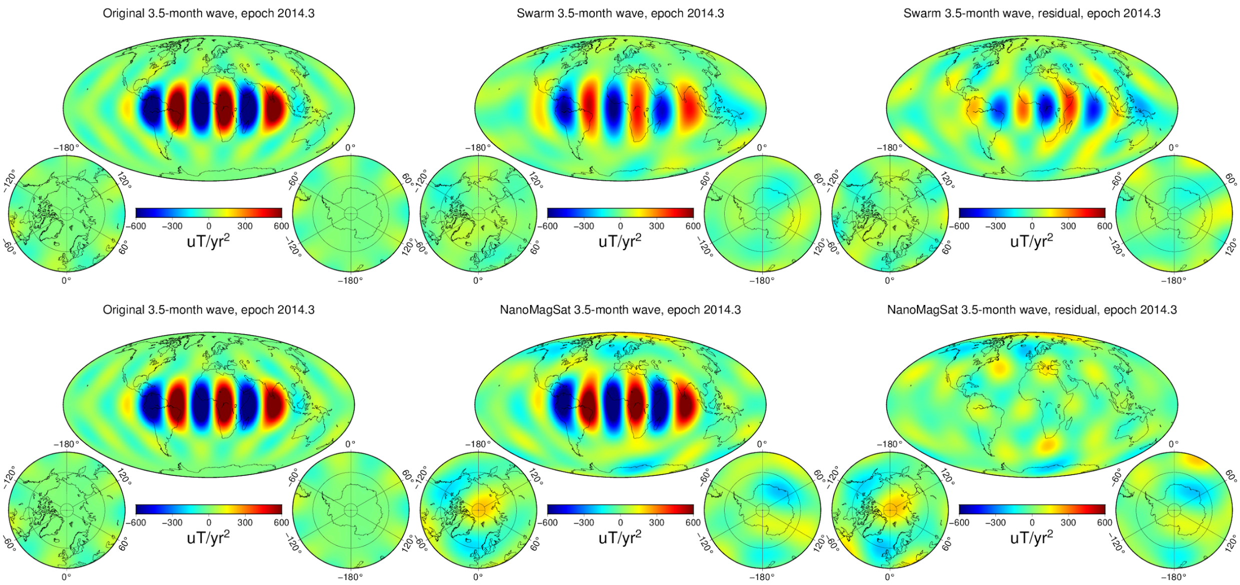

Figure 3.: Original synthetic 3.5-month wave signal from the core field (left), recovered wave signal (middle) and residual signal (right) from the Swarm constellation (top), and the NanoMagSat constellation (bottom). All maps show the second time derivative of the radial component Br of the core field at the middle of the nominal lifetime of NanoMagSat, i.e. epoch 2025.3 (epoch 2014.3 in terms of the synthetic data used) and are plotted up to degree 8 on the core-mantle boundary surface (3480km radius). In contrast with Swarm, NanoMagSat is capable of fully capturing this simulated signal (Model inversions performed by P. Alken, using the software and methodology detailed in [9]).

The NanoMagSat constellation is specifically designed to meet the following requirements:

- For low-medium latitude regions (<60deg), the geographic and LST coverage shall satisfy: Assuming a spatial-LST mesh of cells of size ±6° long., lat. X ±1.5h LST, all these cells shall have been visited within a time of less than 3 months. As a target, all LT below between 60° and 85° should be visited within a time of less than 2 months.
- For high latitude regions (>60deg), the geographic and LST coverage shall satisfy: Assuming a spatial-LST mesh of cells of size (±6° long., lat. X ±1.5h LST), all these cells shall have been visited up to at least 85° latitude (aiming at about 87°, to phase with the Swarm mission if any Swarm satellite is still in operation) within a period of less than 6 months (target of less than 5 months to avoid phasing with seasons).

1.2.2 Ensuring continuity and European leadership

The magnetic field has been near-continuously monitored from space since 1999. Launched in November 2013, the Swarm constellation is currently guaranteed to operate only until 2025 [6]. Beyond Swarm, except NanoMagSat, there are currently no other European planned missions to ensure the continuity of the magnetic field monitoring. China launched two satellites 21/05/2023 (MSS) currently in commissioning phase, only one of which (MSS-1) will provide comparable magnetic data on an 41° inclined orbit [8]. The U.S. have plans to procure magnetic data to support the World Magnetic Model through the Magquest initiative [7].

2 NANOMAGSAT MISSION

2.1 NanoMagSat mission overview

The mission consists of a constellation of three identical 16U nanosatellites with no propulsion, gravity stabilised, and adequate attitude control to ensure stable enough attitude for very accurate attitude restitution. The orbits have been designed to provide the unprecedented spatio-temporal coverage with 2 satellites at 60° inclination offset by 90° in right ascension ascending node (RAAN) complemented by a quasi-polar prograde orbit, optimally with 87.74° inclination (which could be phased with a RAAN offset optimised with respect to the near-polar orbiting Swarm satellites, for optimal complementarity of the two constellations, should at least one of the Swarm satellite still be in operation). A summary can be seen on Figure 4. below.

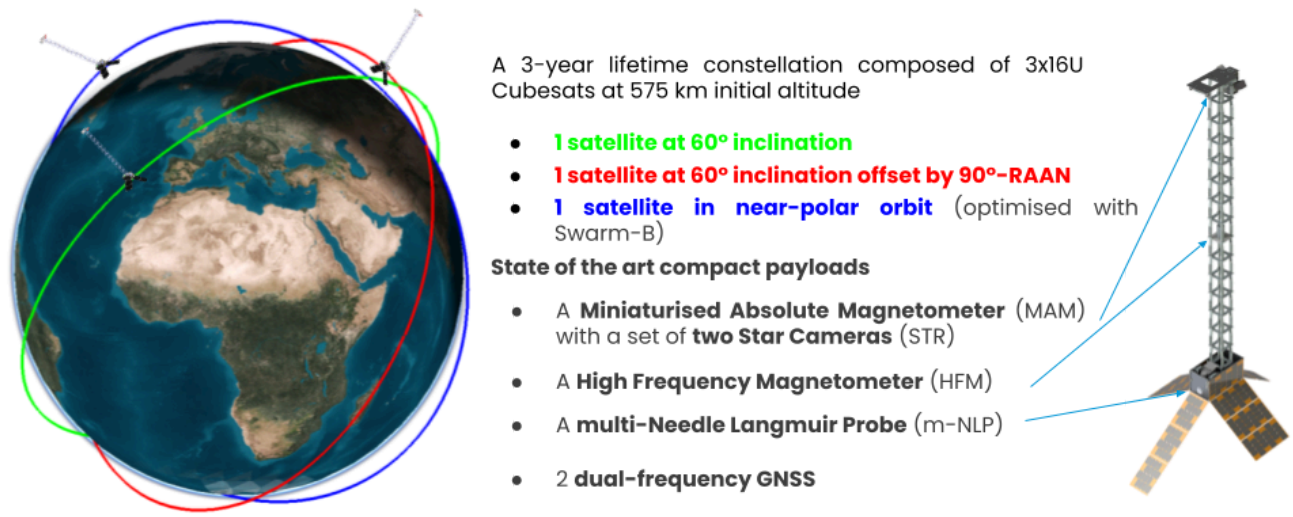

Figure 4. NanoMagSat mission overview

Each satellite will embark an identical payload suite composed of:

- A Miniaturised Absolute Magnetometer (MAM), to provide self-calibrated 1 Hz vector data as well as 2 kHz scalar data, coupled to a pair of star trackers (STR) on the same ultra-stable optical bench, to provide attitude restitution;
- A High Frequency Magnetometer (HFM), to provide 2 kHz vector data;
- A Multi-Needle Langmuir Probes (m-NLP), to provide 2 kHz electron density as well as 1 Hz electron temperature and density;
- Two GNSS receivers: One with two front and rear antennas for GNSS-RO radio occultation, another one GNSS receiver with one top antenna for Precise Orbit Determination (POD) and Total Electron Content (TEC) recovery .

The key challenges of the NanoMagSat mission are the orbits and the magnetic cleanliness. The magnetic cleanliness is required to minimise the noise on the magnetometers (1 nT perturbation limit before compensation, 0.2 nT after compensation), imposing design constraints described in section 2.4.2 Finally, the non-SSO orbits are typically not served by the launch providers and creates an availability/budget risk.

2.2 NanoMagSat mission architecture and consortium

The anticipated associated system architecture with the typical segments leading to the production of data product level 2 is illustrated in Figure 5. below.

The main segment interfaces are:

- Launch-Space segment: through 16U deployers
- Space-Ground segment: through an X-band data downlink and an S-band TT&C link.
- Ground to Payload Data Ground Segment: through a secure link from the ground segment server to the Payload Data Ground Segment server
- Payload Data Ground Segment to the scientific community through an API to access the different data products.

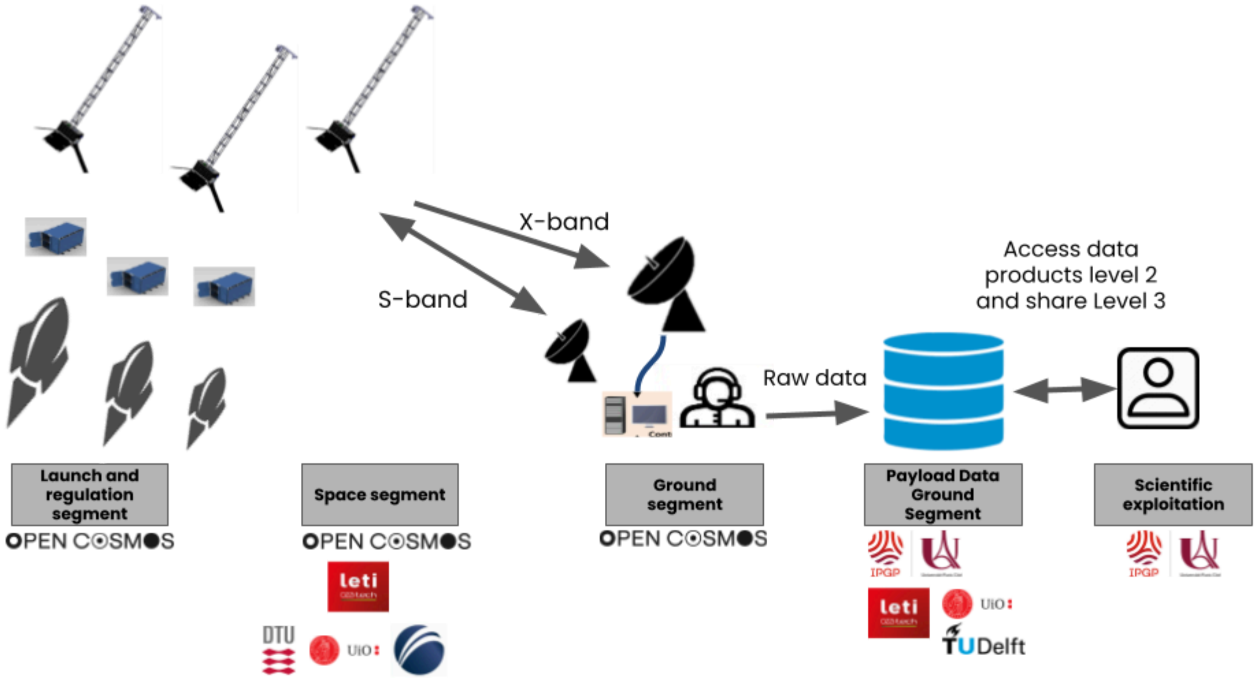

Figure 5. NanoMagSat mission architecture

Open Cosmos: Prime of the consortium, accountable for the delivery of the entire mission, responsible for the space segment (platform and GNSS), launch segment and ground segment

IPGP: Principal investigator of the mission, accountable for the scientific objectives and Payload Data Ground Segment

CEA Leti: Payload manufacturer, accountable for all payloads except the GNSS, responsible for the MAM, HFM, boom, optical bench, m-NLP and star trackers

University of Oslo: manufacturer responsible for the m-NLP and associated scientific objectives

COMET-Ingenieria: manufacturer responsible for the design of the boom and the optical bench

Danish Technical University: Payload manufacturer responsible for the star trackers with deployable baffles

Delft University of Technology: PDGS contributor, responsible for the POD L2 processor

2.3 Spatio-temporal coverage, orbits and launchers

The orbit configuration provides an optimal spatio-temporal coverage such that all points of the grid (±6° long., lat. X ±1.5h LST) are covered within around 38 days. Figure 6. below illustrates the coverage for ±60° latitudes. This is complemented by the polar orbit providing coverage of the polar regions within 140 days compliant with the 6-month target.

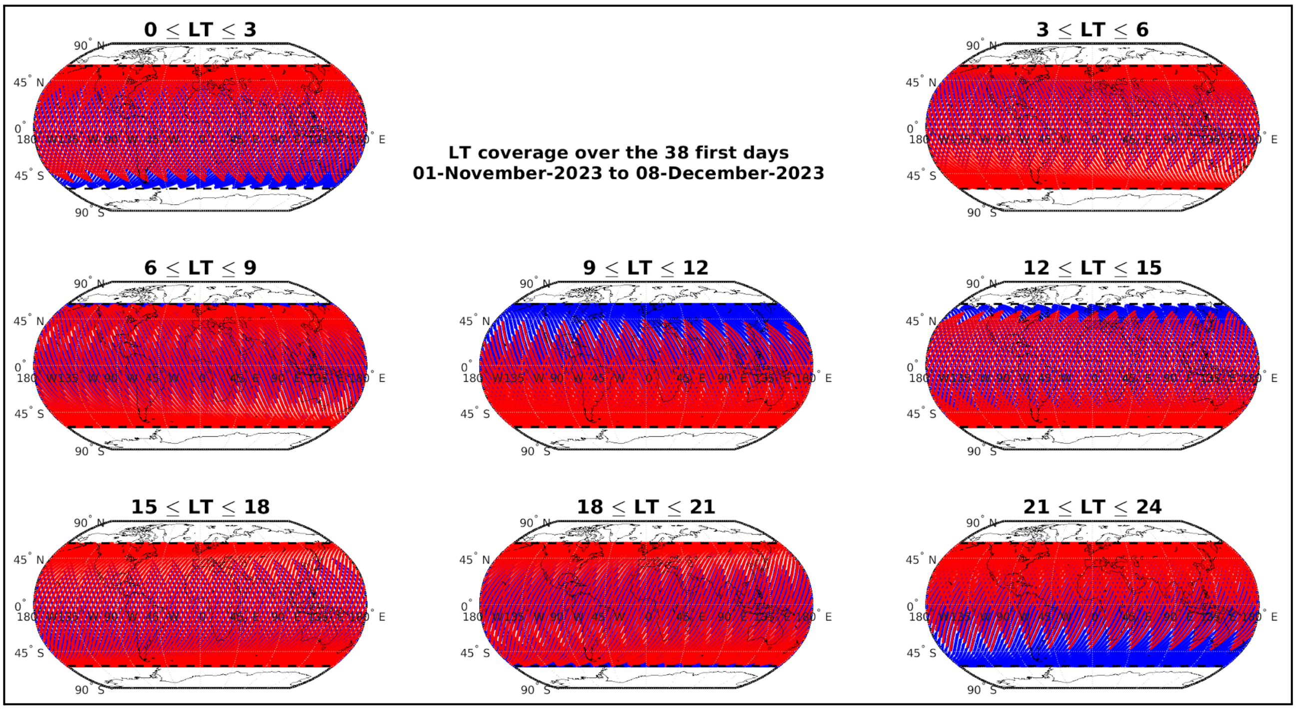

Figure 6.: spatio-temporal coverage for the 60° inclined satellites after the first 38 days with 90° RAAN separation (Note that plotting is such that red dots may hide blue dots). Credits: IPGP

The associated challenge is the availability of launchers for the targeted orbits, specifically the 60°-inclined ones. Anticipated since the consolidation phase, the strategy is to use a mix of launch services including more than a dozen micro-launchers at different stages of development. The current analysis has identified 8 options mixing different offers (micro-launchers, spacetug, rideshare). The main solution is anticipated to rely on 2 launchers: one dedicated launcher with a dispenser to deploy the 60°inclined orbits, and one launcher for the polar orbit (dedicated or rideshare). This trade-off analysis will be updated in the next phase of the project with the target to sign a contract by Preliminary Design Review (PDR).
The 90° phasing in RAAN for the mid-inclined satellite could be impacted by the launch injection errors. This has been assessed as not deviating more than 45° across the mission lifetime when taking the worst consideration: worst inclination and orbit altitude injection errors.

2.4 Magnetic considerations: design impact and magnetic budget

2.4.1 Design impact

The following design guidelines are followed to design a magnetically clean satellite.

Items: the following items have been excluded from the technical baseline, also due to EMI test results:

- Magnetorquers with solid cores
- Reaction Wheels

Additionally, the following items should be avoided in the spacecraft design. If unavoidable, their influence on EMI needs to be analysed. This list is based on lessons learnt from previous activities:

- Fluxgate Magnetometers
- Metals in the vicinity of the MAM sensor
- Soft magnetic materials (special attention must be paid to torquers, motors etc)
- Magnetic materials as a structural material or part of sub-components

Design configuration: the following guidelines shall be followed for the design configuration:

- Avoid using satellite primary structure as ground path, to avoid stray fields caused by this
- Grounding of MLI: Whilst MLI must be grounded, redundant ground connections can cause current loops especially when not at the same temperature as demonstrated on Swarm. They shall therefore be avoided or at least designed in such a way that the maximum currents that could flow through them is sufficiently low that it does not affect the MAM performance
- The PF grounding circuit shall not exhibit any current loop (star grounding configuration must be preferred)
- Current loops shall be avoided (ground loops included), power lines shall be twisted on their forward and return lines back to a single point ground.
- Subsystems are isolated from the frame to avoid return paths through the mechanical structure, which would cause stray fields.
- The battery cells and the solar panels should be magnetically self-compensating
- All magnetic components (Transformers, Chokes, Inductors etc.) should preferably be wound on toroidal cores or pot cores with low stray fields. All coils for magnetic components must be carefully wound with copper wire. No Ni-alloys shall be used.
- The heater elements in the vicinity of magnetic sensors in particular MAM should be of self compensating type and made of non-magnetic materials (RICA-Zoppas supplies such magnetically compensated heaters).

2.4.2 Magnetic budget

The magnetic budget is driven by the requirement of accuracy of 200 pT at the MAM location after compensation. The analysis has been done splitting the contributions in 2 parts:

- The tip of the boom: containing the boom starting from the last 2 elements, the Optical bench, the STR heads and the MAM. The associated contribution has been measured at 20 pT taking ~10% of the 200 pT requirements
- The rest of the satellite with contributions as indicated on Figure 7. as a result of the Risk Retirement Activities in September 2023 for both static (when the power is OFF) and dynamic (power is ON - <u>except for the MAM/HFM DPU which are estimations rather than derived from actual measurements</u>). Note that for the satellite body, the dipole approximation is valid given the length of the boom. A conversion has hence been done between the magnetic field and the equivalent moment: 200 pT at about 2.9 m (boom length) corresponds to approximately 120 mA.m^2. The results show that the current design is compliant with the requirements in both static and dynamic mode. The dynamic mode shows a lesser value to the overall compensations of the different magnetic fields. The static mode shows a worst case as these are due to the material themselves and therefore cannot be compensated and can vary across the lifetime of the satellite due to change in environmental

conditions. For the MAM/HFM DPU, further tests will confirm the estimated value considered conservative due to lessons learnt from Swarm.

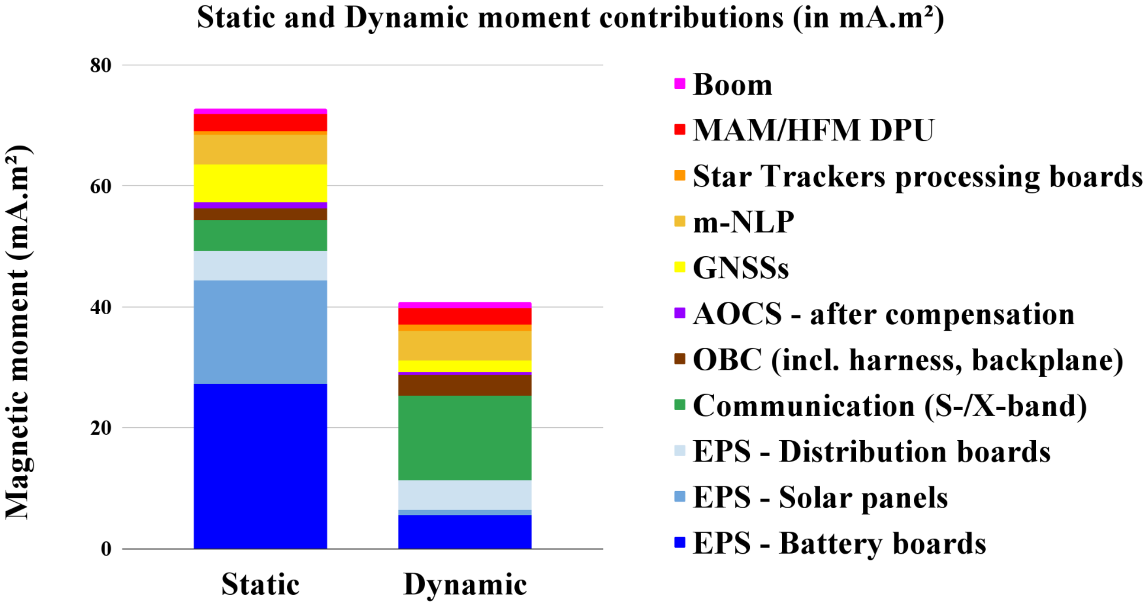

Figure 7. Static and dynamic moment contributions of the satellite based on the test carried out by CEA-Leti and Open Cosmos at CEA-Leti Herveys site in Grenoble. Note that the contribution of the tip of the boom are not included

Given the constraints on external supply, the consortium was able to mitigate the following sources of noise impacting the magnetic budget:

- **EPS - Solar panels:** the wiring on the solar panels is designed to minimise any current loop, tests done during the Risk Retirement Activities have confirmed the associated magnetic stray field to be negligible, with less than 1m.Am^2 of dynamic magnetic moment confirmed by measurement of a representative panel of 8 cells.
- **EPS - Distribution and batteries:** to reduce the current loops, an additional circuit layer was added (see Figure 8.). While the dynamic contribution from current loops has been reduced significantly, the remanent magnetic moment of the battery cells is still large. Nickel tabs have been replaced with tinned copper to reduce this, but further work shall be done to replace the cells stainless steel casing ;

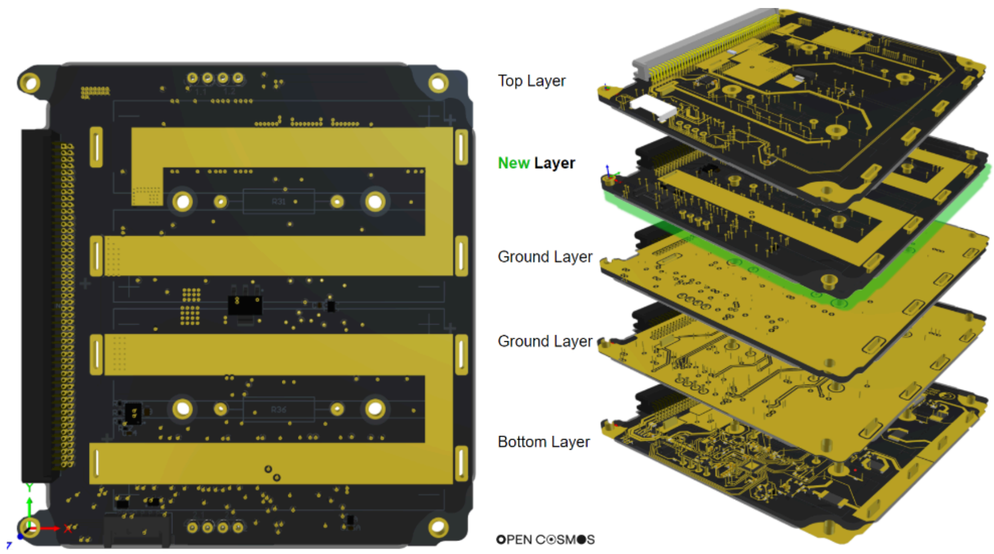

Figure 8.: EPS board design

- **Air coils:** Air coils are used as actuators for the ADCS. During nominal operations, the air coils are expected to produce up to 180 mAm2 each, which is above the acceptable threshold. The currents of the air coils therefore need to be measured and their magnetic field compensated on MAM level. The duty cycle of the air coils will also be updated progressively to avoid sudden changes to the magnetic field.
- **Star trackers:** The two star trackers, flown on other missions alongside magnetometers, have been specifically designed to avoid magnetic materials and reduce current loops.
- **Boom and Optical Bench:** Due to the proximity of the boom and optical bench to the HFM and MAM payloads, specific care has been taken to design them with as low a magnetic signature as possible.

Additionally to the magnetic budget verification, these tests have also provided very valuable insight into the future AIT/AIV sequence and associated procedures. Finally, additional improvements (reduction of the remanent signature of the battery cells casing for instance) have also been identified. Although not mandatory, they are highly recommended as it would further increase the magnetic field products accuracy.

2.5 Space segment - platform

The platform is designed in a 16U CubeSat form factor. The Figure 9. shows the external configuration of the spacecraft, in the deployed configuration, highlighting the key payload, platform, and structural elements.

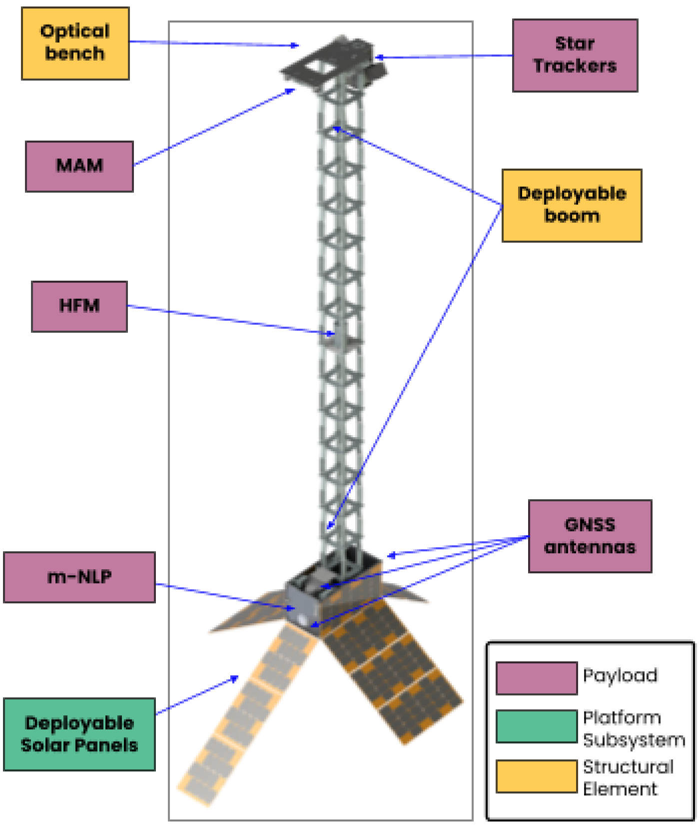

Figure 9. NanoMagSat spacecraft

The mass requirement originates from two key aspects: deployer requirements, and the mass required to satisfy the ballistic coefficient needed to meet the mission lifetime. The total mass of the spacecraft is estimated to be between 28.7 kg and 34.5 kg.

The EPS is sized to fulfil the power requirements at EOL. For over 99% of orbits, EOL average orbital power generation is higher than 48.4 W. Only 2.4 days per year generate less power than is required for nominal operations, with worst-case scenarios being assumed in this analysis.

The ADCS consists of sensors (coarse sun sensors, horizon sensors, and magnetometers) and actuators (aircoils). A gravity gradient control is used alongside the aircoils when the spacecraft is in the deployed configuration.

Due to the limited control capability, the TT&C link budget must close under all conditions. The link budget closes with margins of 7.3dB (Downlink) and 6.9dB (Uplink) respectively.

The HDR Link budget is more challenging due to the lack of attitude stability, therefore, a wide beam antenna has been selected to accommodate for this. With the proposed configuration the downlink budget closes with 4.3dB. Considering that the payloads generate ~5GB per day, the data can be downlinked in four 3-minutes passes.

An overview of the platform in the stacked configuration is shown on Figures 10 and 11. below.

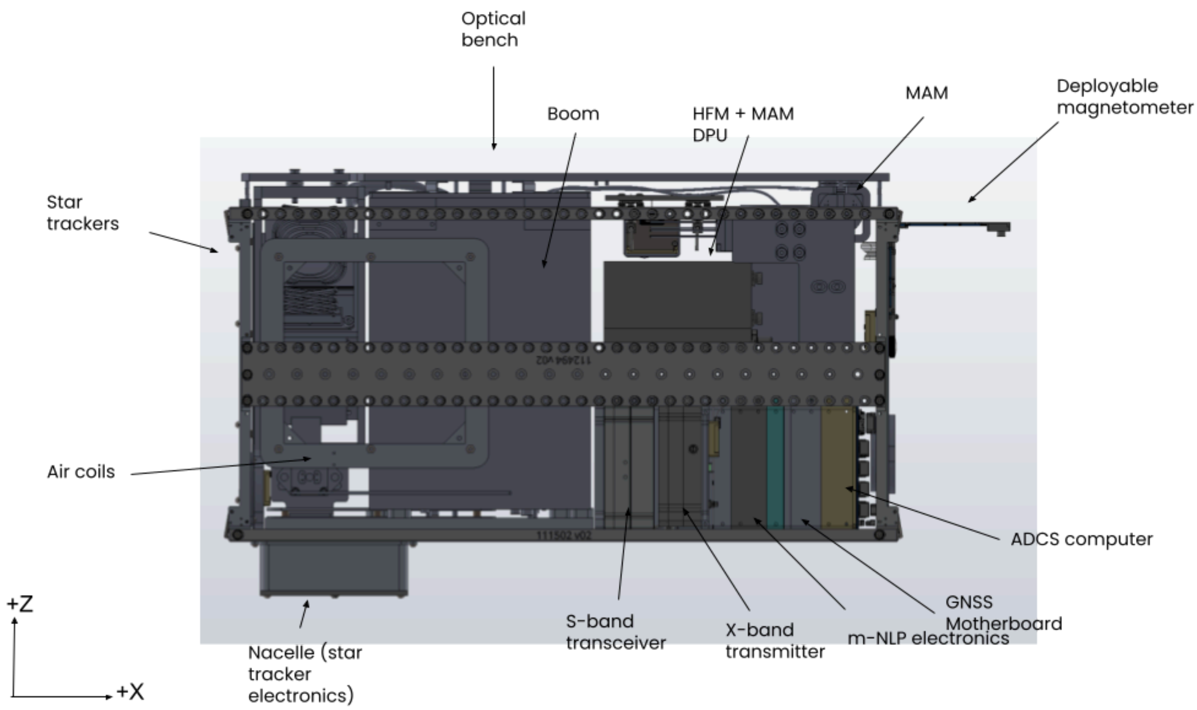

Figure 10.: NanoMagSat satellite platform design +Y view

Approximately 8Us of volume are occupied by the deployable boom and optical bench assembly. Nevertheless, the platform accommodates all the required subsystems and payloads within its available volume.

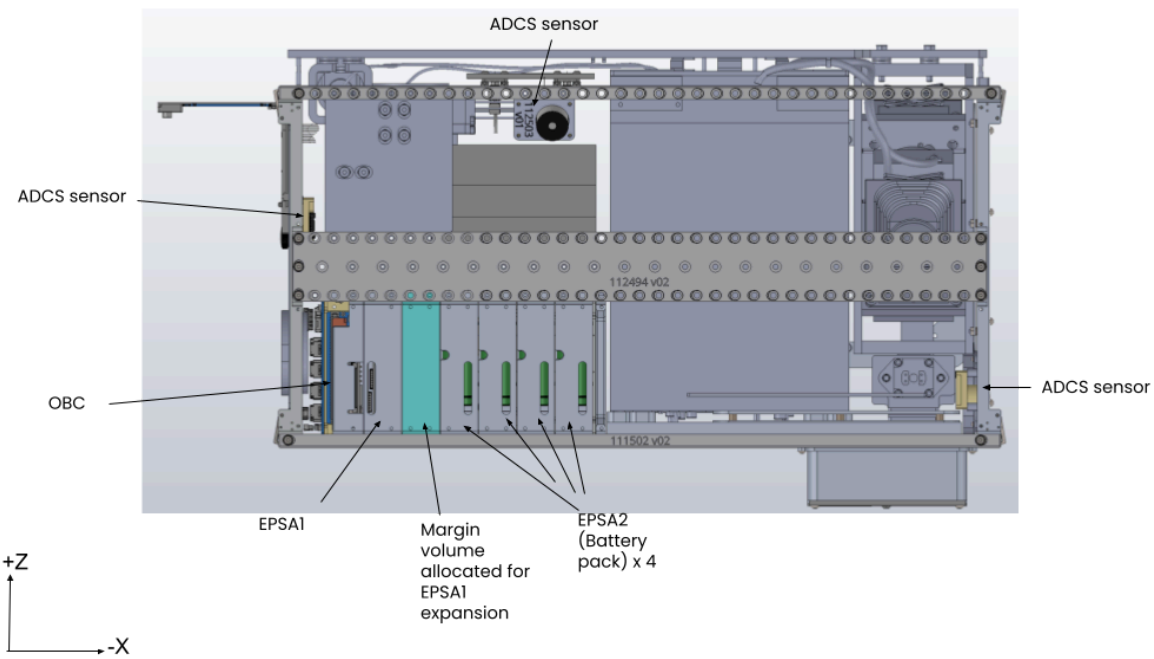

Figure 11.: NanoMagSat satellite platform design -Y view

2.6 Space segment - payload suite

The payload suite is split in 3 blocks, the magnetometer suite, the GNSS receivers and the m-NLP.

The magnetometer suite (See Figure 12.) is composed of a deployable boom hosting the HFM within its deployment mechanism, the MAM hosted on an optical bench at the tip of the boom and collocated with 2 star trackers used for attitude restitution.

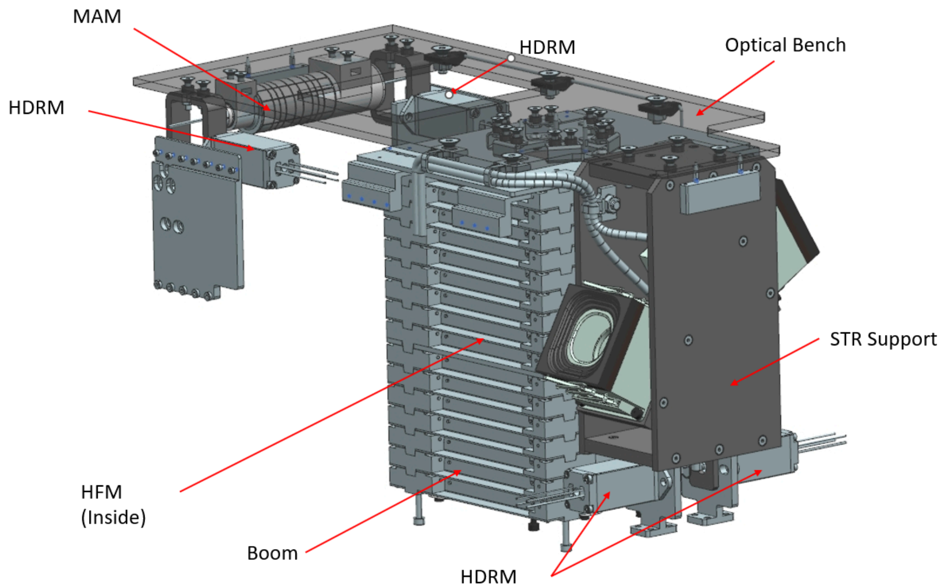

Figure 12.: payload - magnetometer suite

The Boom assembly is composed of the following elements:

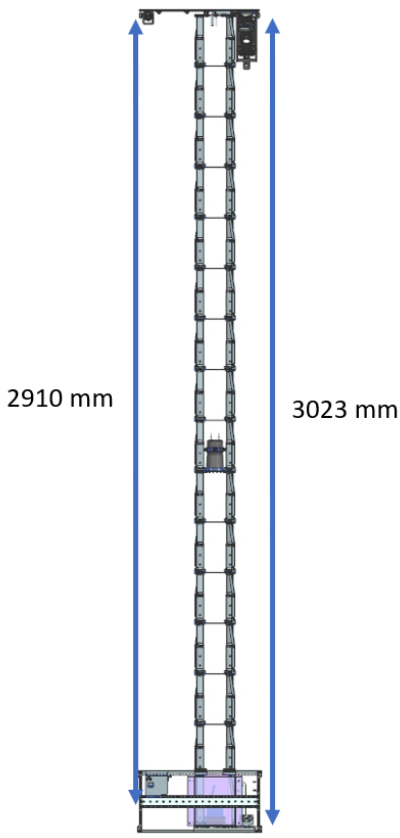

Figure 13.: deployed boom

- Boom structure, composed of 16 deployable modules containing platforms and longerons with axles and springs;
- Speed Control Device, installed at the bottom of the boom, which avoids deployment shocks with passive inertia resistance;
- Optical Bench, composed of a flat part for the MAM accommodation and supporting the Star Trackers, with high thermoelastic stability;
- HDRMs composed of 4 pin-pullers devices and static pins;
- Stowing Harness boxes on the sides and inside the boom.

The main functionality of the boom is to deploy (See figure 13.) the optical bench with associated harnesses and keep the MAM and the HFM at a fixed distance of the platform. Once the satellite will be in orbit, the deployment process consists in following steps:

- Release the HDRM system located in the optical bench;
- Release the “brake” system of the Speed Control Device;
- The deployment will start by the effect of springs;
- When deployment is performed a measurement system will declare deployment successful;
- The deployment is secured geometrically: the final position of the boom longerons and the springs force lock the final position.

There are 2 triple-frequency GNSS receivers with 3 antennas. One receiver with 2 antennas located at the front and back of the platform used for 1Hz (up to 100Hz for scintillation studies) radio-occulation acquisition of pseudoranges and phases of L1, L2 and L5 GPS frequency signals (and equivalent Galileo signals). A separate triple-frequency GNSS receiver with the antenna on the zenith-facing satellite face will be used for 1 Hz TEC measurements, Precise Orbit Determination, real-time operational position, velocity, and timing (PVT) information.

A multi-Needle Langmuir Probe is deployed (see Figure 14.) at the front of the satellite. It carries out measurements of the local plasma density at the same sampling frequency as the HFM magnetometers (2 kHz), thereby allowing detailed investigations of small-scale ionospheric plasma structures as well as cross comparisons with magnetic vector data. It will also have the capability to provide 1 Hz electron temperature and density.

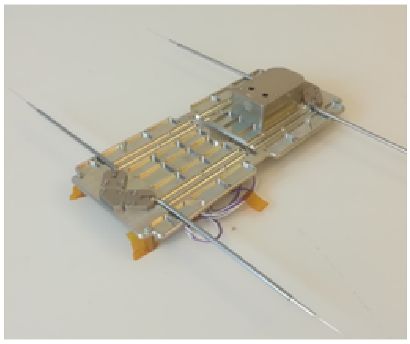

Figure 14.: m-NLP, credits UiO

2.7 Ground segment - satellite operation and payload data ground segment

The ground segment is composed of 3 main elements as illustrated in Figure 15.: the ground stations to operate and download the data, the operation centre and the payload data ground segment as illustrated below. Due to the lack of pointing ability (see section 2.4.1), the number of X-band ground stations has been designed at 4 for the mid-latitude orbits and 3 for the polar orbits to increase the number of opportunities of closing the link budget. The constellation is expected to have one nominal mode with all payload activities. This will generate around 15 GB of data per day for the 3 satellites of the NanoMagSat constellation. The L0 data will be stored by Open Cosmos and processed from L0 to L1 and L2 by IPGP to make the data available to the scientific community.

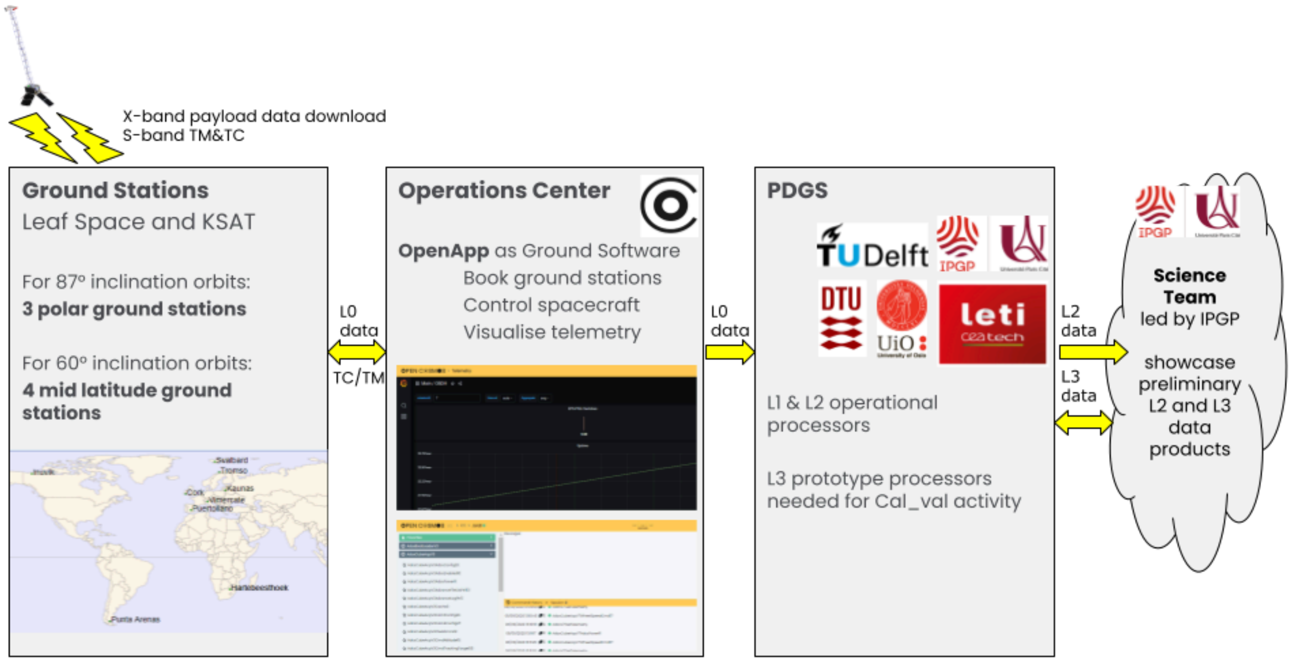

Figure 15.: NanoMagSat ground segment architecture

3 NANOMAGSAT PROGRAMMATICS

3.1 Scout for small satellite science missions

The NanoMagSat mission is to be implemented under the Scout framework, introduced by ESA as part of the Future Earth Observation envelope programme to advance the Earth Science agenda and/or demonstrate new Earth Observation techniques. Scout missions distinguish themselves from Earth Explorers, which they complement, by a more pro-active role of industry and academia ("co-engineering"), a low-cost approach (industrial cost lower than ~35M€) and a rapid development cycle (3 years from start of implementation to flight acceptance/launch).

It is mandatory that Scout missions are based on an observing technique and instrumentation with sufficient scientific and technological maturity from the onset, to secure a quantifiable science return in such a rapid development cycle.

Scout missions shall have a science focus with some innovation features (e.g. sensing technique, miniaturisation, distribution of functions on various satellites), with the aim of providing incremental science either addressing niche applications on its own right or as complement to other missions (e.g. Earth Explorers, Copernicus Sentinels, Meteorology missions or Earth Watch missions). The mission concepts retained may have some value as pre-commercial or technological or educational or outreach vehicles, though such value cannot be the dominant factor in the mission concept selection.

More detailed information about the Scout programme can be found in [11] and [12].

3.2 NanoMagSat status

The idea of the NanoMagSat concept originated just after the launch of Swarm in 2013 and was matured by IPGP and CEA-Leti with CNES support. It has matured through the different phases as illustrated on Figure 16. The Scout call in 2019 provided the opportunity to join with Open Cosmos to present a small satellite science mission. Following a 9 months consolidation study the mission was assessed as viable from the scientific perspective but was not selected for implementation due to technical and budget risks. These risks were addressed during an 18 months Risk Retirement Activities (see [10] for more details).

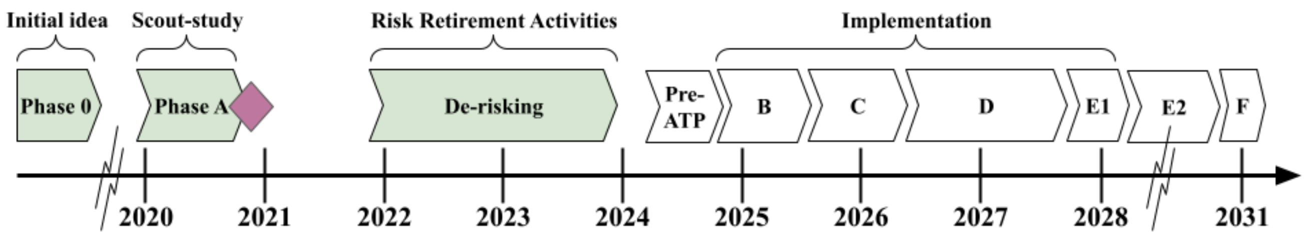

Figure 16.: NanoMagSat schedule overview

In February 2024, the Programme Board for Earth Observation from ESA gave the greenlight to Open Cosmos for the NanoMagSat implementation as part of the Scout framework as described in section 4. The Kick-Off of the implementation activity is expected in Q4 2024 with the possibility to initiate time-critical activities under pre-authorisation to proceed in the meantime.
The key decision points aligned with the typical reviews are:

- PDR end of 2025- beginning of 2026, including the launcher selection;
- CDR mid 2026: finalise design on the basis of the results of the test campaign of an Engineering Qualification Model;
- First Model Acceptance Review: mid 2027
- Launch window of the first satellite end 2027
- Mission Commissioning Review: Q2 2028

References

[1] Hulot, G. et al. (2010), The Magnetic Field of Planet Earth, Space Science Reviews, 152: 159–222, doi:10.1007/s11214-010-9644-0

[2] ESA SP-1279(6) – Swarm – The Earth's Magnetic Field and Environment Explorers, ESA SP-1279(6), April 2014

[3] Courtillot, V. and J.L. Le Mouël (2007), The study of Earth's Magnetism (1269-1950): A foundation by Peregrinus and subsequent development of geomagnetism and paleomagnetism, Rev. Geophys., 45, RG3008, doi:10.1029/2006RG000198.

[4] Hulot, G. et al., in Gerald Schubert (editor-in-chief) Treatise on Geophysics, 2nd edition, Vol 5. Oxford: Elsevier, 33-78, doi:10.1016/B978-0-444-53802-4.00096-8, 2015

[5] The -Virtual - 10th Swarm Data Quality Workshop, ESA-EOPG-EOEP-RP-617, 17/01/2022

[7] ESA website https://earth.esa.int/eogateway/news/big-ambitions-as-swarm-mission-soars-on

[6] Magquest website: https://www.magquest.com/about-the-challenge/

[8] Zhang, K. (2023), A novel geomagnetic satellite constellation: Science and applications. Earth Planet. Phys., *7*(1), 4–21. doi:10.26464/epp2023019

[9] Alken, P. et al. (2020), Co-estimation of geomagnetic field and in-orbit fluxgate magnetometer calibration parameters, Earth, Planets and Space, 72:49, doi:10.1186/s40623-020-01163-9.

[10] Marchese, V. et al (2024), Risk Retirement Activity for the NanoMagSat Mission Concept, 4S Symposium

[11] Pastena, M. et al. (2024), Scout missions: blend New Space with ESA EO science mission expertise, 4S Symposium. 15_PASTENA-Massimiliano_Poster

[12] Pastena, M. et al. Scouts Missions: ESA New Program for Science Mission Based on Small Satellite, 37th Annual Small Satellite Conference, 2023