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# Magnetic cleanliness on NanoMagSat, a CubeSats' constellation science mission

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**Abstract**— NanoMagSat is a constellation of three identical 16U CubeSats, which aims to complete, at a much lower cost, ESA's Swarm constellation of satellites that currently monitor the Earth's magnetic field and ionospheric environment. To produce magnetic and ionospheric environment data, the CubeSats are equipped with two magnetometers, which are very sensitive to magnetic fields. Therefore, to guarantee the accomplishment of the mission and avoid unintended magnetic fields, both external and internal to the spacecraft, degrade the performance of the magnetometers, it is essential to implement a proper magnetic cleanliness control plan. This work explains the DC magnetic cleanliness control plan at system and subsystem level, identifies the magnetic field sources, describes the design guidelines followed on NanoMagSat as well as presents magnetic test results, comparing measurements with analytical and heritage estimations.



Fig. 1. NanoMagSat overview with the boom deployed

## I. INTRODUCTION

### A. NanoMagSat: a three CubeSats' science mission

NanoMagSat mission concept aims to deploy and operate a new constellation of three identical 16U CubeSats (about 30kg mass), carrying innovative miniaturized payloads, to complement and ensure continuity of the ongoing ESA Swarm mission at a much lower cost, also providing additional means of investigating the ionospheric environment.

This project is currently underway for an 18-months Risk Retirement Activities (RRA) phase that started in January 2022 and is funded by ESA in the context of its Scout programme. The contract is led by Open Cosmos (UK), with IPGP (FR) as mission Principal Investigator (PI), and CEA-Leti (FR), COMET-Ingeniería (ES) and Prosix Engineering (ES) as main subcontractors.

NanoMagSat aims at forming the basis of a permanent collaborative constellation of nanosatellites for low-cost long-term monitoring of the geomagnetic field and ionospheric environment from space [1]. The duration of the routine operations shall be at least 3 years to sense signals with periods of up to one year [2].

Each CubeSat will embark a Miniaturised Absolute Magnetometer (MAM) combined with star trackers on an optical bench and a High Frequency Magnetometer (HFM), which are the main mission payloads. They will be integrated in a (approximately) 3-meters non-magnetic boom as shown in Fig. 1 to minimize the external magnetic disturbances.

The main characteristics of the MAM sensor directly derive from the Swarm's ASM-Vs, characterized by a scalar measurement accuracy lower than 50 pT ( $1\sigma$ ) and a resolution lower than  $1 \text{ pT}/\sqrt{\text{Hz}}$ , while its vector measurement resolution is less than  $1 \text{ nT}/\sqrt{\text{Hz}}$ .

The HFM is a vector magnetometer able to deliver vector measurements with an extremely high resolution (less than  $1 \text{ pT}/\sqrt{\text{Hz}}$ ) over a large bandwidth (0-800 Hz).

In addition, to provide ionospheric data, the spacecraft will be equipped with a multi-needle Langmuir probe (M-NLP) and two dual frequency GNSS receivers for recovery of Total Electron Content (TEC), electron temperature and ionospheric radio-occultation data.

In order to embark the mentioned payloads and realise the mission objectives, the CubeSat platform is equipped with:

- A deployable boom, required to keep the magnetometers at a certain distance from the platform
- An optical bench, located at the tip of the boom, where the MAM magnetometer and the star trackers are located.
- An On Board Computer (OBC).
- Electrical Power System (EPS), including power conditioning and distribution boards, batteries and solar panels.
- Structure, composed of primary and secondary structure.

- S-Band communication, for uplink and downlink of Telemetry Telecommand and Command (TT&C).
- X-Band communication, to download payload data.
- AOCS, including a set of sensors and actuators for attitude control.
- Data Processing Units (DPU) of MAM and HFM magnetometers.

Each unit and subsystem is a potential magnetic source either due to the presence of soft/hard magnetic materials or internal current loops. Therefore, a magnetic cleanliness control plan is needed for the proper fulfilment of this mission.

As a result, the aim of the following sections is to share a typical methodology followed during a magnetic cleanliness programme for a space mission, in this case for NanoMagSat during the Risk Retirement Activities (RRA) .

It should be emphasised that when it comes to CubeSats, there are many limitations and differences compared to the development of classic medium/large-sized spacecrafts, especially in terms of magnetic cleanliness.

CubeSats were born to reduce cost and time to realize a space mission, provided that a different level of risk and reliability compared to conventional spacecrafts is taken into account. In fact, the idea behind NanoMagSat is to initiate permanent, low-cost monitoring of the Earth's magnetic field and ionospheric environment.

Nevertheless, one must also consider that CubeSat designs are modular. This means that subsystems are available off-the-shelf and can be used according to mission requirements. This is why CubeSat are ready for flight very quickly, typically within a couple of years. However, investigations on Commercial Off-The-Shelf (COTS) components indicate that they are often not designed considering magnetic cleanliness.

In the particular case of NanoMagSat, it is therefore much more complicated to achieve the required performance in terms of magnetic cleanliness, given the reduced cost and time and also given the reduced possibility of having customised subsystems for the mission.

## B. Magnetic Cleanliness Principles

Magnetic cleanliness is a serious electromagnetic compatibility issue present in most science space missions, encompassing DC to low-frequency magnetic sources. Its main objective is to ensure that the resulting magnetic field at the location of any susceptible payload is under control and does not affect its performance [1]. The magnetic cleanliness is usually assessed at subsystem level as well as at system level [3].

Typical magnetic field requirements at the sensor location are in the order of 0.1 nT to 1 nT, being magnetometers the main sensitive payload. Missions such as Swarm, Cluster, Ulysses, Giotto and LISA Pathfinder defined this threshold as a system-level requirement [4].

For this purpose, the magnetic cleanliness program specifies a maximum magnetic field value that shall not be exceeded at the susceptible payload location. Examples of these payloads are scientific magnetometers, inertial sensors

involving floating proof masses, ultra-stable oscillators, atomic clocks [5]. The specified maximum magnetic field value shall consider the possible presence of magnetic materials unavoidable in the equipment design, the electric current consumption of the equipment and the distance of the equipment from the sensitive element. As a result, an effective way and typical approach to minimize the magnetic disturbances from the spacecraft is to place the sensitive instruments or sensors at the end of a long non-magnetic boom, as the magnetic field of a dipole decreases with the third power of the distance in the far field [5].

To fulfil the magnetic field threshold requirement, it is necessary to simulate the far-field spurious magnetic field generated by the spacecraft in terms of remanent and induced magnetic dipole moments and the current generated by internal circuitry, assuming they represent the units and subsystems of the satellite. Input data can be obtained from tests, analysis or estimated by heritage from previous missions or similar equipment [4].

The derived magnetic dipole moment  $\mathbf{m}$  of individual units is used to calculate the magnetic field  $\mathbf{B}$  at location  $\mathbf{r}$  via:

$$B(r) = \frac{\mu_0}{4\pi} \left[ \frac{3(r-r')((r-r') \cdot m)}{|r-r'|^5} - \frac{m}{|r-r'|^3} \right] \quad (1)$$

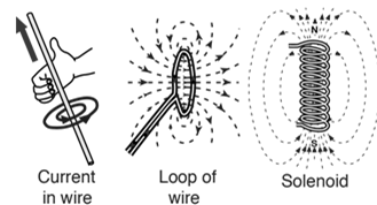
where  $\mathbf{r}'$  is the position of the magnetic moments  $\mathbf{m}$  in the spacecraft coordinate system and  $\mu_0$  is the magnetic permeability of free space [6]. Then, the contribution of all units can be summed-up vectorially to assess the fulfilment of the magnetic field threshold requirement.

This requirement verification starts on an early stage with heritage and analytical data. Later, to increase the reliability of the prediction, the simulation is updated as test data from representative qualification unit models becomes available [4].

## C. Magnetic Field Sources

There are three different classes of DC magnetic field sources [4]:

- Magnetic dipoles
- Electric currents, and
- External magnetic fields (e.g. Earth magnetic field)



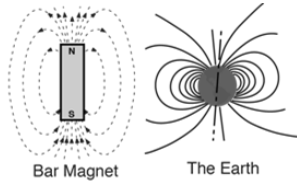


Fig. 2. DC Magnetic field sources [8]

The magnetic dipoles can be further distinguished into induced and remanent dipoles. Remanent magnetic properties are assumed to be hard magnetic, i.e. immune to external magnetic fields with levels below 300  $\mu\text{T}$ , although soft magnetic materials also have a remanent contribution. Moreover, they are present in absence of any external magnetic field. On the other hand, the induced part consists of a linear response of internal magnetization [4] due to the presence of an external magnetic field (e.g. the Earth magnetic field) [7] and it is commonly associated to the behavior of soft magnetic materials, i.e. materials which are easily magnetized and demagnetized.

Electric current in a circular loop also creates a magnetic field. The form of the magnetic field from a current element in the Biot-Savart law can be simplified as an axial magnetic field as follows [8],

$$B_z = \frac{\mu_0}{4\pi} \frac{R}{(z^2 + R^2)^{3/2}} \quad (2)$$

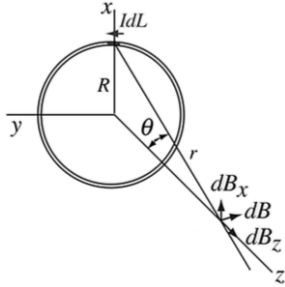


Fig. 3. Biot-Savart law – magnetic field on axis of current loop [8]

where  $\mathbf{I}$  is the electric current in Amperes,  $\mathbf{z}$  is the distance (in meters) along the centreline of the loop,  $\mathbf{R}$  is the loop radius (in meters) and  $\mu_0$  is the magnetic permeability of free space. As it can be deduced, the maximum field is located at the centre of the loop, when  $z$  is zero.

Hence, the traditional major magnetics offenders in a space mission are [9]:

- Hard perm fields: magnets, motors, latch valves, thruster valves, tanks
- Soft perm fields: Mu metal shielding, welding, Kovar cell interconnects
- Stray fields: solar panels, current loops (and power cables), batteries and RF components.

Regarding AC magnetic fields, these are mainly due to the rotation of solar panels or motors, due to currents variations (e.g. during battery charging and/or discharging cycles or during the reaction wheel's acceleration or deceleration phases) or due to stray fields from electronic components (e.g. star trackers' stray fields at the image refreshing frequency).

Depending on the mission needs, AC magnetic field system-level requirements are defined from extremely low frequencies (e.g. 100 nHz) up to several kHz. However, the aim of this work is to focus on DC magnetic cleanliness thus the AC topic is only briefly mentioned here for the sake of completeness.

## II. METHODOLOGY

Based on the magnetic control guidelines suggested on the ECSS standard [5][10] and also based on similar successful magnetic sensitive missions performed in the past such as Swarm, Oersted, Dawn and THEMIS, the following magnetic cleanliness control plan has been developed for NanoMagSat:

### A. System-level magnetic requirements definition

The required magnetic control is governed by the sensitivities of the magnetometer sensors whereby the magnetic field must be reduced to a level where science is not affected [3].

The system-level requirements for NanoMagSat are:

- The combined effect of all perturbation sources between DC and 1 Hz shall be  $< 1 \text{ nT}$  before compensation and  $< 0.2 \text{ nT}$  after compensation at MAM location.
- Noise level between 1 mHz and 2.8 kHz shall not exceed  $1 \text{ pT}/\sqrt{\text{Hz}}$ .

### B. Magnetic moment budget definition

As previously mentioned, the magnetic cleanliness is assessed at system level as well as at subsystem level [3]. Therefore, based on the system-level magnetic requirements (i.e. 1-0.2 nT) and the distance of the magnetometers from the rest of the satellite, the maximum magnetic dipole moment budget for all the units and subsystems can be deduced from equation (1).

Hence, the maximum magnetic dipole moment budget for NanoMagSat:

- Shall not exceed 117  $\text{mAm}^2$

This value is defined assuming all magnetic dipole moments are located 2.86 meters distance from the MAM, which is located at the tip of the boom. Then, it is used to evaluate if all the units and subsystems will respect the threshold. It is important to remark that this maximum magnetic moment has been an input for the definition of the boom length, considering the feasibility not to exceed that value.

This budget is then used to evaluate if all the units and subsystems will respect the threshold. As a first estimation, it can be considered a worst-case scenario in which all magnetic dipole moments are facing the MAM, i.e. without any self-compensation or random orientation.

Once the magnetic perturbations generated by the various subsystems and the satellite itself have been characterized on ground, corresponding corrections considering both the Earth

magnetic field intensity and the satellite attitude can be applied to the data delivered by the magnetometer, to increase the measurements accuracy. This is achieved thanks to the so-called level 1b correction algorithms.

### C. Spacecraft design guidelines

To minimize magnetic fields on NanoMagSat magnetometers, the following design guidelines are followed:

- *Distance control*: increase the distance between source and the sensitive payload (e.g. using a non-magnetic boom).
- *Material control*: minimize the number of magnetic materials wherever feasible, in particular hard magnetic materials as they are expected to remain unaffected in the presence of ambient fields of 0.05 mT to 0.5 mT. Eliminate soft magnetic materials such as invar, Kovar, nickel and their alloys, as their magnetic signature depends on several parameters including their history, making any compensation or correction very challenging.
- *Common self-compensation*: this means that, when more than one same unit is used, they should be paired in such a way that their residual fields approximately cancel each other.
- *Current loop control*: reduce the area of current loops and lower the electric current as much as possible (e.g. back-wiring each solar panel, minimizing current loops in printed circuit boards, etc.).
- *Demagnetisation (deperm)*: reduce the remanent magnetic dipole moment of soft magnetic materials by exposing the hardware to a peak alternating magnetic field (usually 5 mT) and decreasing this field exponentially in each of the three orthogonal axes.

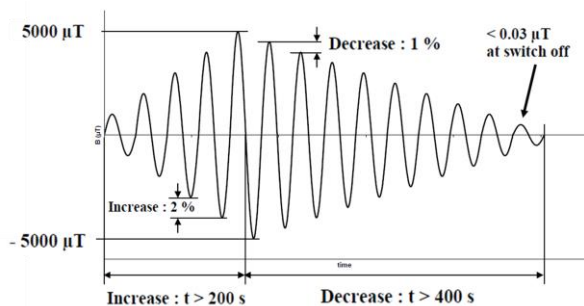


Fig. 4. Deperm waveform [10]

### D. Verification plan

The verification plan consists in a combination of analyses and testing activities executed as early as possible (in the latter case as soon as a representative model of the unit is available) as a means to early predict if the design will fulfil the system-level magnetic requirements.

It is an iterative process. At the start of a project, the magnetic dipole moment of each unit or subsystem and,

therefore, the magnetic field at the magnetometer location is predicted mainly based on analysis and heritage from earlier missions or hardware prototypes.

Hereunder the DC magnetic moment budget at the start of the RRA of the main subsystems is shown, derived from the consolidation study phase performed in the past:

TABLE I. INITIAL MAGNETIC MOMENT BUDGET

Unit or subsystem	Initial magnetic moment allocation (mAm <sup>2</sup> )	Method
EPS (batteries)	30	heritage
EPS (power conditioning and distribution)	20	heritage
AOCS	20	heritage
Solar panels	50	heritage (very conservative approach without back-wiring)
MAM & HFM DPUs	15	heritage + margin
Star tracker and optical bench	1	Swarm heritage
M-NLP	5	Brik-II EM measurement + margin for the electron emitter
GNSS Antennas	1	guess
Comms TT&C	5	guess
Structure + OBC	10	measured during the previous consolidation phase

This table provides some hints about in which hardware emphasis should be placed (e.g. batteries, power distribution boards and solar panels).

Later on, as measurement data becomes available, the reliability of the prediction will be progressively improved. The spacecraft's magnetic fields at sensor locations will then be calculated by summing all measured subsystems' extrapolated magnitudes of the dipolar moment. The extrapolation will be based on the relative orientation of the hardware and the location of the centre of mass of the hardware in terms of spacecraft coordinates. From these measurements the calculation of the perturbation fields at magnetometers location will be derived, considering the fall-off laws with the distance of the various sources (with the inverse of the third power of the distance for a dipole) [3].

### E. Environmental control

The objective of the environmental control is to avoid remagnetisation due to handling, testing and/or exposing the units to high environmental fields. Consequently, special precautions are required such as using magnetically clean tools, keeping distance from magnetic materials, avoiding storage on steel tables and utilising low-magnetic transport container, trolleys and ground support equipment.

As a reference, subsystems/spacecraft should not be exposed to a uniform external magnetic field exceeding 300  $\mu$ T in order to minimize permanent magnetization [3].

### III. TEST RESULTS

In this section it is presented the measurement data available so far from NanoMagSat and the redesign activities carried out on those units or subsystems where a high magnetic contribution was found.

The DC and AC magnetic characterization is being executed by CEA-Leti at their magnetic facilities in Herbeys (France). In order to obtain the DC magnetic moment of the equipment, the following procedure is being followed:

- The equipment to be characterized is set on a non-magnetic goniometer at roughly one meter east of a first scalar reference magnetometer.
- A second reference magnetometer is set approximately two meters away west from the first one so that its measurement can be considered as not affected by the magnetic signature of the equipment to be characterized.
- The relative positions of the magnetometers and of the centre of the equipment are measured.
- Differential scalar measurements are then performed for different orientations of the equipment with reference to the ambient magnetic field and the scalar reference sensors (approximately 30 positions).
- The measurements are then post-processed to determine the remanent and induced characteristics of the equipment.
- This magnetic moment determination has to be performed with equipment successively “OFF” and “ON”.

Regarding the measurement of the AC magnetic signature (from ~1Hz to 1 kHz), it is executed as follows:

- The equipment to be characterized is set in the close vicinity of a 3-axis fluxgate sensor (with a bandwidth > 2 kHz).
- The fluxgate measurements are recorded at different locations with reference to the equipment and for different operation modes of the equipment.
- These measurements are further post-processed and the AC signature of the equipment is then analyzed.

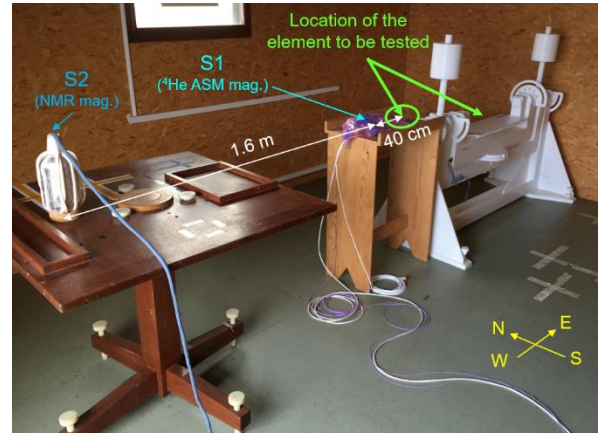


Fig. 5. Herbeys magnetic test facility

Hereunder it is shown the induced and remanent DC magnetic moment measured for each unit and subsystem:

TABLE II. MAGNETIC MOMENT BUDGET COMPARISON

Unit or subsystem	Initial magnetic moment allocation (mAm <sup>2</sup> )	Measured remanent magnetic moment (mAm <sup>2</sup> )	Measured induced magnetic moment (mAm <sup>2</sup> )
EPS (batteries)	30	27.2	5.6
EPS (batteries and distribution boards)	20	*	*
AOCS	20	*	*
Solar panels	50	17.1	*
MAM & HFM DPUs	15	*	*
Star tracker and optical bench	1	*	*
M-NLP	5	*	*
GNSS Antennas	1	12	18.6
Comms TT&C	5	1.2	*
Structure + OBC	10	1.5	*

\* Available on Q2 2023

It shall be noted that at the time this work is being written, there are still many equipment that have not been subjected to any test, thus most of the measurements are still not available. It is expected that all platform’s hardware will be tested by Q2 2023. Nevertheless, a clear conclusion can be derived with those subsystems already tested:

- the measurement of the magnetic field emissions of representative models is a must for a proper magnetic cleanliness control plan due to its unpredictable nature. Although heritage and analytical data can be very useful during early design phases as they provide hints about requirements’ feasibility, the presence of unforeseen soft and hard magnetic materials or the difference of current loops design between heritage and representative models may significantly mislead the real magnetic dipole moment.

Additionally, for the reader’s interest, it is highlighted below examples of re-design activities developed on different units and components that where necessary to reduce their magnetic dipole moment:



- *GNSS Antennas:* based on heritage data, the contribution of the antenna to the overall magnetic moment budget was initially considered negligible. However, during the magnetic measurement it was discovered that it contained magnetic material due to the high induced and remanent magnetic field measured, being the vector moment  $6.2 \text{ mAm}^2$  and  $4 \text{ mAm}^2$  after deperm, respectively. Considering that the satellite will integrate three GNSS antennas, it is a remarkable value. The antenna was then disassembled and magnetically characterised at component level. It was discovered that the cover, which is intended for the protection of the internal components, contained ferromagnetic materials. Currently, it is being investigated the replacement of such cover with a non-magnetic inox one, ensuring the integrity and functionality of the GNSS antenna is not degraded.
- *EPS circuit boards:* current loops were redesigned and minimized by reducing the area between forward and return lines, hence reducing the magnetic fields, also known as back-wiring technique. The expected magnetic moment is one order of magnitude lower than initially estimated.
- *Battery tabs:* initially, the battery cells were attached to the EPS circuit board via nickel tabs due to its high conductivity. However, nickel is a ferromagnetic material with high magnetic permeability. Therefore, the magnetic dipole moment measured of each tab was  $0.3 \text{ mAm}^2$  which, considering that thirty-two tabs will be needed, is a considerably high value. As a result, these tabs were replaced with copper tabs, which is non-magnetic and has a similar electrical conductivity.
- *Battery cells:* several COTS battery cells were individually tested. The magnetic dipole moment varied between  $0.24$  and  $3.23 \text{ mAm}^2$  after deperm. There is a considerable difference among them because of the internal mix which makes it impractical to remain always the same. Moreover, the battery cells remagnetise after several charging and discharging cycles which makes the magnetization behaviour even more unpredictable. It is also suspected that the cell's case contains ferromagnetic material, thus it is currently on-going an investigation to find a battery with a better magnetic behaviour.

#### IV. CONCLUSIONS

In order to meet the magnetic cleanliness requirements of a spacecraft, it is necessary to plan and carry out a magnetic cleanliness programme at subsystem and system level. In fact, as described above, spacecrafts are characterised by a magnetic field due to current loops, the materials used and their behaviour in response to the external field in which they are orbiting.

In the particular case of CubeSats such as NanoMagSat, the magnetic cleanliness programme is even more complex due to the low-cost nature and the use of off-the-shelf

components and subsystems. Nevertheless, a proper magnetic cleanliness control plan is crucial to reduce the spacecraft dipole moment and achieve the required mission performance.

Furthermore, based on the test results shared above, the importance of measurement data of representative unit models is revealed as differences between test and analytical or heritage data can be significant due to many factors, e.g. unexpected presence of soft or hard magnetic materials, slight modifications on PCB layouts (i.e. different current loops area and orientation), unintentional remagnetisation of units due to an improper environmental control, etc.

As previously stated, the objective of the current NanoMagsat RRA is to increase the TRL of the main elements of the satellite, so as to decrease the risk on its critical elements. One of these is in fact the magnetic cleanliness. For this reason, a deployable boom, payloads electronics, and the development of a spacecraft with a low magnetic signature were developed.

During this RRA, all platform's subsystems and the Engineering Model (EM) of the boom will be tested by Q2 2023 at subsystem and system level. Currently, the last phase of the RRA is underway and, at the time this paper is being written, there are still many subsystems planned to be tested.

Once all the results of the test campaign done at CEA-Leti facilities will be available, the magnetic budget will be updated and compared to the mission requirements. At this moment, based on the conservative analyses performed already, it is expected that the system-level requirement will be achieved once the relevant L1b compensation algorithm is implemented.

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