Monitoring the Earth's magnetic field with nanosatellites

G. Hulot[1], J.M. Léger[2], P. Vigneron[1], T. Jager[2], F. Bertrand[2], P. Coïsson[1], A. Laurens[3], B. Faure[3]
[1]Université de Paris, Institut de Physique du Globe de Paris, CNRS, F-75005, France; [2]CEA-Leti, MINATEC Campus, Grenoble, France; [3]CNES, Toulouse, France.

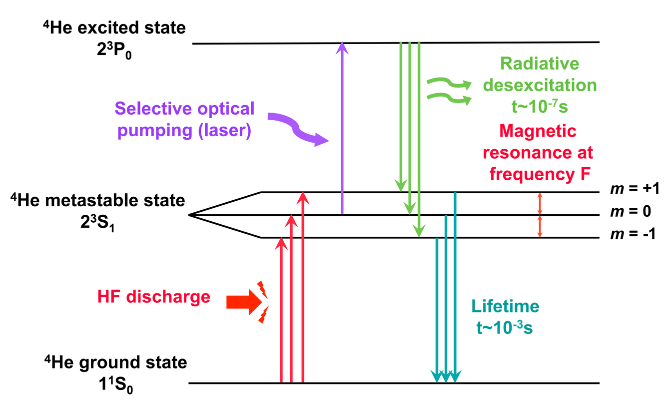
If you wish to join/support the project, please let us know (gh@ipgp.fr)

JULY 8-18 JUILLET 2019 | MONTRÉAL, CANADA
27th IUGG General Assembly
Assemblée Générale de l'UGGI
International Union of Geodesy and Geophysics | Union Géodésique et Géophysique Internationale
IUGG Centennial | 1919-2019 | Centenaire de l'UGGI
A01p-187

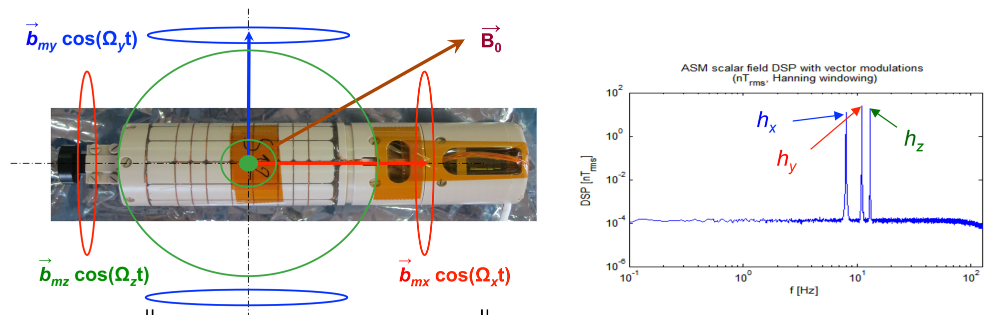
Summary

Thanks to the successive Oersted, Champ and Swarm missions, the Earth's magnetic field has been continuously monitored from LEO orbits since 1999, complementing ground-based observatory data by providing accurately calibrated scalar and vector measurements with the global coverage needed for investigating the many sources of this field. The three satellites of the ESA Swarm mission are currently planned to remain in operation up to hopefully 2024, and possibly more for the higher satellite. Further monitoring the field from space with absolute magnetometry beyond that date, however, is of critical importance for improving our understanding of the very rich dynamics of the various components of this field. In this poster, we report on our ongoing efforts to achieve this goal with the help of nanosatellites, focusing on the NanoMagSat project that plans to take advantage of an advanced Miniaturized Absolute scalar and self-calibrated vector Magnetometer (MAM) based on a concept (ASM) successfully tested on the Swarm mission. The development of this MAM instrument is now well advanced and a prototype of this sensor is currently under construction. NanoMagSat first aims at an ~60° inclination circular 500 km altitude orbit before the demise of Swarm to allow for orbit crossing and a quick local time coverage, compensating for the slow local time coverage of the Swarm constellation. Additional similar low-cost nanosatellites could also be launched to form the basis of a constellation of multiple high-precision nanosatellites for permanent monitoring of the Earth's magnetic field and ionospheric environment from space.

1 Principle of the Swarm ASM magnetometers



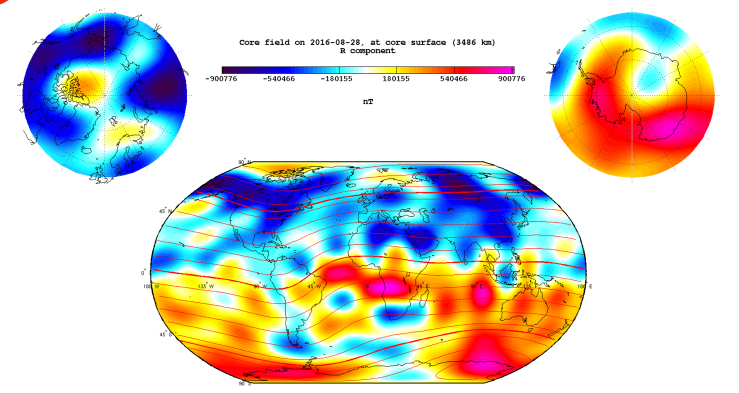
- The ASM is a **magnetic field to frequency converter**, with B=F/γ.
- γ is the ^{4}He gyromagnetic ratio for the 2^3S_1 state, and F is the magnetic resonance frequency between the Zeeman sublevels (proportional to B), measured through magnetic resonance with a signal enhanced by optical pumping (using a linearly polarized fiber laser on Swarm). Magnetic resonance is optimized by ensuring that both the Radio-Frequency excitation field and the polarization direction of the laser are near-perpendicular to the orientation of the magnetic field to be measured. This was achieved thanks to a piezoelectric motor on Swarm (see **Box 4**).
- The ASM has a **high internal acquisition rate (1 kHz)**, which **made it possible to acquire absolute scalar data at 250 Hz rate** (cut-off at 100 Hz, "Burst mode") **or dual-purpose scalar/vector data at 1 Hz** ("vector mode"), thanks to the design described below (for details, see Gravrand et al., 2001).



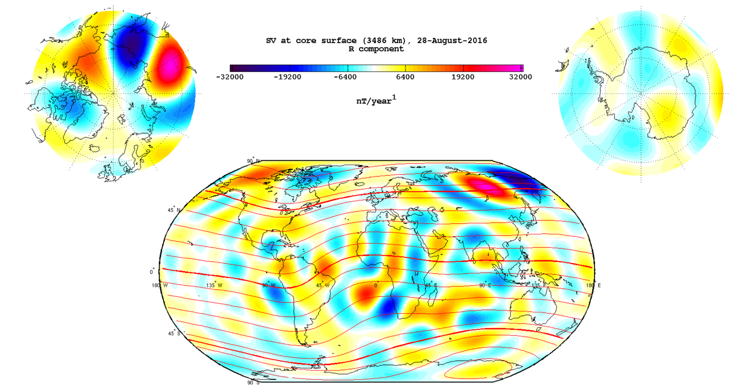
$$\left\|\vec{B}_{tot}\right\| = \left\|\vec{B}_o + \sum_{i=x,y,z} \vec{b}_{mi}\cos\left(\Omega_i t\right)\right\|$$

- **Three perpendicular coils** wired on Peek material **generate periodic magnetic fields with known amplitudes** (b_m~ 50 nT) **at three different known (and adjustable) frequencies beyond 1 Hz** (at about 8 Hz, 11 Hz and 13 Hz).
- **Real time analysis of the scalar field measured at 1 kHz makes it possible to measure the absolute scalar field together with all field components along the three coil axis at 1 Hz** (cut-off at 0.2 Hz, "Vector mode").
- **Both ASM burst and vector modes successfully work on Swarm** (see Léger et al., 2015; Fratter et al., 2016, and **Boxes 2 and 3**).

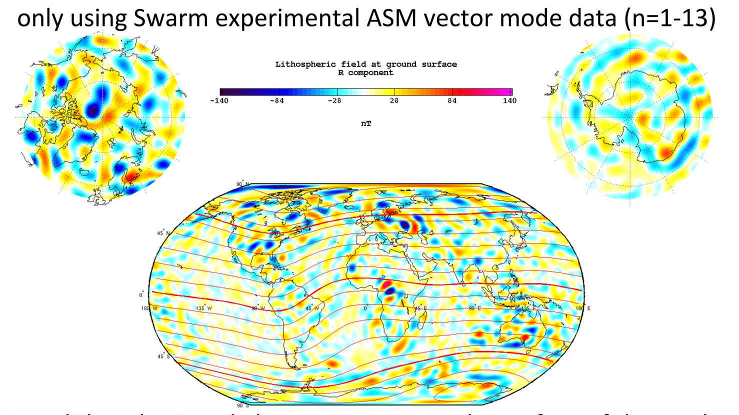
2 Global field modelling using experimental ASM vector mode data



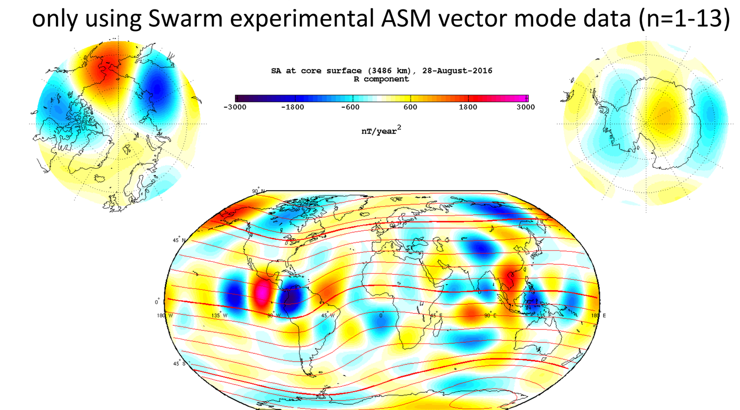
ASMV core field model component Br at core surface on 28/08/2016 only using Swarm experimental ASM vector mode data (n=1-13)



ASMV core field model component dBr/dt at core surface on 28/08/2016 only using Swarm experimental ASM vector mode data (n=1-13)



ASMV lithospheric radial component Br at the surface of the Earth only using Swarm experimental ASM vector mode data (n=15-45)

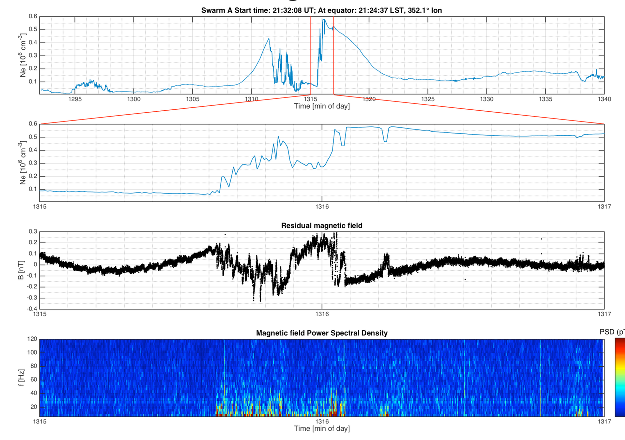


ASMV core field model component d²Br/dt² at core surface on 28/08/2016 only using Swarm experimental ASM vector mode data (n=1-13)

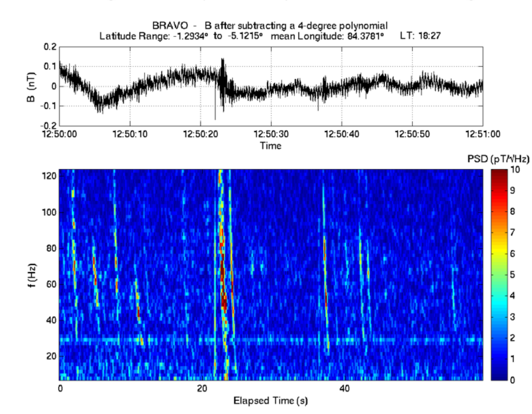
- **1 Hz Swarm experimental vector mode data have successfully been used** in combination with star camera attitude data, **to build models of the core and lithospheric fields** (here updated models based on Hulot et al., 2015). These models have been **validated by comparison with analogous models derived from the Swarm nominal data** (combining ASM scalar and VFM relative vector data) **and the CHAOS-6 (version x9) model based on much more data** (Finlay et al., 2016).
- These results **validate the possibility of using ASM vector mode data for such scientific goals**, without the need for an additional (VFM type) relative vector magnetometer (see also talk by Vigneron et al., session A01c on Friday 12/07/19 at 17:30).

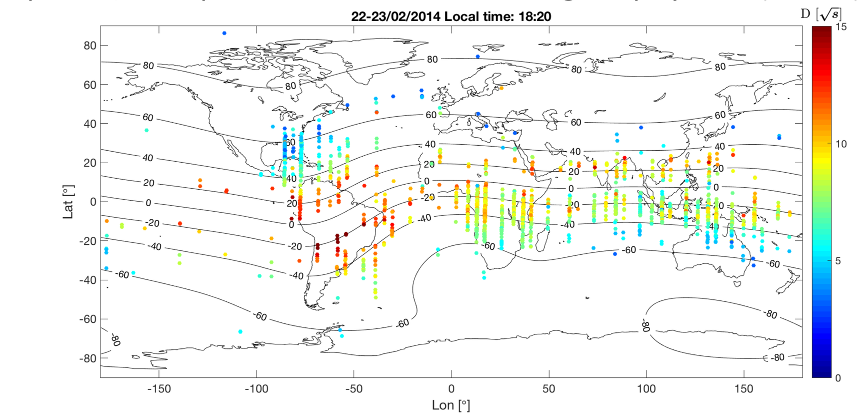
3 Ionospheric studies using burst mode ASM data

- Burst mode sessions run during commissioning of Swarm revealed the ability of the ASM Burst mode to detect ionospheric signals related to plasma bubbles and whistlers within the 20-120 Hz frequency range. Burst mode data are now regularly acquired and have become a new Swarm L1b data product. A study has been funded by ESA to take advantage of these data to produce derived products about the state of the ionosphere below the satellites. The MAM instrument could provide even better data (up to 1 kHz) for such studies, which could also benefit from the high-frequency even more sensitive magnetic vector HFM instrument, as well as the high frequency m-NLP Langmuir probe, also planned on the NanoMagSat payload (**Box 6**).



Example of **high frequency signals detected when crossing plasma bubbles** (19/01/2014, 21:30 local time)





ELF frequency whistlers produced by lightning in the neutral atmosphere below the satellites, the dispersion of which **can be used to investigate the state of the ionosphere along the whistler paths between their entry points in the ionosphere and the satellites** (here on 22-23/02/14, LT 18:20, **for more details** see talk by Coïsson et al. in session A16d on Sunday 14/07/19 at 17:15).

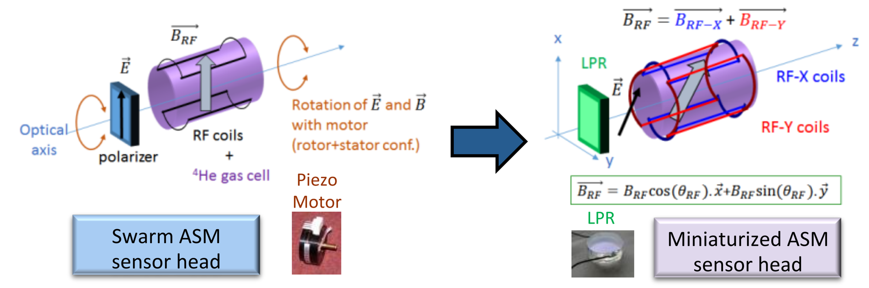
References

- Finlay et al., Recent geomagnetic secular variation from Swarm and ground observatories as estimated in the CHAOS-6 geomagnetic field model, *Earth Planets Space,* 68:112, doi: 10.1186/s40623-016-0486-1, 2016.
- Fratter et al., Swarm Absolute Scalar Magnetometers first in–orbit results, *Acta Astronautica*, 121, 76-87, doi: 10.1016/j.actaastro.2015.12.025, 2016.
- Gravrand et al., On the calibration of a vectorial ^{4}He pumped magnetometer, *Earth Planets Space,* 53, 949-958, 2001.
- Hoang et al., The multi-needle Langmuir probe system on Board NorSat-1, *Space Science Reviews*, 214:75, DOI: 10.1007/s11214-018-0509-2, 2018.
- Hulot et al., Swarm's absolute magnetometer experimental vector mode, an innovative capability for space magnetometry, *Geophys. Res. Lett.*, 42, doi: 10.1002/2014GL062700, 2015.
- Hulot et al., Nanosatellite high-precision magnetic mission enabled by advances in a stand-alone scalar/vector absolute magnetometer, IGARSS 2018 extended abstract, 978-1-5386-7150-4/18/$31.00, 6324-6327, DOI : 10.1109/IGARSS.2018.8517754, 2018.
- Léger et al., In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites, *Earth Planets Space,* 67: 57, 2015.

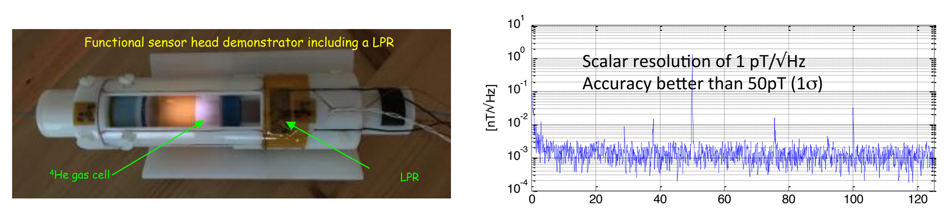
4 Building a Miniaturized ASM (MAM)

- Sensor head :

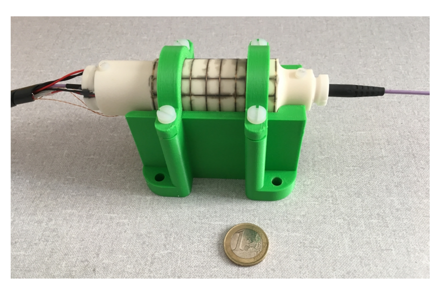
Polarization of the laser signal and of the radio-frequency excitation field is now achieved using a liquid crystal polarization rotator and two orthogonal RF coils (right, in the figure below) to avoid having to rely on a piezoelectric motor (as in the Swarm ASM, left):



This allows a **reduction of the size of the sensor head**, while maintaining **similar performances**, compared to Swarm.

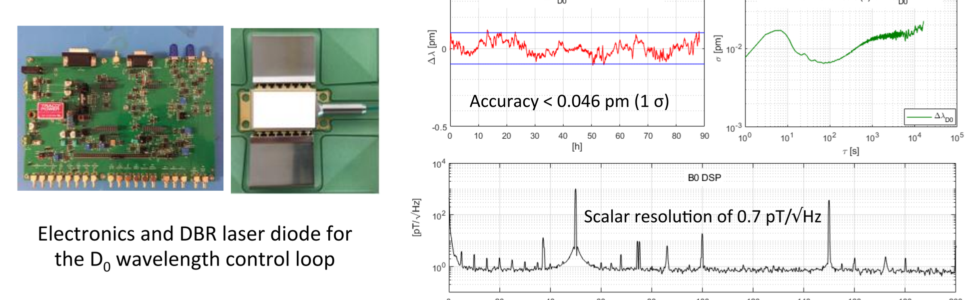


Replacement of the Peek material by Al_2O_3 for the structure, and **monolithic structure** ensuring the stability of the exciting coils (see bottom left figure of **Box 1**) to **improve long-term stability** of these coils **by one order of magnitude**.



- Laser source and DPU size :

Replacement of the athermal fiber laser (used in the Swarm ASM) **by a 1083 nm laser diode** allows a **simplification** of the laser source and **DPU volume reduction** (**performances kept**).



Electronics and DBR laser diode for the D_0 wavelength control loop

Overall **DPU volume reduction by a factor of 3 (possibly 5) is achievable**.

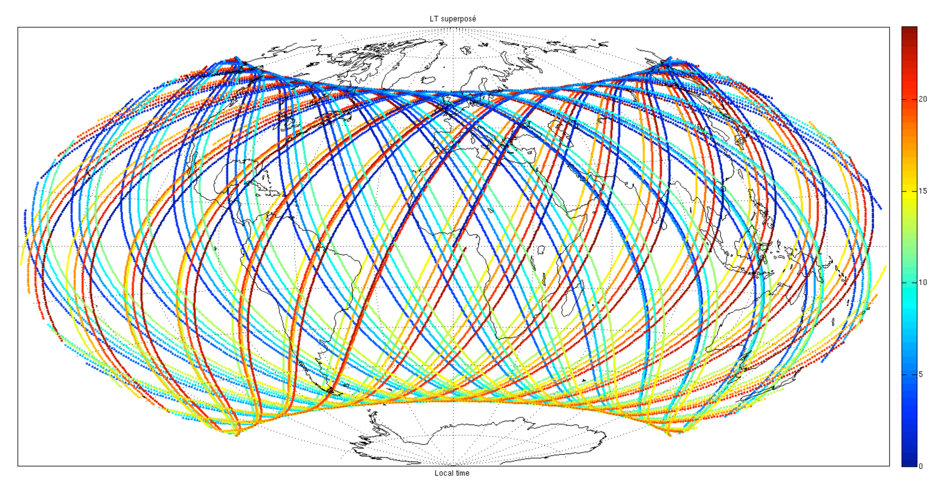
- Improving performance :

Better optimization of the vector modulation amplitudes and of the vector mode processing, taking more non-linear effects into account, has been **shown to be possible**.

Possibility of running the instrument in dual mode, simultaneously providing 1 Hz vector data and Burst scalar data has been **established**.

5 Constellation concept and science goals

- **Orbits of the three Swarm satellites only cover four local times (LT) each day** (accounting for the ascending and descending orbits, and for the fact that two satellites orbit side-by-side), with a LT separation that reached 6h00 in April 2018, and **a global LT drift (of 2,7 h/months)** that provides a **coverage of all LT in 4,4 months**. In August 2021, orbits will again be in a co-planar configuration (counter-rotating orbits), and LT coverage will degrade.
- **A circular LEO (at ~500 km) with 60° inclination for a first NanoMagSat would provide a complete LT coverage in only one month** (36 days) between latitudes -60° and 60° **(and useful ties points crossing at 60° angle)**, most beneficial for magnetic field, ionospheric and lightning whistler investigations.
- **Additional copies of NanoMagSat could also be launched to complement/replace the LEO Swarm orbits** (with complementary polar coverage and slowly drifting LT characteristics).



Local times provided by orbits on days 1, 9, 18 and 27, illustrating the full LT coverage a LEO 60° inclination orbit would provide in 36 days

- **Such a constellation launched before decommissioning of Swarm would help improve**:
- temporal resolution of **ionospheric Sq field models** (monthly),
- temporal resolution of **core field secular variation and acceleration** (sub-annual),
- **lithospheric field models** (removing North-South biases),
- investigations of **currents induced in the solid Earth, and currents produced by oceanic circulation**,
- investigations of **instabilities, currents and waves in the ionosphere at equatorial and non-polar latitudes**,
- Investigations of **ELF lightning induced whistlers.**

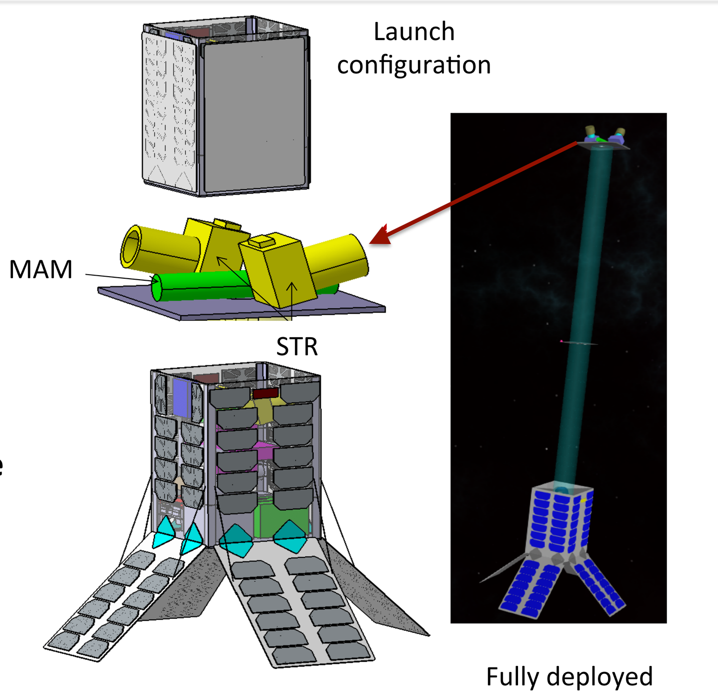
6 The NanoMagSat 12U concept

A joint CNES/IPGP/CEA-Léti Phase 0 study and further work since already established the possibility of building a **12U nanosatellite** (20 cm x 20 cm x 30 cm, when folded) that could accommodate the following payload:

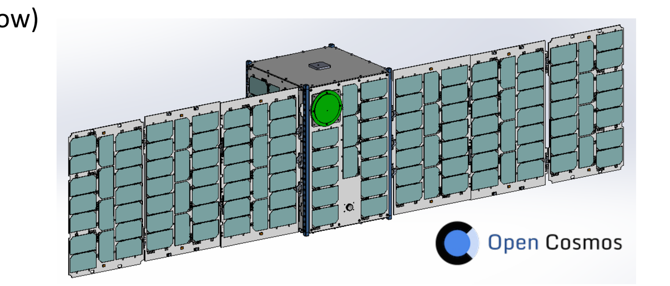
- **MAM magnetometer *simultaneously* providing 1 Hz vector *and* up to 1kHz scalar data**, located on an optical bench at the tip of a boom.
- A set of **two star cameras** (STR) located on the same optical bench for accurate attitude restitution (1 Hz sampling rate).
- A **miniature high frequency magnetometer (HFM) providing relative vector magnetic values in the 0.01 Hz-1kHz range with very low noise level (see Box 7)**, further down the boom (or on the body of the satellite) to complement the MAM high frequency scalar values.
- A **cubesat multi-needle Langmuir probe m-NLP**, providing **Ne at 1 kHz**, the location of which remains to be finalized (**see Box 7**)
- Available cubesat **dual frequency GPS**.

Need for AOCS:

- **Gravity gradient stabilized solution could be used**, with a 2 m long deployable boom radially oriented outwards is viable.
- **Propulsion only for initial phase and basic orbit altitude maintenance** (low need for orbit control), aiming at 3+ years lifetime.
- **Minimum attitude control** for initial detumbling and rough attitude requirements (avoiding systematic spinning).

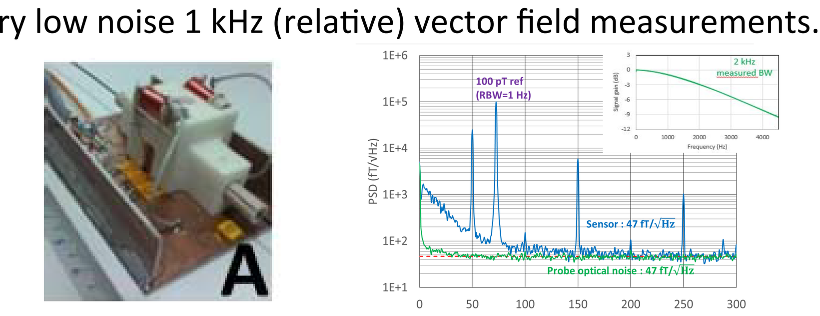


Initial Phase 0 concept (above) that could be adapted to available Open Cosmos 12U plateforms (here without a boom, below)

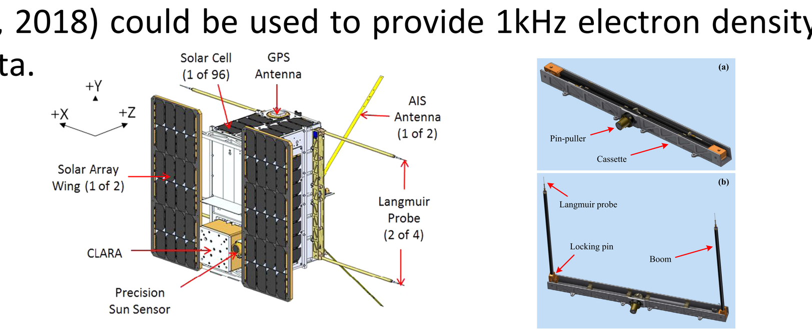


7 High frequency HFM and m-NLP

- A miniature High Frequency vector Magnetometer (**HFM**) developed by CEA-Léti for MagnetoEncephaloGraphy applications, can be adapted to provide complementary very low noise 1 kHz (relative) vector field measurements.



- A 4 needle Langmuir Probe (**m-NLP**) concept by University of Oslo, already flown on the Norsat-1 cubesat (Hoang et al., 2018) could be used to provide 1kHz electron density data.



8 Conclusion and Perspectives

- **Swarm has not only proven to be a scientific success, it also allowed in-flight science validation of the CEA-Léti ASM magnetometer dual mode concept.**
- **A miniaturized version of this ASM will shortly be available.**
- **A Phase 0 study with CNES, followed by very active ongoing studies, points at the possibility of relying on available 12U platforms (such as proposed by Open Cosmos) to build a nanosatellite concept with a high TRL payload and SRL readiness.**
- **Several such NanoMagSats could quickly be developed for a multiple launch in 2024, to complement, enhance and take over the Swarm constellation magnetometry and ionospheric science goals.**
- Such a **NanoMagSat concept could pave the way to permanent low-cost multi-satellite collaborative observation of the geomagnetic field and ionospheric environment, complementing the INTERMAGNET** (http://www.intermagnet.org/) **network of ground-based magnetic observatories.**