Towards low-cost permanent space-borne observation of the geomagnetic field and ionospheric environment

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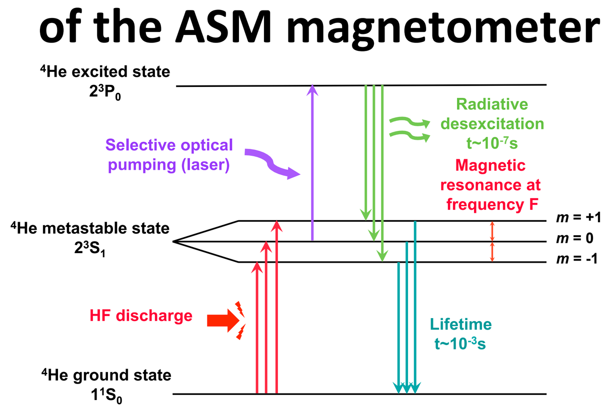
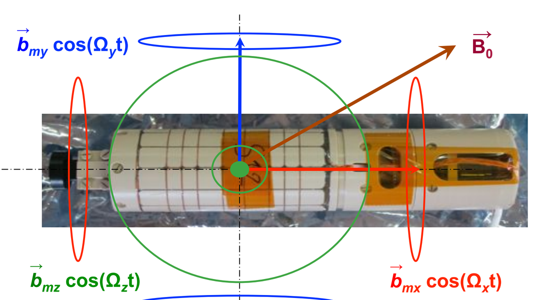
Summary

Space-borne observation of the Earth's magnetic field and of the ionospheric environment started early on in the history of space exploration. Only since 1999, however, has continuous low Earth orbiting observation successfully been achieved, thanks, in particular, to the Oersted, CHAMP and Swarm missions. These missions have demonstrated the usefulness of long-term continuous observation from space for a wealth of applications, ranging from understanding the fast and small scales of the Earth's core dynamo, to investigations of still poorly understood ionospheric phenomena. Here we point out that such observations could be achieved by much cheaper free-orbiting gradient stabilized 12U nanosatellites, such as the "NanoMagSat" nanosatellite concept currently under phase 0 within CNES. Such satellites would not require sophisticated orbit or attitude control, and would take advantage of a miniaturized version of the absolute magnetometer designed by CEA-LETI, which currently operates on the Swarm mission. This instrument is capable of simultaneously providing absolute scalar and vector measurements of the magnetic field at 1 Hz sampling rate, together with higher frequency (250 Hz sampling rate) absolute scalar data. It would be coupled with star imagers for attitude restitution, together with other instruments providing additional measurement capabilities for ionospheric science and monitoring purposes (vector field measurements beyond 1Hz, plasma density, electron temperature, TEC, in particular). Because Swarm will very likely ensure data acquisition on polar orbits for at least another 10 years, a first "NanoMagSat" satellite could be launched on an inclined orbit (within the 60° range) to provide a much-needed fast local time coverage of all sub-auroral latitudes. Beyond this maiden mission, "NanoMagSat" satellites could next be used as a baseline for the progressive establishment and maintenance of a permanent international network of a small number of satellites, operated and coordinated simultaneously and in a way analogous to the Intermagnet network of ground magnetic observatories.

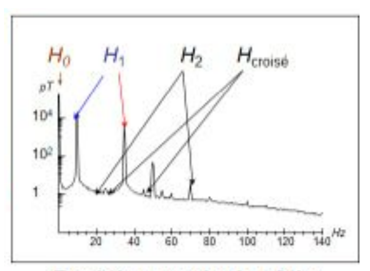
1 Principle and miniaturization of the ASM magnetometer



- The ASM is a magnetic field to frequency converter, with $B=F/\gamma$.
- 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.
- This instrument has a high internal acquisition rate (1kHz), which makes it possible to acquire scalar data at 250 Hz rate (cut-off at 100 Hz, "Burst mode") and to acquire "vector mode" data at 1 Hz, thanks to the design described below (for details, see Gravrand et al., 2001).



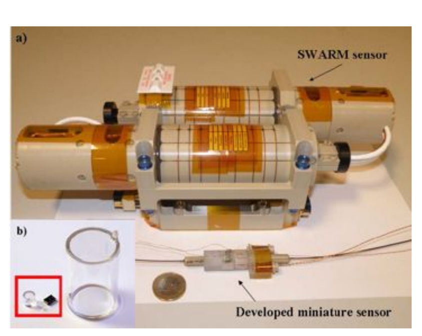
$$\left\|\vec{B}_{tot}\right\| = \left\|\vec{B}_o + \sum_{i=x,y,z} \vec{b}_{mi}\cos(\Omega_i t)\right\|$$



Real time analysis of the scalar output

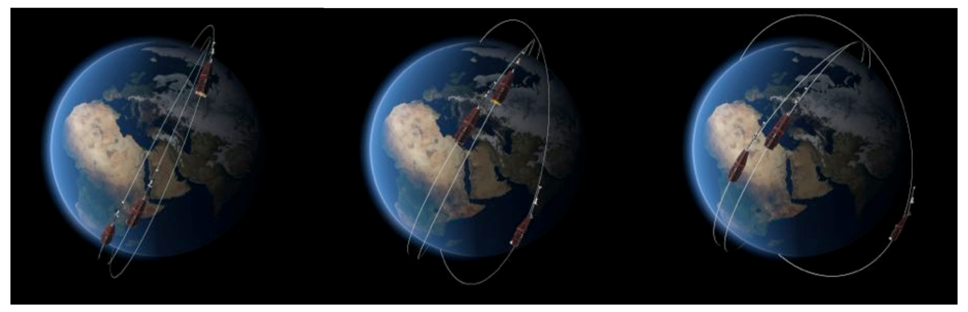
- Three perpendicular coils generate periodic magnetic fields with known amplitudes (b_m~ 50 nT) and three different known (and adjustable) frequencies beyond 1 Hz (at about 8 Hz, 11 Hz and 13 Hz).
- Real time analysis of the scalar field measured at 1 kHz makes it possible to measure the scalar field together with all field components along the three coil axis at 1 Hz (cut-off at 0.2 Hz, "Vector mode").

- This vector mode successfully works on Swarm (see Léger et al., 2015; Fratter et al., 2016, and box 3).
- A miniaturized version of this instrument with expected improved performance is currently developed by CEA-Léti (see Rutkowski et al., 2014).



2 The ESA SWARM mission in brief

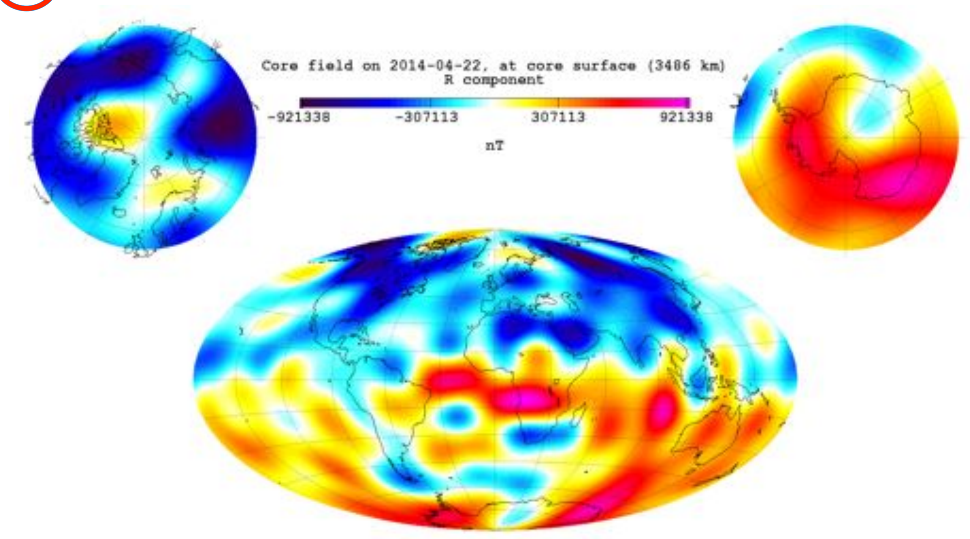
- Three identical satellites launched on November 2013, two satellites side-by-side (1.4° separation) on a polar LEO (87.4°, currently at about 460 km altitude), with a local time (LT) drift of about 2,7h/month, a third satellite on a slightly higher orbit (88°, currently at about 520 km), allowing for a progressive LT separation.



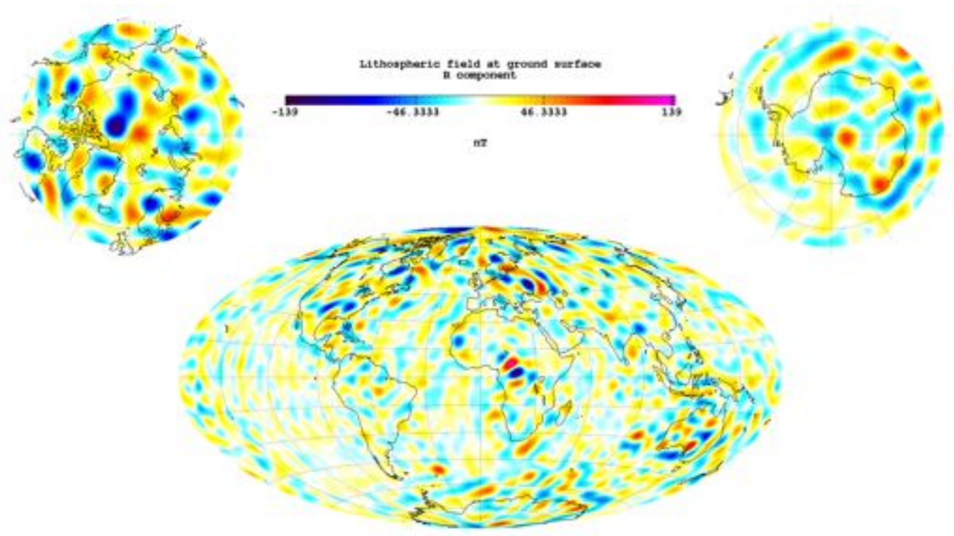
End of April 2014 — 3 hrs: April 2016 — 6 hrs: April 2018

- Expected lifetime: Complete constellation up to at least 2022, higher satellite up to at least 2024.
- Payload:
  - ASM magnetometer (CEA/LETI, CNES), that can operate in vector mode (1Hz) or Burst mode (250 Hz) (see box 1)
  - Fluxgate magnetometer (1Hz/50 Hz) and star camera (DTU Space, 2 Hz)
  - Accelerometer (VZLU, CZ), 1 Hz
  - Electric Field Inst. (Charge particle imager, UC; Langmuir Probe, Uppsala, 2 Hz)
  - GPSR (Ruag), 1 Hz
- Scientific goals: Investigation of the magnetic fields of the core, lithosphere, ionosphere, magnetosphere, oceans and of the electrical currents these induce, as well as of the ionospheric environment.
- Technical goals relevant for the NanoMagSat project: demonstrating the usefulness of the ASM's burst and vector modes (the latter, experimental).

3 Field modelling using the ASM vector mode



Main field radial component Br at the surface of the core in 2014 (n=1-13) reconstructed thanks to Swarm experimental ASM vector mode data

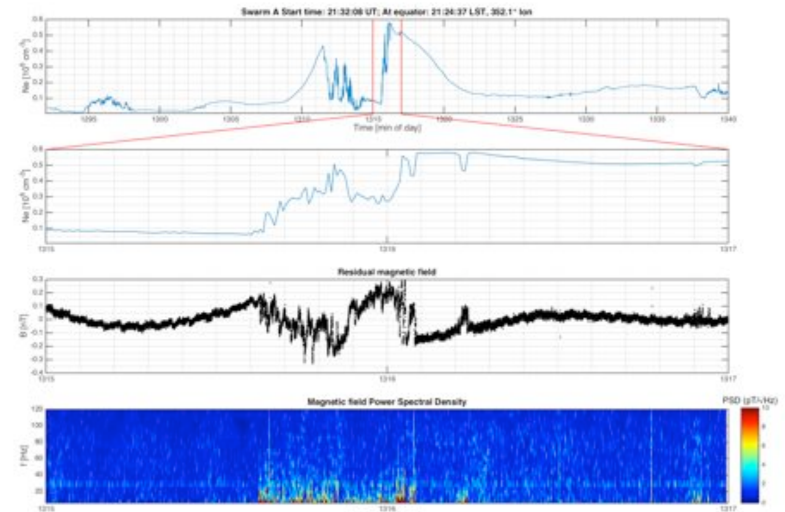


Lithospheric radial component Br at the surface of the Earth (n=15-45) reconstructed thanks to Swarm experimental ASM vector mode data

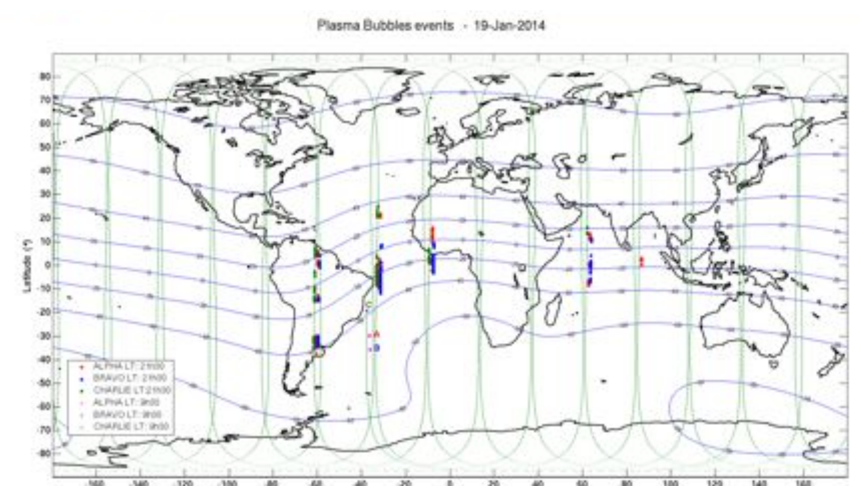
- 1 Hz Swarm experimental vector mode data have successfully been used in combination with star camera attitude data, to build models of the core and lithospheric fields (cf. Hulot et al., 2015; Vigneron et al., 2015).
- These models have been validated by comparison with analogous models derived from the Swarm nominal data (combining ASM scalar and VFM relative vector data).
- 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.

4 Ionospheric studies using the ASM burst mode

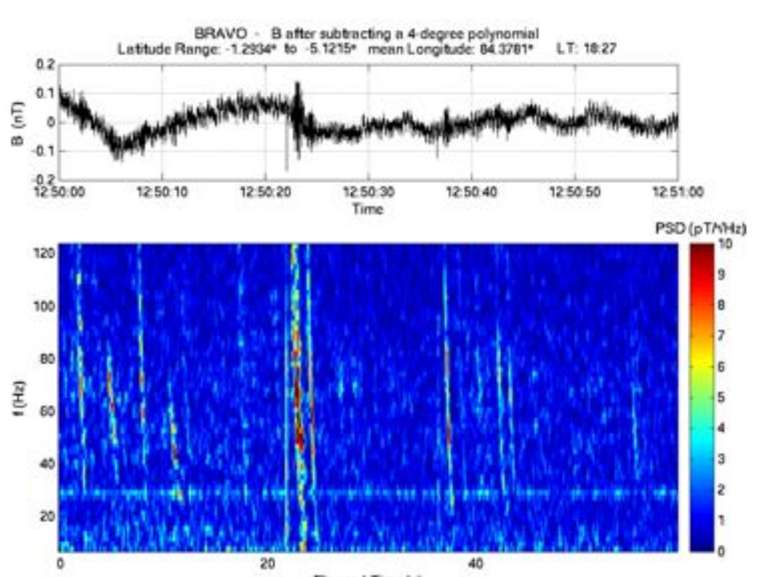
- Several (one or two days long) burst mode sessions were run during commissioning of Swarm. This allowed performance analysis of the instruments, and also made it possible to detect scientifically relevant ionospheric signals.
- Below is an example of high frequency signals detected when crossing plasma bubbles (19/01/2014, 21:30 local time):



- Below are locations where similar signals could be detected by the ASM instruments on board the three Swarm satellites within the 10-50 Hz frequency range on the same day (19/01/2014). These signals were detected by the three satellites (which were following each other closely on a "pearl on a string" configuration on that day), only at night (21h30 LT), and never on day side (9h30 LT). These signals were detected in a way consistent with signals detected by the Langmuir probes. This shows that the burst mode can robustly detect high frequency signals associated with plasma bubbles.



- Interesting "whistler" signals could also be detected by the ASM burst mode. Those illustrated below occurred on 22/02/2014, when the local time was 18:27, at an equatorial latitude and longitude of 84°. These whistlers were simultaneously detected by all satellite and are unambiguously associated with the occurrence of lightning within the troposphere (for more details, see **Poster AE33B-0447** "Whistler-like Signals Detected Simultaneously by Swarm Satellites" by Coïsson et al.).



References

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.

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.

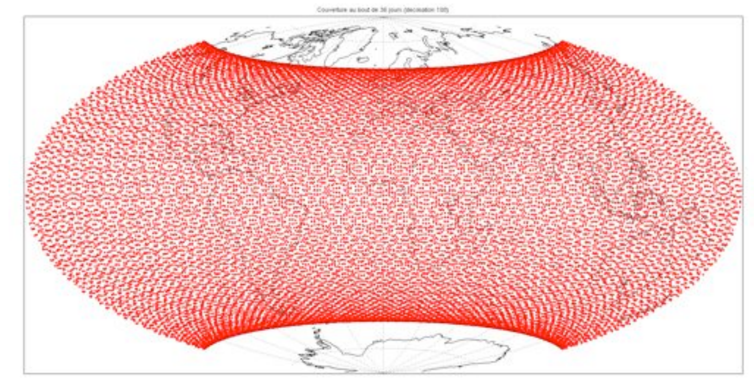
Léger et al., In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites, *Earth Planets Space,* 67: 57, 2015.

Rutkowski et al., Towards a miniature atomic scalar magnetometer using a liquid crystal polarization rotator, Sensors and Actuators A 216, 386-393, 2014.

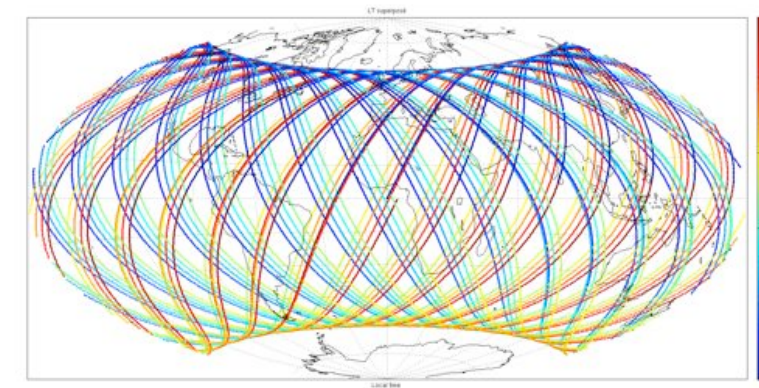
Vigneron et al., A 2015 International Geomagnetic Reference Field (IGRF) Candidate Model Based on *Swarm*'s Experimental Absolute Magnetometer Vector Mode Data, *Earth Planets Space,* 67 : 95, doi : 10.1186/s40623-015-0265-4, 2015.

5 Motivations for a circular LEO orbit at 60° inclination

- Orbits of the three Swarm satellites still do not provide an optimal local time (LT) coverage: only four local times (accounting for the ascending and descending orbits, and for the fact that two satellites orbit side-by-side) are currently being covered each day, with a LT separation that will reach 6h00 only in April 2018, and a global LT drift (of 2,7h/months) that provides a coverage of all LT in only 4,4 months (see box 2).
- A circular LEO (at ~500 km) with 60° inclination would provide a complete LT coverage in only one month (36 days) between latitudes -60° and 60°. These are latitudes for which such a LT coverage would be most beneficial.



36 days of geographic coverage a LEO 60° inclination orbit would provide (1 point every 100s)



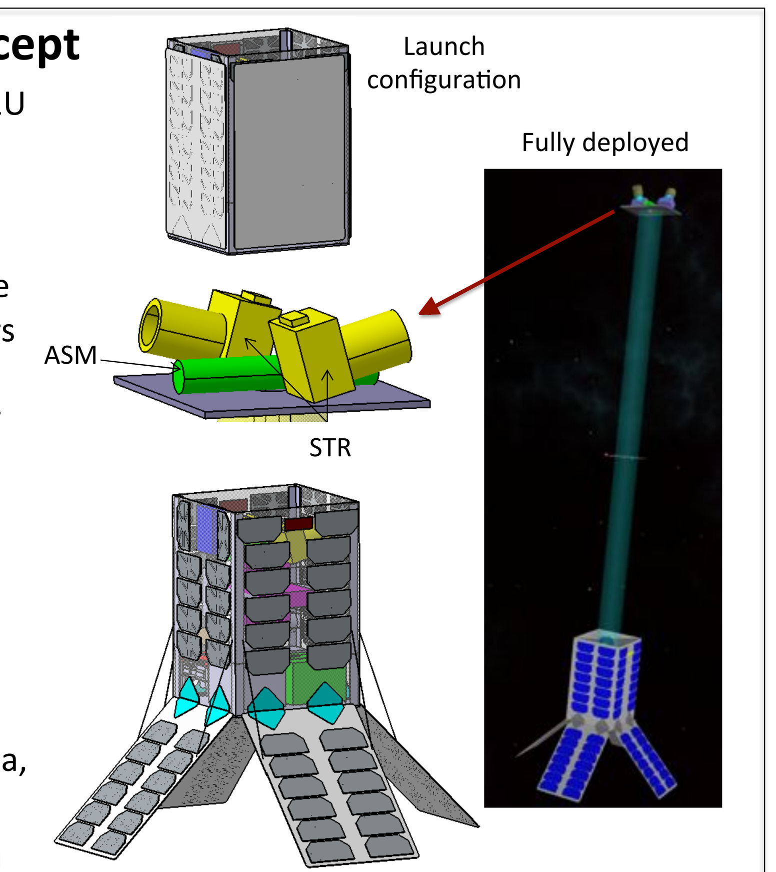
Local times provided by orbits on days 1, 9, 18 and 27, illustrating the full LT coverage a LEO 60° inclination orbit would provide in 36 days

- In addition, a LEO 60° inclined orbit would provide tie points crossing at 60° angle, allowing artefacts linked to the systematically North-South path of the orbits of the Swarm satellites (and of all previous absolute magnetometry missions) to be corrected for (which would be most beneficial for the reconstruction of the lithospheric field, in particular).

6 The NanoMagSat 12U concept

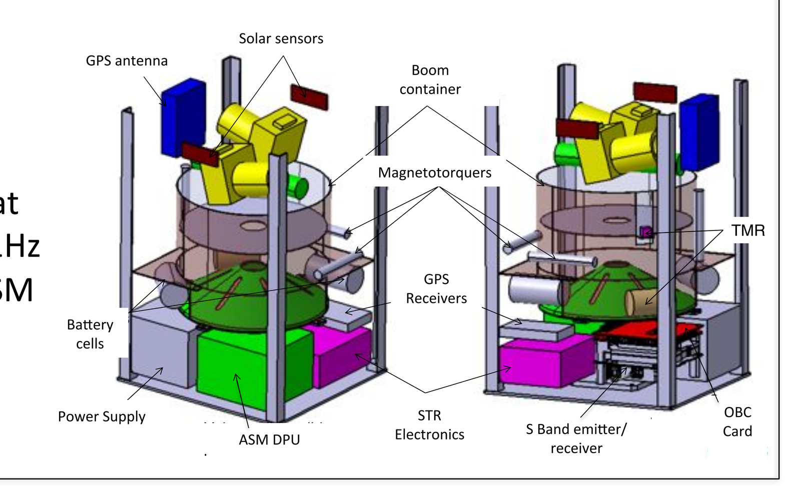
A CNES study (now phase 0+) points at the possibility of building a 12U nanosatellite (20cmx20cmx30cm, when folded) consisting of :

- A gravity gradient stabilized solution, with a 2m long deployable boom radially oriented outwards, avoiding the need for a permanent attitude control system (stability has been shown to be compatible with the payload needs, miniaturized magnetotorquers in the main body covering the need for minimum occasional and emergency attitude control), and offering magnetic cleanliness for the main magnetic payload (see below).
- No propulsion (no need for orbit control).
- Deployable solar panels to cover power needs.



The envisioned payload would consist of:

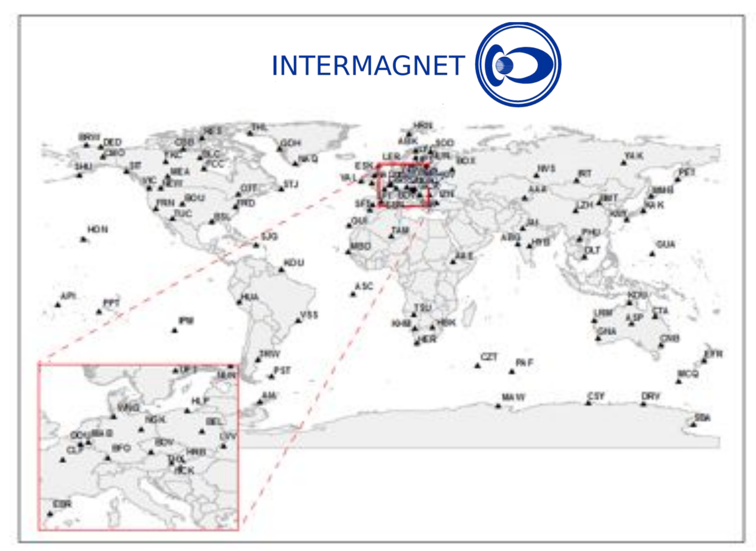
- Improved miniaturized absolute ASM magnetometer capable of *simultaneously* providing 1Hz vector *and* 250Hz (possibly higher frequency, depending on data transmission constraints) scalar data, located on an optical bench at the tip of the boom.
- A set of two star cameras (STR) located on the same optical bench for accurate attitude restitution (1Hz sampling rate).
- An advanced miniature high frequency magnetometer (based on the Tunnel MagnetoResistance TMR concept) providing relative vector magnetic measurements in the 0.01Hz-500Hz range (possibly higher), located at mid-boom to complement the ASM at high frequencies and improve quality of the ASM vector data at 1Hz (correcting for natural signals occasionally interfering with the ASM vector modulations, see box 1).
- A dual frequency GPS (antenna on the side of the main body).
- A Langmuir probe, the location of which remains to be defined.



7 Scientific goals and perspectives

We aim at a launch on a 60° inclined orbit before decommissioning of Swarm (still useful if only one polar orbiting satellite remains in operation). NanoMagSat 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.



The Phase 0 has been extended to improve on the miniaturization of the ASM and on the design of the satellite and to further investigate electromagnetic compatibility issues.

Detailed end-to-end simulations of the scientific benefit such a mission would bring will be carried out in 2017, in the context of a working group organized within the premises of the International Space Science Institute in Bern **(if you are interested in participating in these simulations, please get in touch with G. Hulot, gh@ipgp.fr)**.

Beyond Swarm, NanoMagSat would pave the way to permanent low-cost (5-10 M€ single unit initial cost range) multi-satellite collaborative observation of the geomagnetic field and ionospheric environment, complementing the INTERMAGNET network of ground-based magnetic observatories.