Ideas for Future Magnetic Field Missions

André Laurens – CNES, Toulouse, France

with contributions of

Gauthier Hulot – CNRS/IPGP, Paris, France
Jean-Michel Léger – CEA/LETI, Grenoble, France
Outline

Earth’s Magnetic Field
- Sources, scales, historic observation
- Why studying it?

Space-based magnetometry
- Why from space?
- Former space missions - The SWARM mission
- Current knowledge

The NanoMagSat concept
- Mission profile
- Space system
- Perspectives
Earth’s Magnetic Field

Sources, scales, and observation

Why studying it?
Earth’s Magnetic Field

Earth’s Magnetic Field has various sources

• The main source is the geodynamo located in the core
• This field is causing rocks’ magnetization, which is a secondary source
• Other sources are electric currents in the ionosphere, the magnetosphere, the Solid Earth and even in the oceans

In the liquid and conductive core sits a self-excited dynamo

Earth’s crust rocks are magnetized by the core field

Ionized by the Sun and stirred by thermal tides, electric currents flow through the ionosphere

In the magnetosphere, the charged particles’ motion induces large scale electric currents
Earth’s Magnetic Field sources and orders of magnitude

Magnetospheric signals at Chambon-la-Forêt

Short-term variations during a magnetic storm

Magnetospheric signal and induced currents $\rightarrow$ few 100 nT
Earth’s Magnetic Field sources and orders of magnitude

Secular variations at Chambon-la-Forêt

Variations due to geodynamo field long-term evolution
→ \( \approx 20 \text{ nT/year} \) on a total field of \( \approx 40 \text{ 000 nT} \)
Earth’s Magnetic Field sources and orders of magnitude

Geomagnetic “jerks” at Chambon-la-Forêt

Sudden changes in geodynamo field evolution, so that it is mandatory to monitor its acceleration \( \textbf{few nT/yr}^2 \)

- associated time resolution < 1 year
Earth’s Magnetic Field historic observation

Measurements since 1840

INTERMAGNET
- An international network of 150 ground observatories
- Complemented by sea- & airborne measurements
Why studying Earth’s Magnetic Field?

Science objectives

• Main field:
  • Improve understanding of the geodynamo
  • needs observations continuity over long-term durations (observatory policy)
  • with a good spatial resolution (up to degree 20 in spherical harmonics)
  • with a good temporal resolution (< 1 yr)
  • to study short-term phenomena (geomagnetic jerks and pulses)

• Crustal field:
  • Improve crustal field mapping

• Magnetospheric field:
  • Improve description of magnetospheric field and enhance reconstruction of Earth’s deep conductivity

• Ionospheric field and environment:
  • Study electric currents, coupling between ionosphere and magnetosphere, ionosphere’s instabilities, waves, and response to magnetic storms

Internal field dominated:
- by core field up to degree 13
- by lithospheric field for degrees > 13

Crustal field derivative:
- can be observed up to degrees 16-17 thanks to space data
Why studying Earth’s Magnetic Field?

Applicative and Societal issues

• Provide a reference model of main field (IGRF-type) regularly updated (<< 5-year period) for various purposes:
  • Navigation (smartphones, ships, planes, submarines)
  • Spacecraft attitude determination and control
  • Drilling guidance
  • Radio waves modelling and propagation analysis
  • Magnetosphere morphology determination (radiation belts)
• Predict main field evolution, thus of magnetic field structure, for a mid-term prediction (decennial scale) of magnetic conditions to be experienced by long-life satellites
• Monitoring of magnetic activity for the need of Space Weather forecasting:
  • prevention of power distribution networks hazards
  • planning of activities requiring magnetic quietness
• Monitoring of ionosphere state for the need of Space Weather (input parameters to ionosphere models, perturbations detection)
  • determine ionosphere perturbed areas, likely to cause GNSS localisation errors, or radio or GNSS signal losses

A. Laurens - Summer School Alpbach 2019
Space-based Magnetometry

Why from space?

Former space missions - The SWARM mission

Current knowledge
Why Space-based Magnetometry?

Ground observatories’ geographical coverage is uneven:
- Highly linked to human presence, poor on seas
- Fixed position: can see only temporal variations

Satellites provide even and dense geographical coverage but:
- Continuously moving: 1 orbit ≈ 90 mn
- Can see spatial and temporal variations, but always combined
- Reduced sensitivity $\rightarrow \frac{1}{R^2}$

Ground- and space-based measurements are complementary!
Magnetometry Space Missions

Kosmos-49

- 1964-1965: technology demonstration satellite of Soviet Union’s Dnepropetrovsk Sputnik program
- Secondary mission: scientific research on the Earth’s magnetosphere

POGO (Polar Orbiting Geophysical Observatory)

- Polar orbiting satellites of NASA’s OGO program (1964 – 1971)
- First global survey by satellite of the earth's magnetic field

Magsat (Magnetic Field Satellite)

- NASA + USGS (*) LEO satellite (1979 – end of mission after 6 months) part of NASA’s Small Explorers program
- Objectives: first global and detailed measurement of Earth’s magnetic field
- Payload: vector magnetometer (first measurement of field’s 3 components) + absolute scalar magnetometer + star tracker for field orientation reconstruction

(*) United States Geological Survey
Magnetometry Space Missions (cont’d)

Oersted

• Geomagnetic research microsatellite mission of Denmark (several Danish institutes + NASA/CNES/DLR/ESA contributions)

• Objectives: highly accurate and sensitive measurements of the geomagnetic field and global monitoring of the high energy charged particles in the Earth's environment

• Launched 1999 (for an initial 14-months mission) on a slowly drifting elliptical polar orbit, altitude = 655/857 km, inclination = 96.5°; regular operations halted 2014

• Payload:
  • Scalar Magnetometer (OVH for Overhauser Magnetometer) [LETI]: measurement principle: proton magnetic resonance; absolute error < 0.5 nT; range: 16,000 - 64,000 nT; sampling 1 Hz; provides in-flight calibration for the vector magnetometer
  • Vector Magnetometer [DTU+DSRI]: triaxial fluxgate magnetometer; angular resolution: 1 arcsec; absolute error < 1 nT; range: ±65,536 nT; resolution < 0.25 nT; 100-20 vector samples/s modes; resolution < 0.1 nT
  • Charged Particle Detector [DMI]: high energy electrons (50 keV - 1 MeV), protons (250 keV - 30 MeV), alpha-particles (1-100 MeV)
  • ASC (Advanced Stellar Compass) [DTU]: provides an attitude reference, precision: a few arcsecs
  • TRSR (TurboRogue Space Receiver) [NASA/JPL]: accurate determination of satellite position, ionospheric electron content measurement, atmospheric soundings (density, pressure, temperature)
Magnetometry Space Missions (cont’d)

CHAMP (Challenging Minisatellite Payload)

- German geophysical minisatellite mission of GFZ (GeoForschungsZentrum), in cooperation with DLR
- Objectives:
  - Global long-to medium-wavelength recovery of the static and time variable Earth gravity field from orbit perturbation analyses
  - Global Earth magnetic field recovery
  - Atmosphere/ionosphere sounding by GPS radio occultation
- Launched 2000; Initial orbit: 418/474 km (decaying to 300 km after 5 years), inclination 87.275° (near polar but non SSO); end of mission: 2010 (natural deorbitation)

Payload:

- **BlackJack** (dual-frequency GPS receiver) [NASA/JPL]: precise (cm accuracy range) orbit determination and continuous coverage; ionospheric electron content, atmospheric soundings; experimental GPS reflectometry for ocean’s surface altimetric measurements
- **STAR** (Space Three-axis Accelerometer for Research mission) [ONERA]; measures non-gravitational accelerations of the satellite (drag, solar and Earth radiation pressure); determines Earth’s gravity field from purely gravitational orbit perturbation
- **LRR** (Laser Retro Reflector) [GFZ]: passive optical device for accurate satellite tracking from ground laser ranging stations of the SLR network
- **MIAS** (Magnetometer Instrument Assembly System): scalar magnetometer (OVH, LETI), 2 fluxgate vector magnetometers (FGM, DTU), 2 star imagers (DTU) to provide attitude information for FGM
- **ASC** (Advanced Stellar Compass) [DTU]: accurate attitude reconstruction
- **DIDM** (Digital Ion Drift Meter) [AFRL]: measures the Earth’s electric field parallel to the magnetic field (in-situ measurements of the ion distribution and its moments within the ionosphere)
- **PLP** (Planar Langmuir Probe): in combination with DIDM, gives S/C potential, electron temperature and density
Magnetometry in Space: the SWARM Mission

A « constellation » of 3 identical satellites for magnetic field and ionosphere study

- proposed by DTU (Copenhagen), GFZ (Potsdam), IPGP (Paris)
- selected 2004, as 5th mission of ESA Earth Explorer program
- launched November 2013

Payload:

- Absolute Scalar Magnetometer (CEA/LETI, CNES), 250/1Hz + 1Hz experimental vector data (3-axes field modulation)
- Vector Field Magnetometer and Star Tracker (DTU Space), 50Hz, 1Hz
- Accelerometer (VZLU, CZ), 1Hz
- Electric Field Inst.: Thermal ion imager (UC); Langmuir Probes (Uppsala), 2Hz
- GPSR (Ruag), 0.1 Hz

mass: 369 kg (dry) 468 kg (wet)
Magnetometry in Space: the SWARM Mission (cont’d)

Orbital configuration

• 2 satellites – Alpha and Charlie – fly side-by-side (separation in longitude ~150 km at equator) on a quasi-polar orbit (inclination 87.35°) altitude 460 km BoL, then decaying

• 1 satellite – Bravo – on a higher quasi-polar orbit (inclination 87.95°), altitude 530 km BoL, inducing a relative Local Time drift \textit{wrt} Alpha and Charlie

This concept has been shown to be very successful for, e.g.,

• Improving the recovery of the core, crustal, ionospheric, and ocean tidal fields

• Investigating field aligned currents

Willingness (and enough fuel) to maintain the constellation for at least a full solar cycle (until at least 2024)

Swarm Bravo (at higher altitude) could last even far beyond
Current knowledge of Earth’ Magnetic Field

Main field at core surface
1840-2010

Reconstruction from historical data since 1840, and former space missions data: POGO (1965-1970), MAGSAT (1979-1980), DE-2, Oersted (since 1999) and Champ (2000-2010) – units: mT

Gillet et al, GGG, 2013
Crustal field at Earth’s surface – 2010

Reconstruction from CHAMP data (2000-2010) – initial altitude 450 km, finale 250 km – units: nT

Model MF7, S. Maus
Crustal field at Earth’s surface – 2015

Reconstruction from 14 months of SWARM data (2014-2015)
– altitudes 450 to 520 km – units : nT
Towards a near-real time monitoring of large scale magnetic field

<table>
<thead>
<tr>
<th>Model</th>
<th>Input data</th>
<th>Max degree/order</th>
<th>Conductivity model dim</th>
<th>Cadence</th>
<th>Update rate</th>
<th>Latency</th>
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<tbody>
<tr>
<td>Exact Track (MMA_F)</td>
<td>Swarm satellites</td>
<td>1/1</td>
<td>1-D</td>
<td>1.5 hr</td>
<td>daily</td>
<td>4 days</td>
</tr>
<tr>
<td>Comprehensive Inversion (MMA_C)</td>
<td>Swarm satellites</td>
<td>3/1 (external) 5/5 (induced)</td>
<td>4-0</td>
<td>1.5 hr (deg 1, order 0) 6 hr (otherwise)</td>
<td>nearly</td>
<td>1.5 months</td>
</tr>
<tr>
<td>Preliminary Disturb. Index (VMIC)</td>
<td>Ground observatory</td>
<td>1/0</td>
<td>1-D</td>
<td>&lt;=1 hr</td>
<td>&lt;=1 day</td>
<td>&lt;=1 day</td>
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<tr>
<td>Vector Magnetic Disturbance Index (VMI)</td>
<td>Ground observatory</td>
<td>1/1</td>
<td>1-D</td>
<td>&lt;=1 hr</td>
<td>no schedule as required</td>
<td>&lt;=1 month</td>
</tr>
</tbody>
</table>

Processing the ring current signal is possible at orbit timescale – units : nT
Current knowledge of Earth’s Magnetic Field (cont’d)

Reconstruction of Earth’s mantel conductivity from magnetic field data

Processing of the internal signal induced by the ring current signal at low frequencies (periods over 1 day)

Velimsky et al., 5th Swarm DQW
Towards a better description of « Solar Quiet » ionospheric field at mid latitudes

Comprehensive Model, DTU/NASA

Dedicated Model, NOAA/IPGP

Measurement of ionospheric field, units : nT
Current knowledge of Earth’ Magnetic Field (cont’d)

Detection of $M_2$ ocean tide signals

Measurement of $|B_r|$ from M2 ocean tide signal, with:
- 2 years of SWARM data (left)
- 10 years of CHAMP data (right) - units : nT
The NanoMagSat concept

Mission profile
Space system
Perspectives
The NanoMagSat concept

A brief history

• 2014 : first idea of a smallsat dedicated to magnetometry (G. Hulot, IPGP and J.-M. Léger, CEA-LETI)
• 2015 : CNES selects for a phase 0 study the NanoMagSat concept proposed by G. Hulot and J.-M. Léger
  • Based on a miniaturized new generation of SWARM’s ASM
  • Taking advantage of nanosatellite emergence for designing a low-cost mission
  • Aiming to complement the SWARM constellation
• 2015-2016 : conduct of NanoMagSat phase 0
NanoMagSat: mission profile at end of phase 0 study

To complement and extend SWARM constellation, which has limitations

- Polar orbits do not allow crossing points, and North-South tracks introduce North-South artefacts
- Local time coverage is slow (~4 months for full coverage) and thus prevents fast recovery of global scale signals


- Improvement is possible with help of at least one additional satellite at ~60° inclination
  - Crosses both SWARM’s orbits and its own orbit at (almost) all latitudes
  - Provides an East-West measurement component, to mitigate North-South anisotropies
  - Faster local time coverage (~1 month for full coverage)
NanoMagSat: mission profile (cont’d)

NanoMagSat’s core ambition

• To build and launch this additional (Delta) satellite to complete the Swarm constellation, before Swarm’s demise

• To demonstrate the possibility of building a LEO nanosatellite for monitoring the magnetic field and ionospheric environment at a much lower cost than the Swarm satellites

• To set the standards for expending the INTERMAGNET network of ground observatories to space by relying on a fleet of cheap nanosatellites (beyond Swarm)
NanoMagSat: mission analysis

Orbit altitude: a compromise between lifetime and sensitivity to the magnetic field

- Estimated $S/m = 0.025$  
  *(average LEO satellite $S/m = 0.01$)*
- No impact of orbit inclination

Local time drift due to J2 effect

Local time drift along the orbit
Station visibility slots

- Typical values for Toulouse and Kourou
- 550 km, 5° minimum elevation, 6 months simulation

Visibility passes:
Station: Toulouse
Duration: min/max/moy (mn): 1.045 / 10.307 / 7.879
Average frequency (#/day): 7.056
Total average duration (mn/day): 55.593

Station: Kourou
Duration: min/max/moy (mn): 1.214 / 10.276 / 8.038
Average frequency (#/day): 3.483
Total average duration (mn/day): 27.998
NanoMagSat: payload configuration

A focused instrumental suite

- Miniaturized ASM: 250 Hz scalar mode, 1 Hz vector mode
- Star tracker for precise attitude determination
- High frequency vector magnetometer: TMR(*) as a candidate
- Total Electron Content measurement via bi-frequency GPS

(*) Tunnel Magneto Resistance
NanoMagSat: spacecraft concept at end of phase 0 study

All in a 12U-CubeSat

• Gravity gradient (passive) stabilisation
• Innovative boom (MA2C, CNES patent): deporting the magnetometer + gravity gradient
• Avionics suite: OBC and S-Band TM/TC (CubeSat form factor) developed by CNES R&D program
• Budgets:
  • Mass: 17.6 kg with margins
  • Power: 16.4 W worst case

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NanoMagSat perspectives

Short-term objective: flying NanoMagSat
- As “Swarm Delta” : a complement to SWARM constellation
- As a forerunner of a future extension in space of INTERMAGNET observatories

Long-term objectives
- Space-based monitoring of main field long-term evolution
  - Study of the geodynamo, IGRF-like model permanently updated for applicative or societal uses,
  - Long-term monitoring of ionospheric et magnetospheric fields

New space architectures allowing new programmatic schemes
- Incremental deployment of a constellation by successive satellite batches
  - Achieving a progressive local time coverage
  - Taking advantage of opportunistic programmatic conditions
  - Allowing long-term constellation maintenance and replenishment
- Possible partnerships involving countries already contributing to ground-based observation of magnetic field
- Towards a collaborative structure, “InterMagSat”, as a natural counterpart of Intermagnet ground observatories network
Thanks for your attention!
Any question?
Short bibliography

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