A Magnectic Subsystem Technology Demostrator based on Chip-scale Sensors for Magnetically Sensitive Space Missions

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Abstract: A significant number of space missions require thorough measurements of the magnetic environment, either because one of the aims is to explore terrestrial or interplanetary magnetic fields, or because the performance of the instruments on-board is itself susceptible to magnetic effects. Missions belonging to the second category can be found in the area of high precision experiments of Fundamental Physics, such as high sensitivity atom interferometry or laser interferometer gravitational waves detectors.

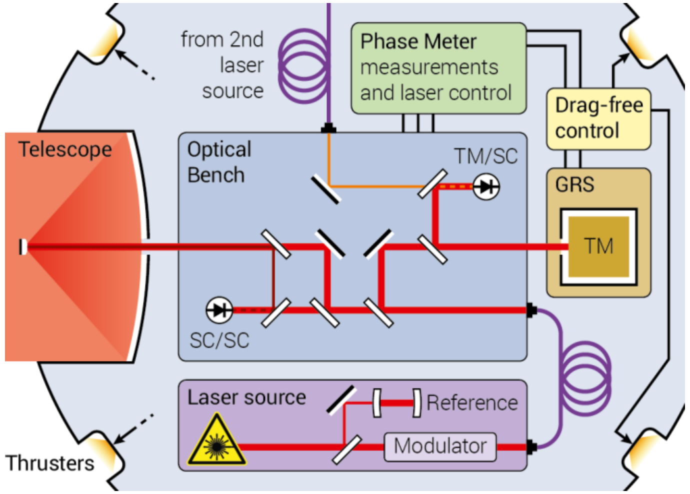
A Magnetic Measurement Subsystem has been designed and developed for a CubeSat platform with the purpose of guiding the technological progress towards space missions with strict constraints on long-term stability and magnetic cleanliness at sub-millihertz frequencies.

The special characteristic of the technology demonstrator is that the chip-scale magnetic sensors are magnetically shielded to low-frequency fluctuations by using a permalloy enclosure. This will allow the in-flight noise characterization of the sensors and the dedicated electronic noise reduction techniques under LEO environment.

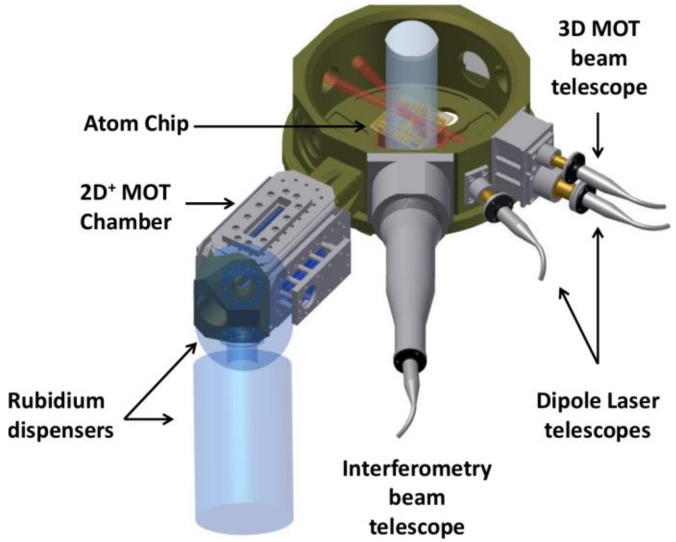
Context of the research

- Space missions that are extremely sensitive to the magnetic field environment require a **dedicated magnetic measurement subsystem** to assess the effects on the scientific results.

- **Space-based laser interferometer GW detectors**
  - Formed by 3 drag-free satellites with "free-falling" test masses.
  - Laser interferometer between S/C with noise levels of pm $Hz^{-1/2}$.
  - Spacecraft isolates the test mass from stray forces.
  - **Magnetic forces** contribute to the total acceleration noise.
  - Monitor the magnetic field with low-noise conditions at **sub-millihertz frequencies.**

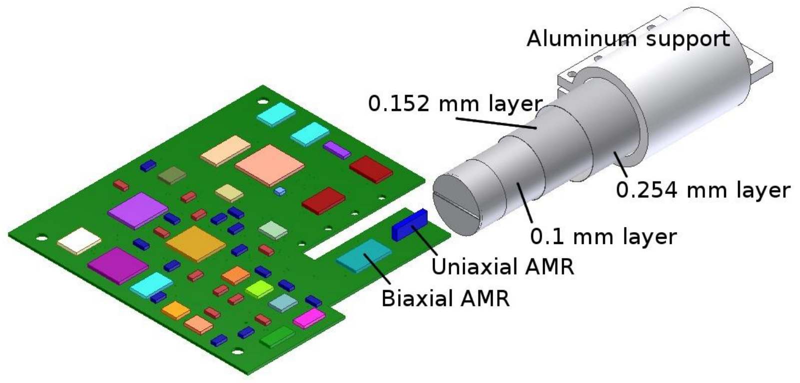


- **Space-borne atom interferometer to test the weak equivalence principle**
  - Magnetic stray fields induce differential acceleration noise.
  - Strict gradient requirements (down to 0.3 nT/m).
  - Magnetic shielding factor > 10^4.
  - Active compensation of **slowly varying external fields**.
  - Magnetic coils and magnetometers will be placed along the shielding.
  - **Compact low-noise sensors** are required.

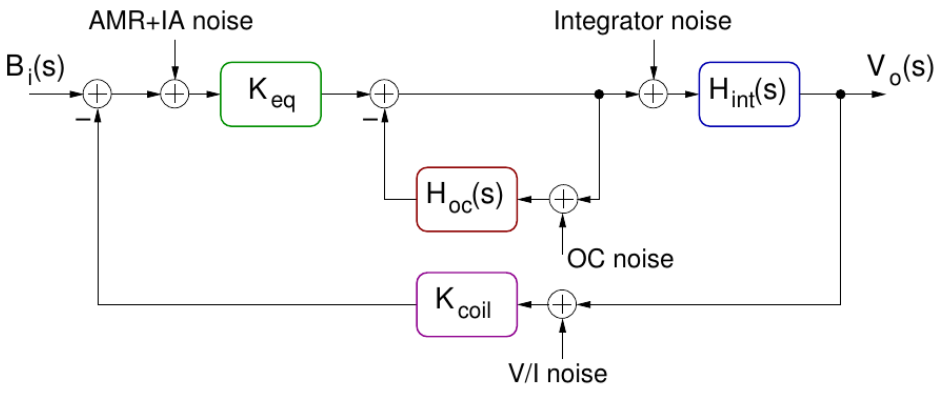


Description of the Work and Methodologies

- Two sensing techniques for compact magnetometers are currently studied:
  - On-chip magnetoresistive sensors.
  - Novel atomic magnetometers.
- A low-power small-sized payload based on a magnetoresistive sensor was developed.
- Make the **validation of the technological concept under operational mission conditions** in a CubeSat platform.
- Magnetic sensors were placed inside a **mu-metal enclosure** to shield the environmental magnetic field.
- Noise estimation was quantified analytically and verified by on-ground measurements.
- **Critical source of excess noise** at low frequency is due to the sensor's **intrinsic flicker noise and thermal dependence.**
- Dedicated modulation and closed-loop techniques are performed to ameliorate the excess noise at sub-millihertz frequencies.
- Demanding CubeSat constraints regarding power consumption, physical dimensions, and weight.
- Autonomous operation (MCU and memory devices are integrated in the payload).



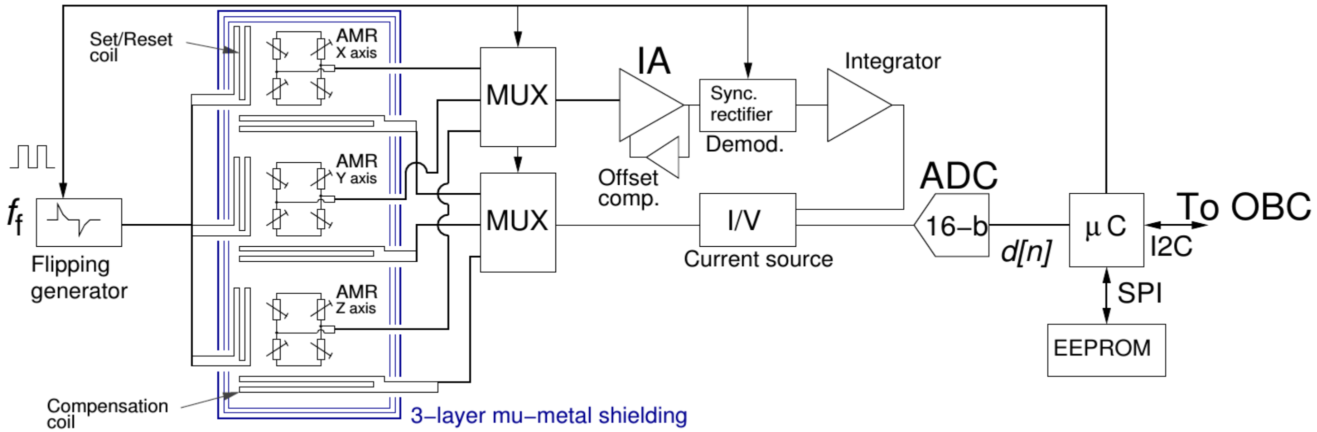
CubeSat payload with the three mu-metal layer for magnetic shielding



Analog signal processing including noise sources and feedback loops

Results (I)

Block diagram of the CubeSat payload



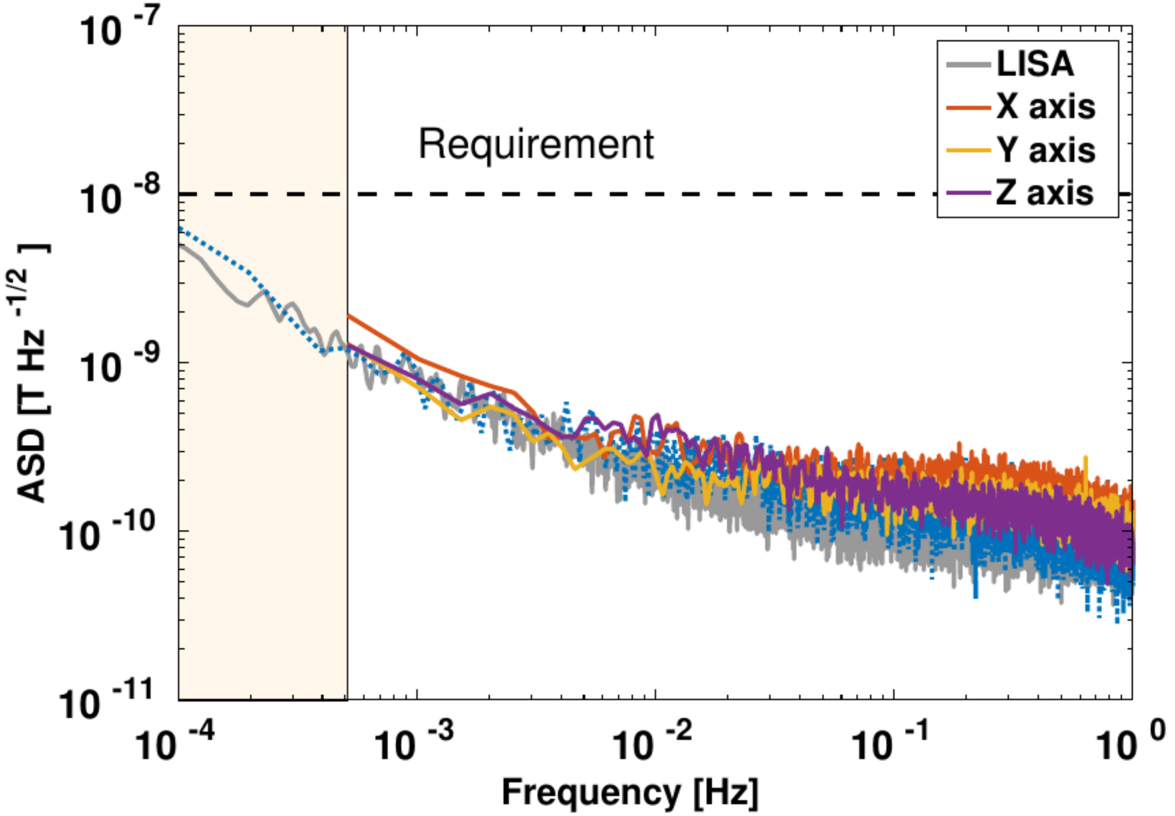
Flight model of the CubeSat payload

Specifications of the magnetic monitoring system

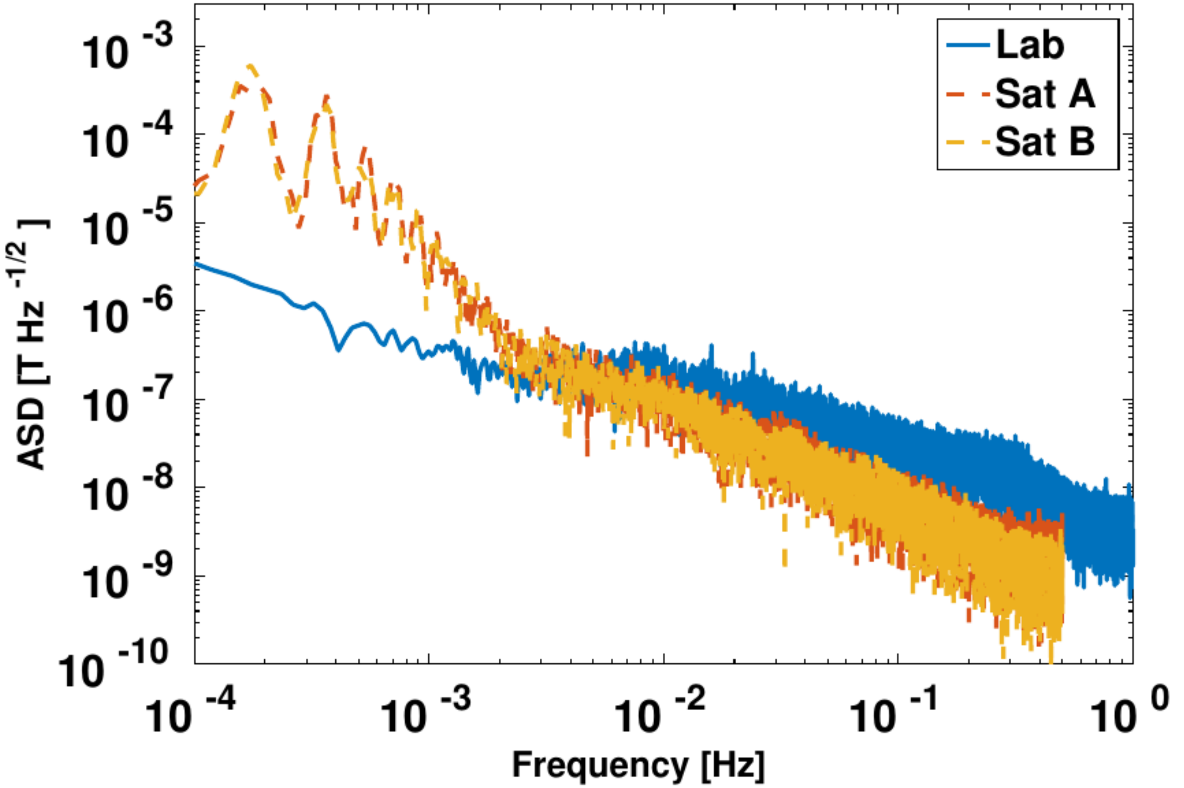
Parameter	Symb.	Value
Field range	B_{range}	$\pm 15\,\mu\mathrm{T}^{(a)}$
RTI temp. coeff. (Sensor + FEE)	TC_{rti}	$3 \cdot 10^{-6} \Delta R_{\mathrm{b,n}}\,\mathrm{V/K}$
Noise density	$S_{\mathrm{B}}^{1/2}$	$0.14\,\mathrm{nT\,Hz^{-1/2}}$ at 1 Hz $1\,\mathrm{nT\,Hz^{-1/2}}$ at 1 mHz $5\,\mathrm{nT\,Hz^{-1/2}}$ at 0.1 mHz
Input current	I_{bridge}	5 mA
Input voltage	V_{bridge}	$4.25\,\mathrm{V}^{(b)}$
Linearity error		0.1% FS
Sensitivity	s_{AMR}	$254.5\,\mathrm{mV}/\mu\mathrm{T}^{(c)}$
ADC resolution	ΔB_{ADC}	0.6 nT
Equivalent resol.	$\Delta B_{\mathrm{eq.}}$	$0.01\,\mathrm{nT}^{(d)}$
Bandwidth	BW	2.75 Hz
AMR operat. temp.		-55°C to +150°C
Spatial resolution		< 1 mm
Power consumption	P_{max} P_{nominal} P_{standby}	0.32 W 0.26 W 0.025 W
Weight		76.6 g

Results (II)

Equivalent magnetic field spectral density of the CubeSat Payload



Spectra of the laboratory magnetic environment and SWARM Mangetometers at LEO



I. Mateos et al., Design of a CubeSat payload to test a magnetic measurement system for space-borne gravitational wave detectors, S&A, 273 (2018)

Impacts and Prospects for the future

- **Increase the technological maturity** of the magnetic measurement system based on chip-scale sensors.
- The experiment will serve to understand the **noise behavior under a long-term space environment**.
- **Best noise characteristics published so far** with anisotropic magnetoresistive sensors in the millihertz bandwidth.
- **Magnetoresistive** sensors are identified as potential candidates for the development of **high-performance magnetometers for magnetically sensitive space missions.**
- CubeSat constraints do not influence the noise performance of the system in the measurement bandwidth.
- **Prospects for the Future** ➡ Evolved versions of the experiment are being developed for future CubeSat platforms employed for testing emerging technologies in space:
    - ALISIO (IAC)
    - CubeSatCarrier (H2020)
    - UCAnFly (Fly Your Satellite program – ESA)