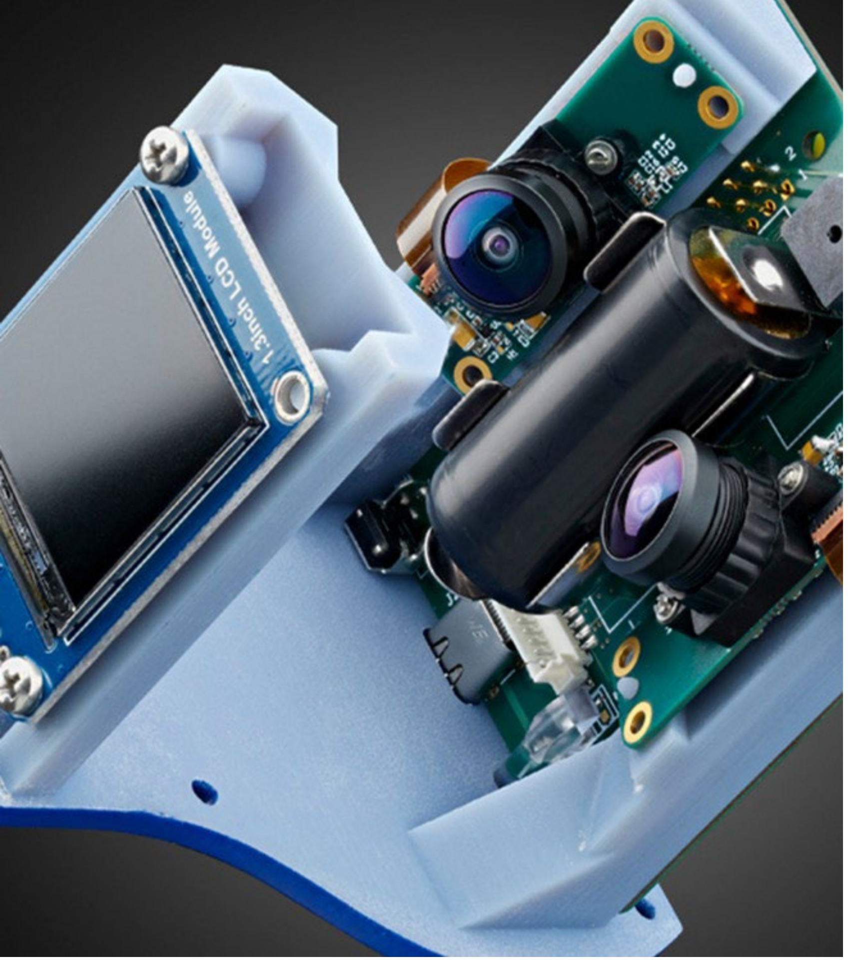

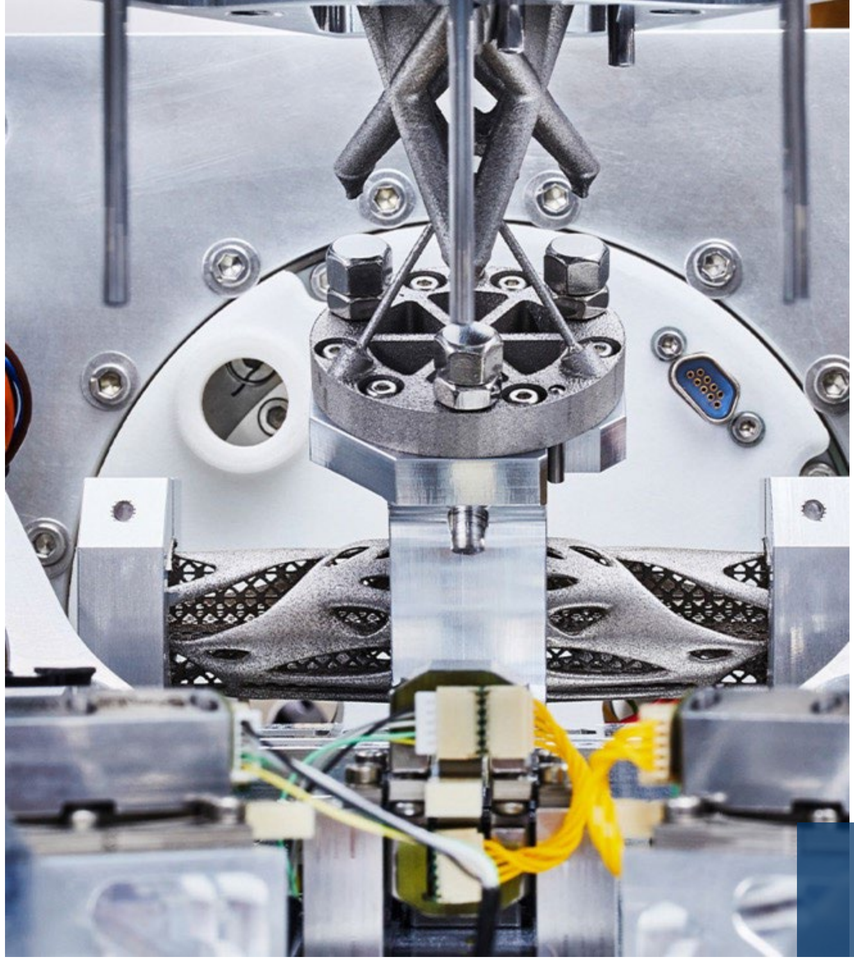

9 September 2025

OPTICALLY PUMPED MAGNETOMETERS FOR EARTH OBSERVATION (AMARETTO) FINAL REVIEW MEETING

ESA Contract No. 4000145835/24/NL/FFi

csem ICFO GFZ Helmholtz Centre for Geosciences

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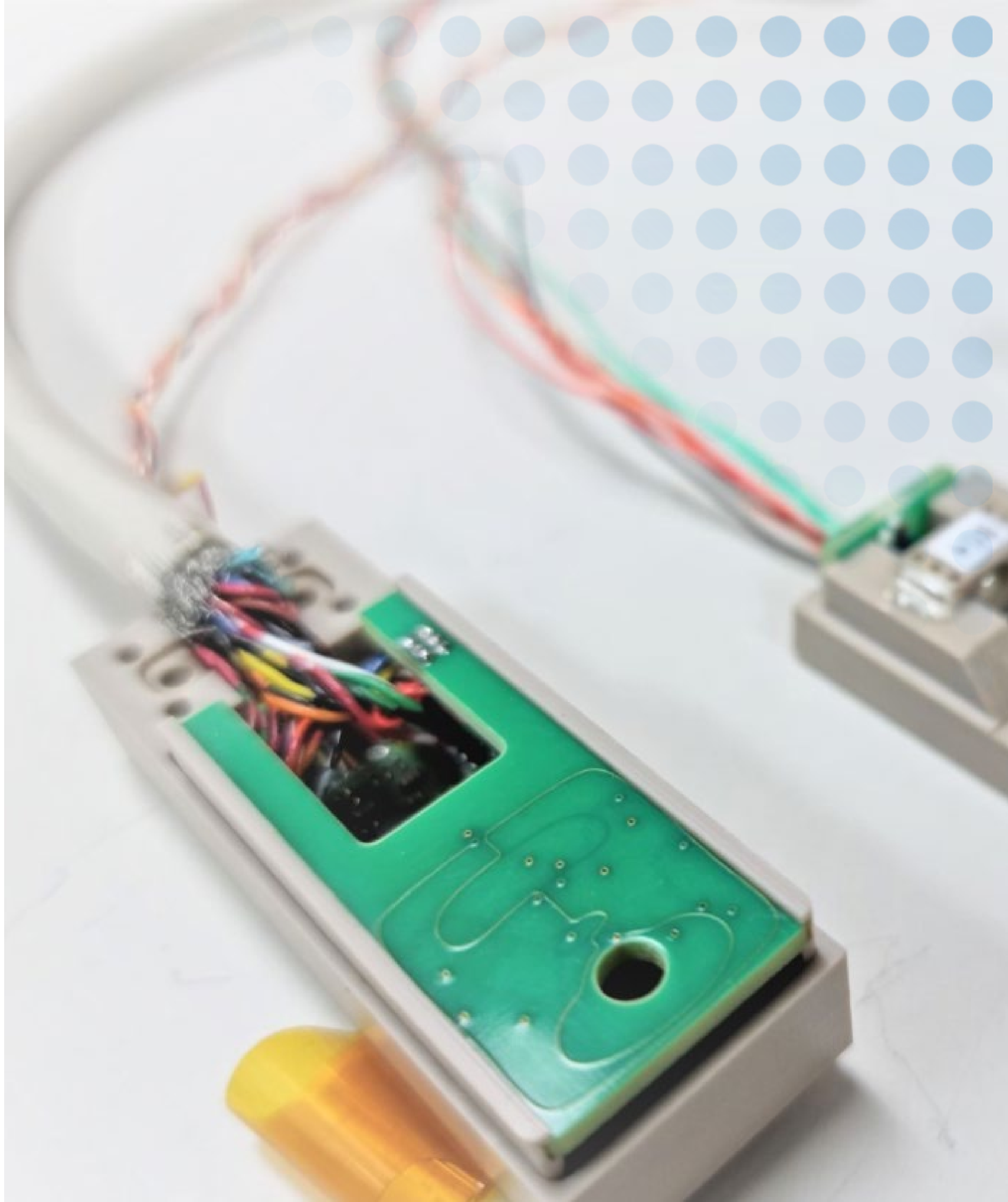
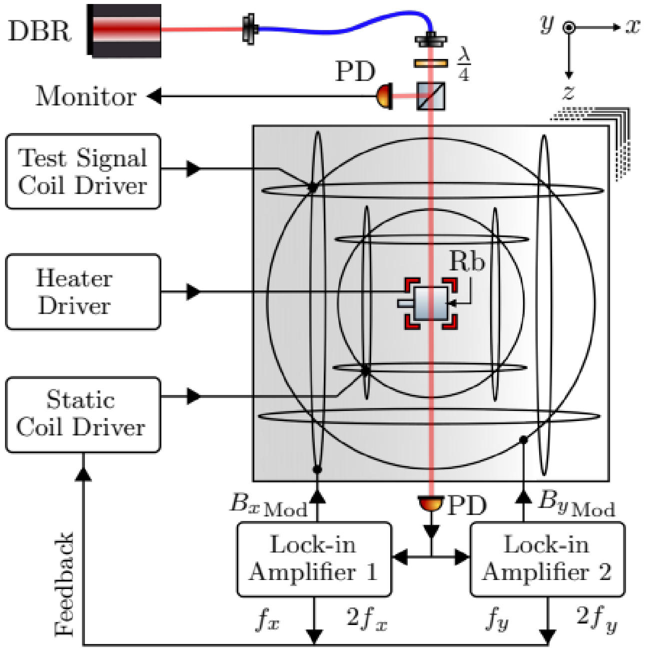
UPDATE ON REQUIREMENT DEFINITION



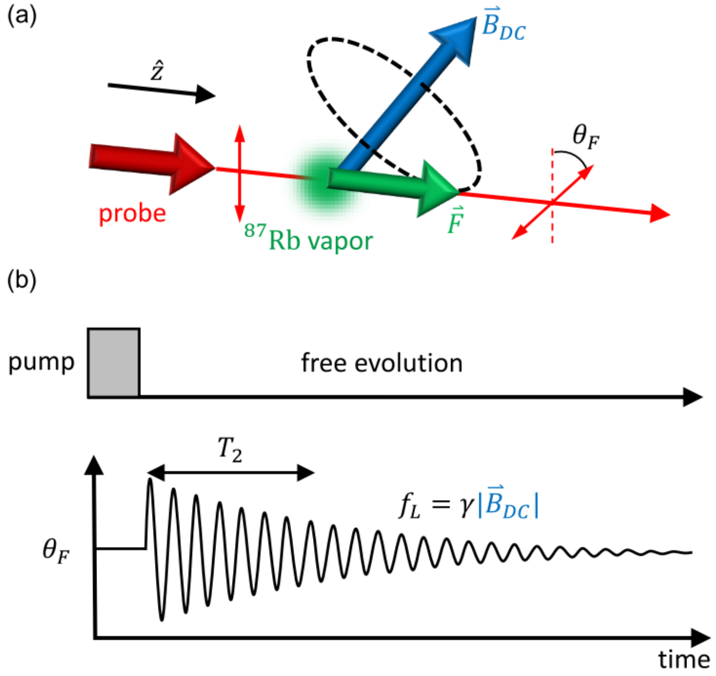
MOTIVATION

- The scalar and vector OPMs are merged into one self-calibrating vector OPM
- Vector OPM technology: zero-field nulling using rubidium 87
- Scalar OPM technology: free-induction decay
- Original requirements for two sensors are merged into one set of requirements

10.48550/arXiv.2408.12994



Vector OPM



Scalar OPM

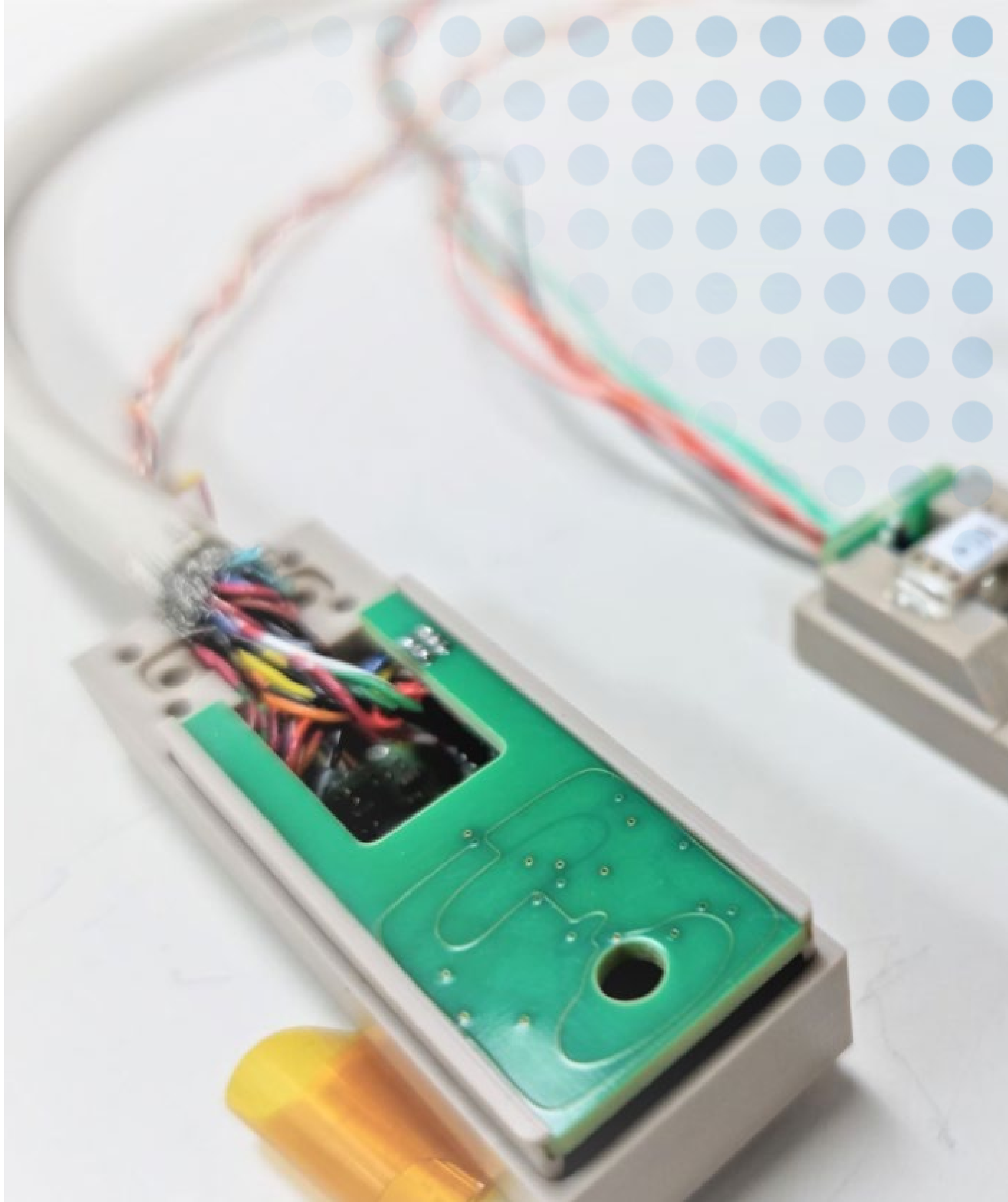
INSTRUMENT-LEVEL REQUIREMENTS 1/2

Ref.	Parameter	Value	Unit	Remark
Functional				
RQS10	1 highly accurate vector magnetic field strength signal			
RQS20	Functional modes ON and OFF			
RQS30	No maintenance in OFF mode			
RQS40	“health status” and telemetries to debug and assess lifetime behaviour			
RQS50	Data rate / Cadence	250	Hz	Needed for external fields detection
RQS60	Warm-up time	< 3600	s	
Performance				
RQS110	Dynamic range	65	μT	
RQS120	Bandwidth	400	Hz	Bandwidth is half burst mode data rate (RQS60)
RQS130	Resolution	10	pT/sqrt(Hz)	Value calculated from RQS120
RQS140	Accuracy	< 0.8	nT	Over the full instrument lifetime (RQS370)
RQS150	Drift	3	pT/month	TBC: value calculated from RQS140 and RQS370
RQS160	Deadzone	Deadzone free		

INSTRUMENT-LEVEL REQUIREMENTS 2/2

Ref.	Parameter	Value	Unit	Remark
Size, Weight and Power consumption				
RQS210	Mass	< 200	gr	Design goal: < 100 g
RQS220	Volume	< 200	cm^3	Design goal: < 100 cm^3
RQS230	Voltage supply	TBD	V	TBD in function of satellite /mission
RQS240	Sensor power consumption during warm-up	< 3	W	Under vacuum, over the full range of temperature (RQ310), design goal: <2W
RQS250	Power consumption	< 2	W	Under vacuum, over the full range of temperature (RQ310)
Environment				
RQS310	Operating temperature	-15 to 55	°C	
RQS320	Storage & OFF mode temperature	-55 to 85	°C	
RQS330	Random vibration	TBD	grms	Mission / satellite dependent, TBD according to [AD 1]
RQS340	Micro-vibration	TBD	mg	Mission / satellite dependent, TBD according to [AD 1]
RQS350	Shock	TBD	g	Mission / satellite dependent, TBD according to [AD 1]
RQS360	Radiation	TBD	Krad	Orbit and inclination dependent, TBD according to [AD 2]
RQS370	Lifetime	20	years	
RQS380	Operates both in vacuum and ambient conditions			

SENSOR OPERATION PRINCIPLE

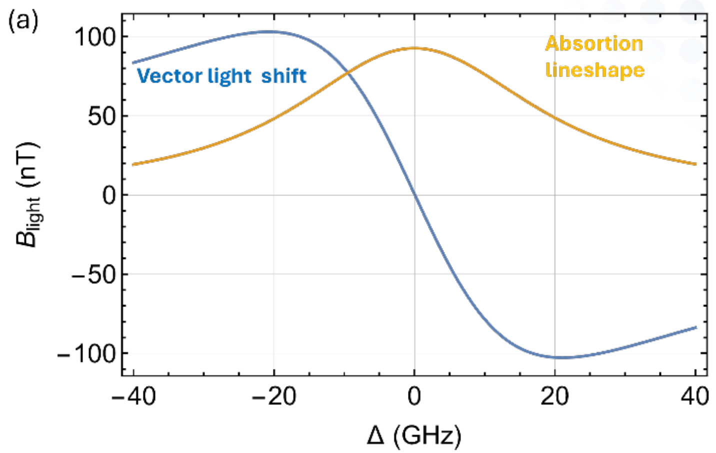


OVERVIEW

- Features:
  - Dual-use, scalar and vector, sensor

    ➔ Tempting to merge the two OPMs types in one cell to save SWaP
  - Three orthogonal rubidium zero-field nulling (ZFN) vector OPMs in one MEMS vapor-cell

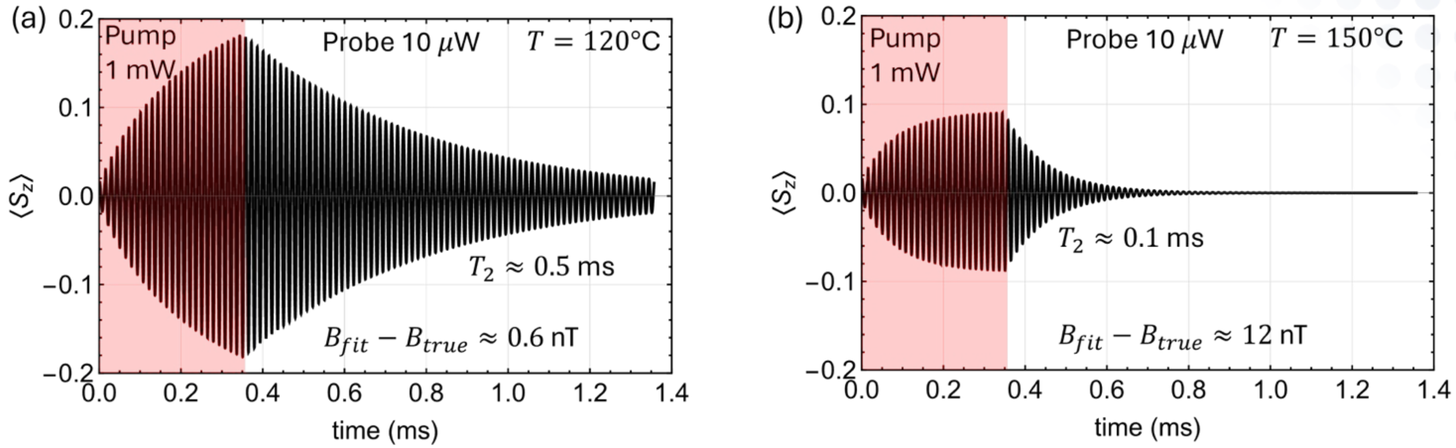
    ➔ Single-axis ZFN vector OPMs suffer from systematics (e.g. vector light-shift) on light-propagation axis. Might even need an extra vapor-cell to stabilize the laser frequency.

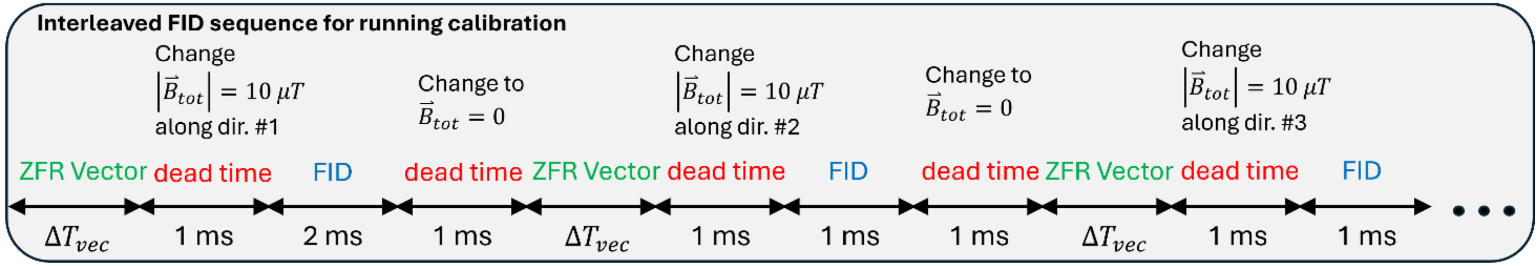


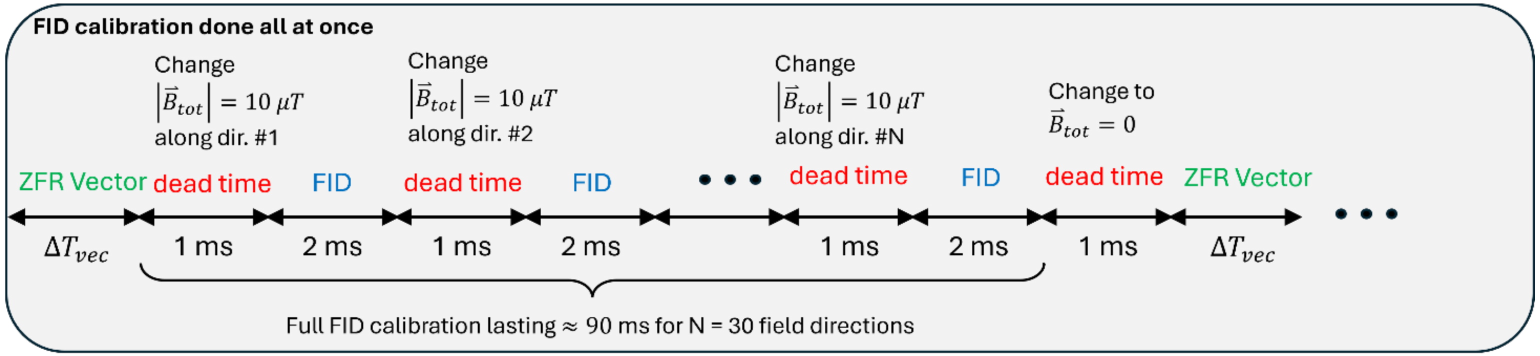
- Challenges
  - Involved recalibration scheme introducing deadtimes in data stream
  - Field homogeneity mut be scaled to bigger volume

CALIBRATION PROCEDURE

- Scalar measurement by means of free-induction decay (FID) technique
- Two possible procedures:
  1. Vector and scalar measurements are continuously interleaved
  2. Continuous vector mode is interrupted by a scalar recalibration
- 27 degrees of freedom (9 for each cavity) + statistics = 90 ms procedure





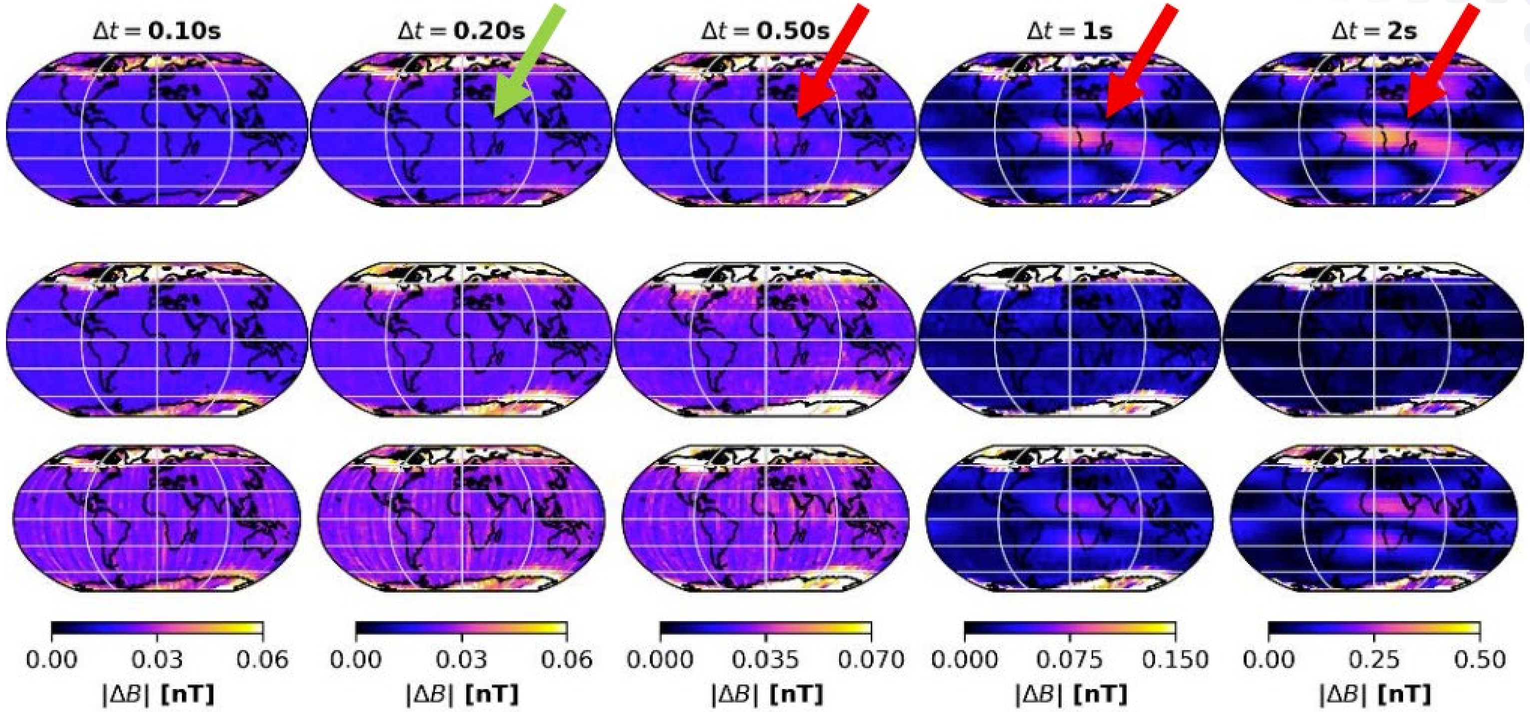


MAXIMUM ALLOWED CALIBRATION DEADTIME

- 50+ hours simulations of data quality with deadtimes using SWARM A data (similar results using SWARM B data)

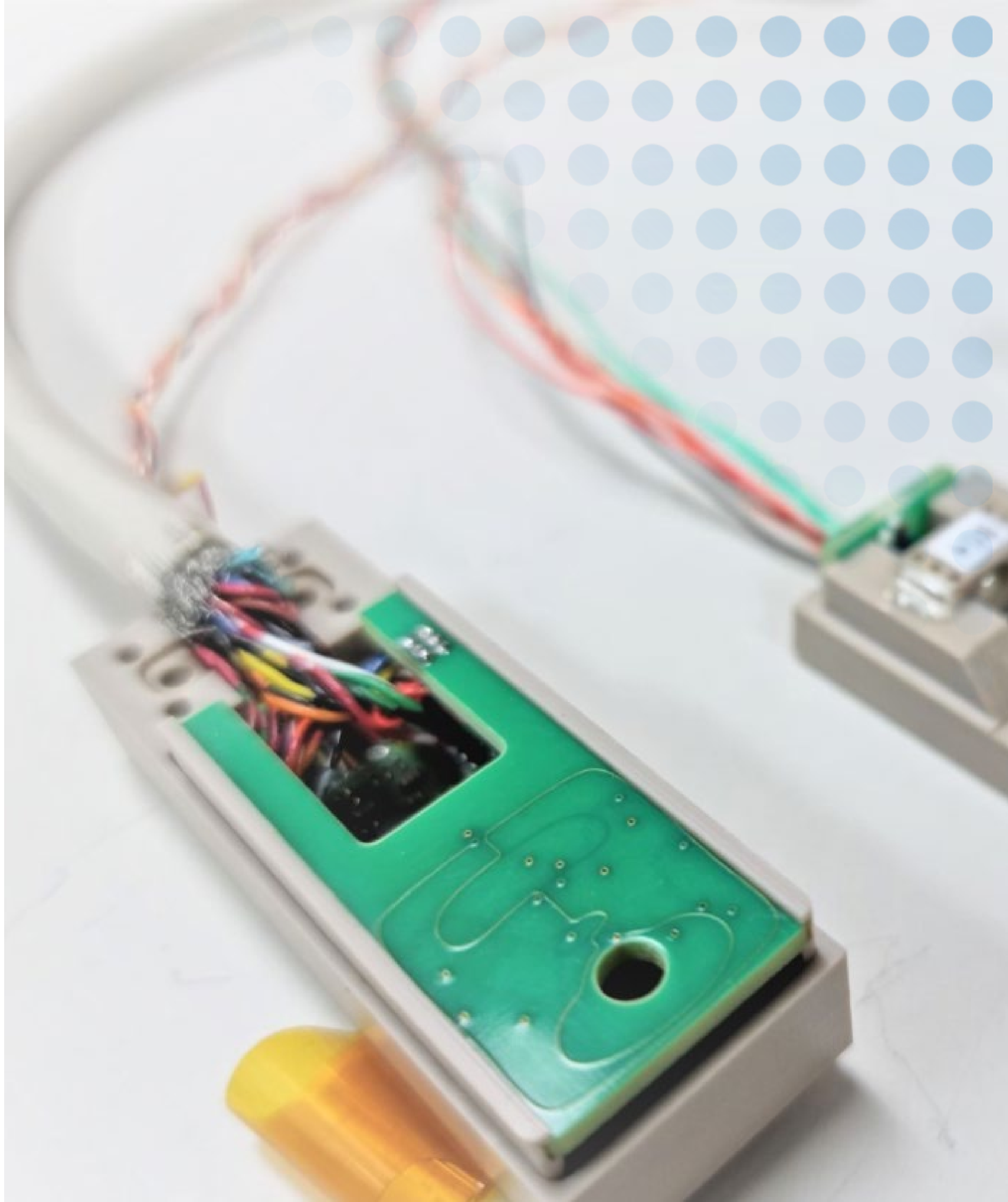
Swarm A

Gap Size [seconds]	99th Percentile [nT]	95th Percentile [nT]	Source
0.02	0.052	0.036	HR
0.04	0.114	0.077	HR
0.1	0.136	0.091	HR
0.2	0.141	0.094	HR
0.5	0.155	0.103	HR
1	0.205	0.099	LR
2	0.363	0.282	LR
3	0.798	0.619	LR
5	2.21	1.708	LR
10	8.799	6.809	LR



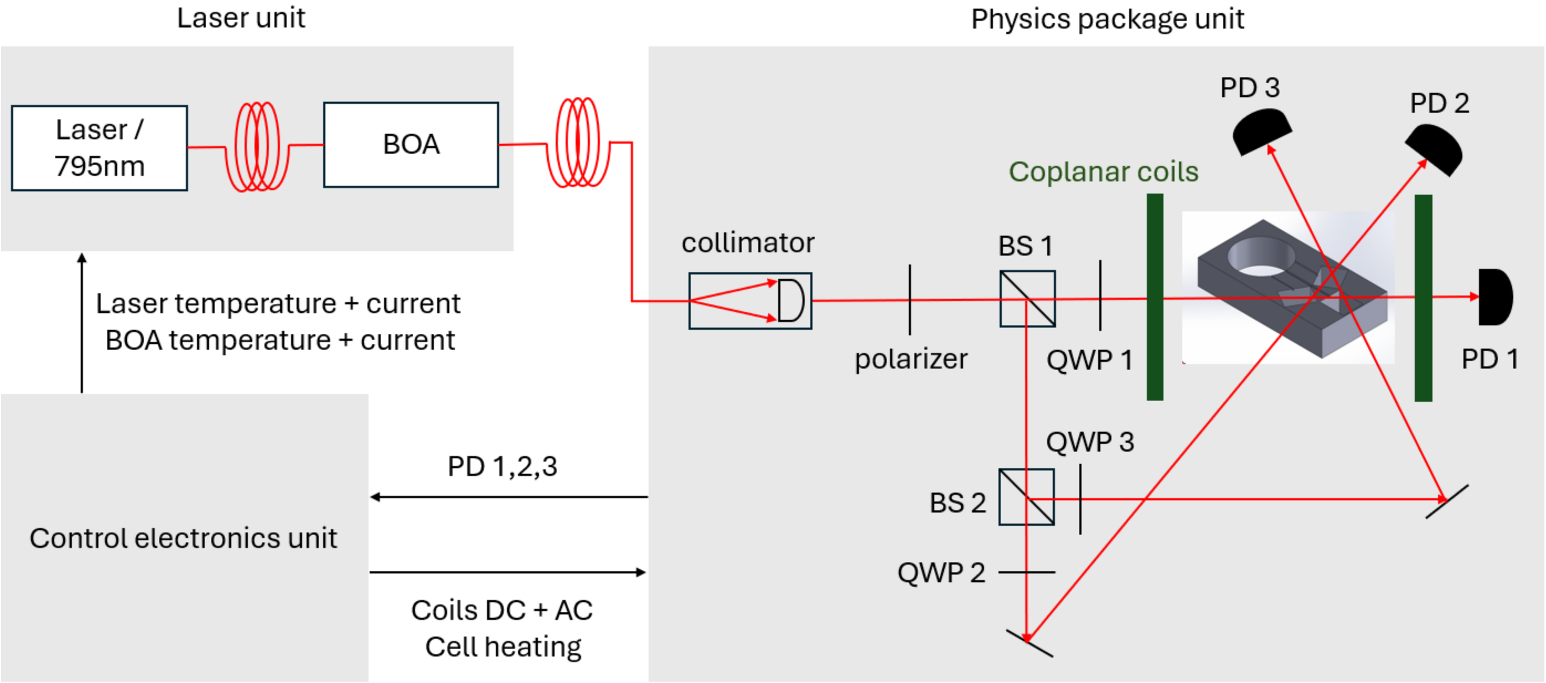
➔ 100ms deadtime leads to 0.136 nT error

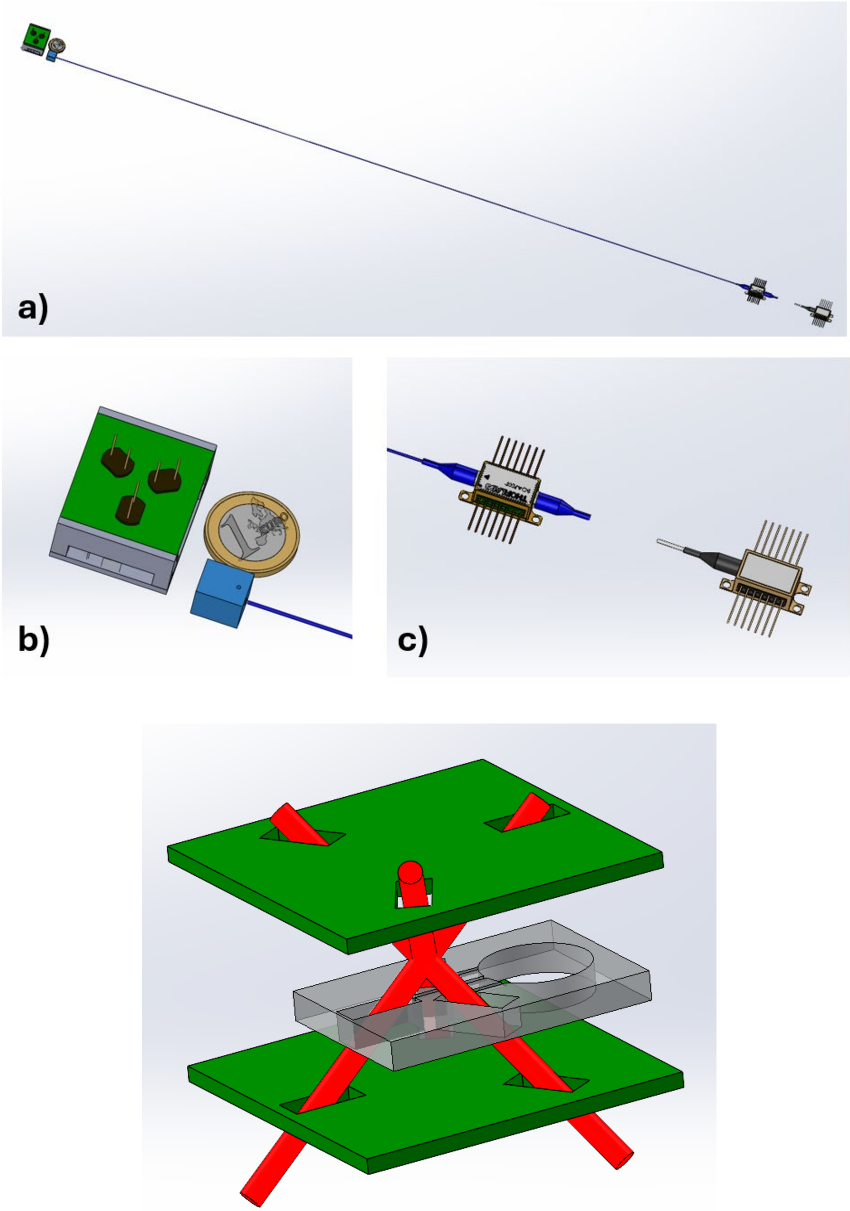
HIGH-LEVEL SENSOR CONCEPT



HIGH-LEVEL CONCEPT

- Single laser source with semiconductor optical amplifier (SOA/BOA)
- One MEMS vapor-cell with three cavities
- Light is distributed using free-space optics





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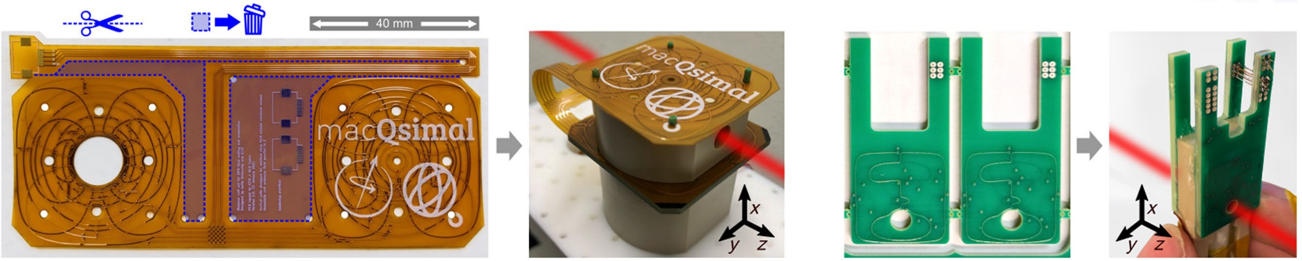
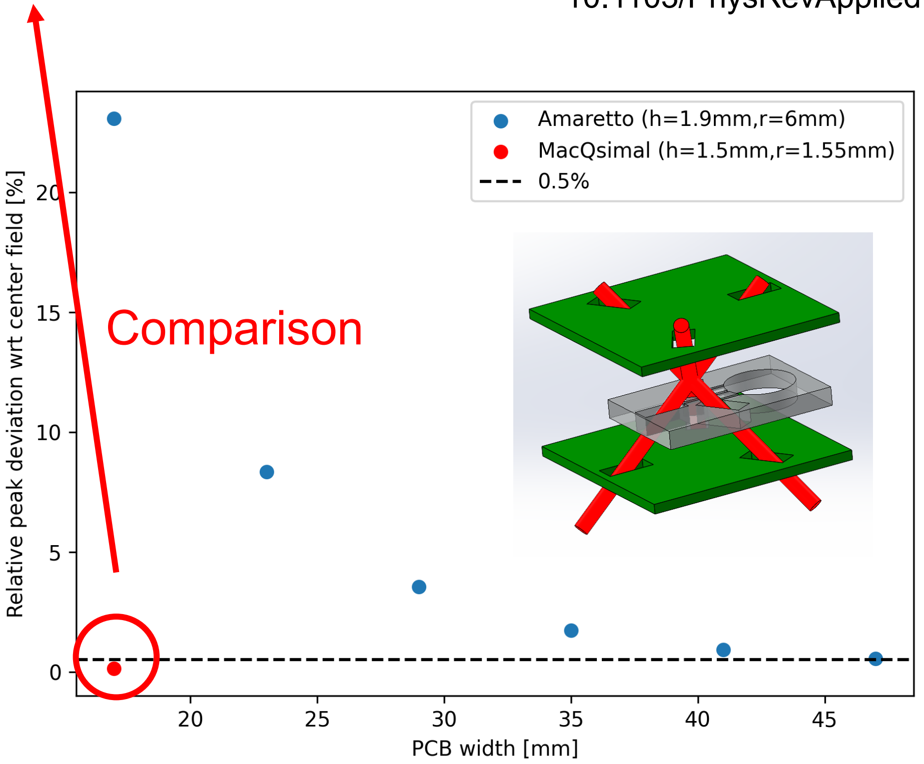
SWAP / SIZE AND WEIGHT

- Estimated from CAD
- 3 sets of coplanar PCB coils (one for each axis) simulated with *bfieldtools*
- Final size of PCB coils unknown because vapor-cell is bigger
- Simulation with pair of square Helmholtz coils lead to worst case scenario of 47mm wide PCB coils to match smaller vapor-cell field homogeneity ➔ updated SWaP



10.1103/PhysRevApplied.18.014036



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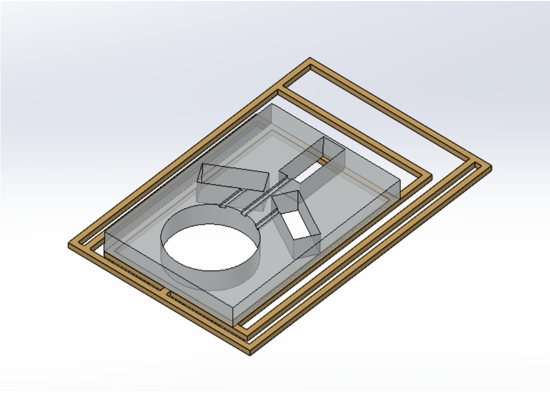
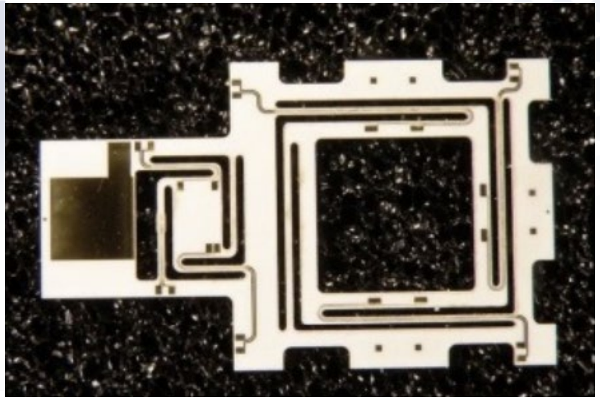
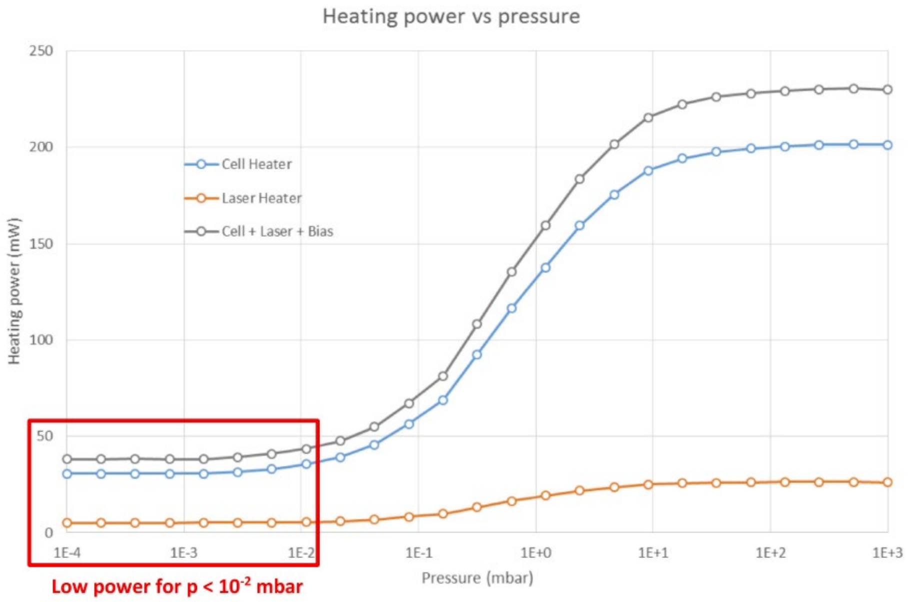
SWAP / AND POWER

- Preliminary estimate of SWaP from electronics, cell heating and laser consumption
- Heating efficiency is improved in vacuum thanks to isostatic holder





Func.	Des.	Current [mA]	Voltage [V]	Power [mW]	N° of devices	Power [mW]	Package	Size [mm]
TIA	ADA4350	10	5	50	3	150	TSSOP-28	10x7
ADC	ADS8688	16	5	80	1	80	TSSOP-38	10x7
FPGA	Igloo nano AGLN250	100	1.5	150	1	150	VQG100	14x14
DAC	AD5676R	4	5	20	1	20	LFCSP	4x4
Others						300		
Total						700		



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ESTIMATED PERFORMANCES AND SWAP

	Size [L]	Weight [g]	Power [W]
Laser	0.10	40	1
Physics package	0.08	30	50mW + coils
Control electronics	0.06	50	0.7
Total	0.24	120	1.75
Requirements	0.20	200	2.00

- SWaP requirements close to be met, with some unknows
- Final error is already largely dominated by non-sensor related error sources

Error	Value
Instrument	0.19 nT
Other sources	0.54 nT
Total	0.73 nT
Requirement	0.80 nT

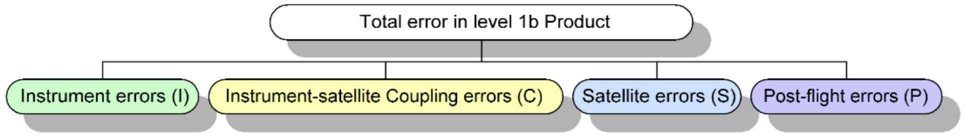

***Figure 6.1**: Error sources contributing to the final Level 1b product error.*

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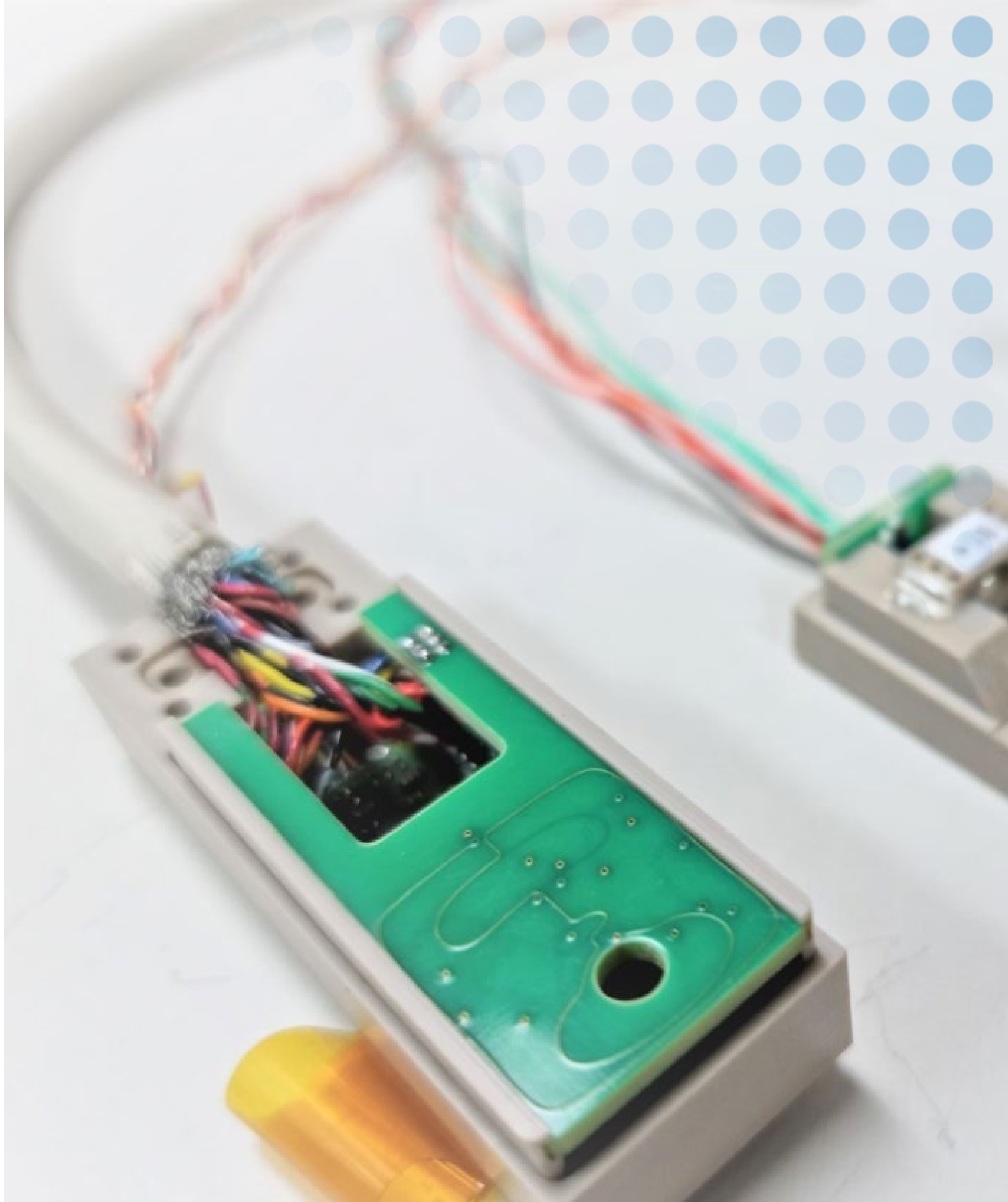
TECHNOLOGY DEVELOPMENT PLAN



MODEL PHILOSOPHY AND DEVELOPMENT PLAN

Phase	Model	Start TRL	Target TRL	Start date	End date	Prototype, demonstrator. Normally more than just labo experiment.
DR	De-Risk	2-3	3	Q1 2026	Q4 2026	Objective 1: Demonstration of the proposed interrogation scheme in a laboratory experiment with representative key elements (cell, laser). Objective 2: Confirmation of achievable performances (sensitivity, accuracy, drift) Objective 3: refinement of the high-level architecture and update of the system requirements
B	Elegant Breadboard (EBB)	3	4-5	Q1 2027	Q3 2028	Objective 1: Prototype, demonstrator close to the final equipment in terms of mass, volume, power consumption functionality. Objective 2: Preliminary design of the laser, physics and control sub-systems in view of the EM. Objective 3: Evaluation of critical elements in term of environment (radiation, vibration, shock, temperature). The Material, Parts and Processes Evaluation will be conducted in this phase as continuation of the derisk activity.
C1	Engineering Model (EM)	4-5	6	Q4 2028	Q2 2030	Objective 1: Engineering Model design and MAIT. EM will be form fit and function identical to the FM. Preliminary environmental test will be conducted with EM. Objective 2: QM/FM design.
C2	Engineering Qualification Model (EQM) or Qualification Model (QM)	6	7	Q3 2030	Q1 2032	Objective 1: One QM Model identical to the FM that will be submitted to a test campaign with environmental constraints higher than expected in the reality. Objective 2: One EQM for long-term testing. EQM's may use not qualified EEE parts (mainly for schedule reason) but the selected replacement parts must be in the same packaging and with same performances. Objective 3: The product qualification review will be conducted at the end of this phase. Full qualification of the product will be conducted after successful FDM operation in orbit.

CONCLUSION

- A state-of-the-art review of OPM magnetometers and scientific spaceborne earth observation magnetometry has been realized
- Based on these review, observation scenarios have been identified, and performance requirements have been deduced
- Instrument-level requirements have then been gathered for a self-calibrating vector OPM instrument
- A sensor operation principle and a high-level sensor design were formulated
- A model philosophy and a development plan were proposed

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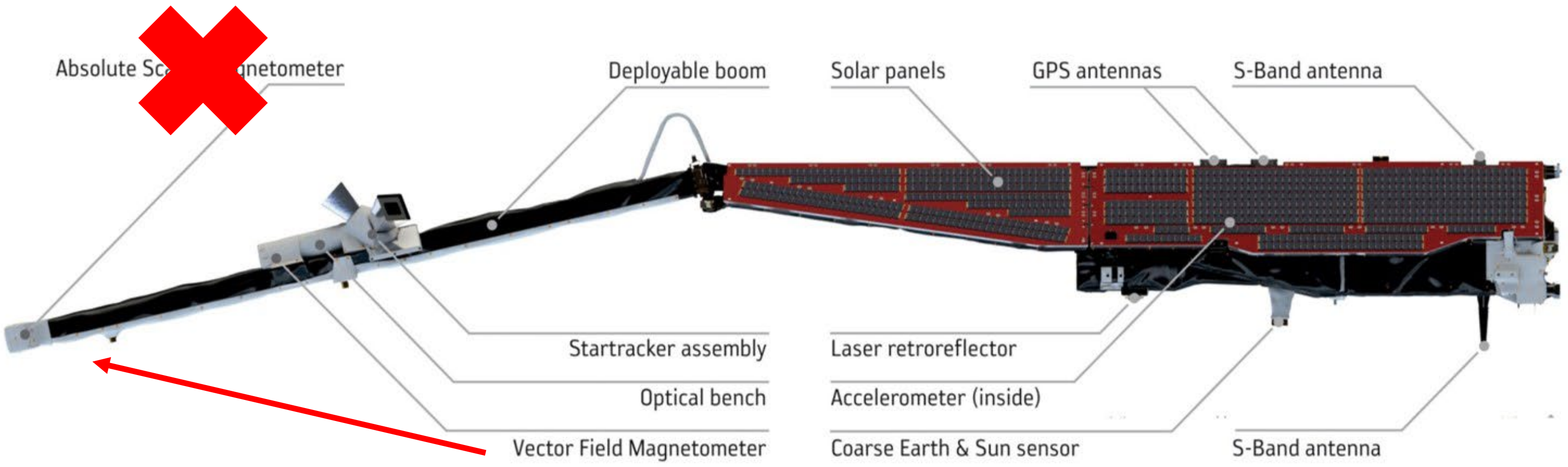
FACING THE CHALLENGES OF OUR TIME

SUPPLEMENTARY MATERIAL / STAR TRACKER STRAY FIELDS



$$\frac{m}{d^4} < \frac{2\pi}{3\mu_0}\frac{\Delta B}{\Delta x}$$