Advanced DC and AC Magnetic Verification (ADAM)

Final Presentation (FP)

18 April 2024

Ref.: ADAM.2021-4169.FP.001

DEFENCE AND SPACE

ADAM Team

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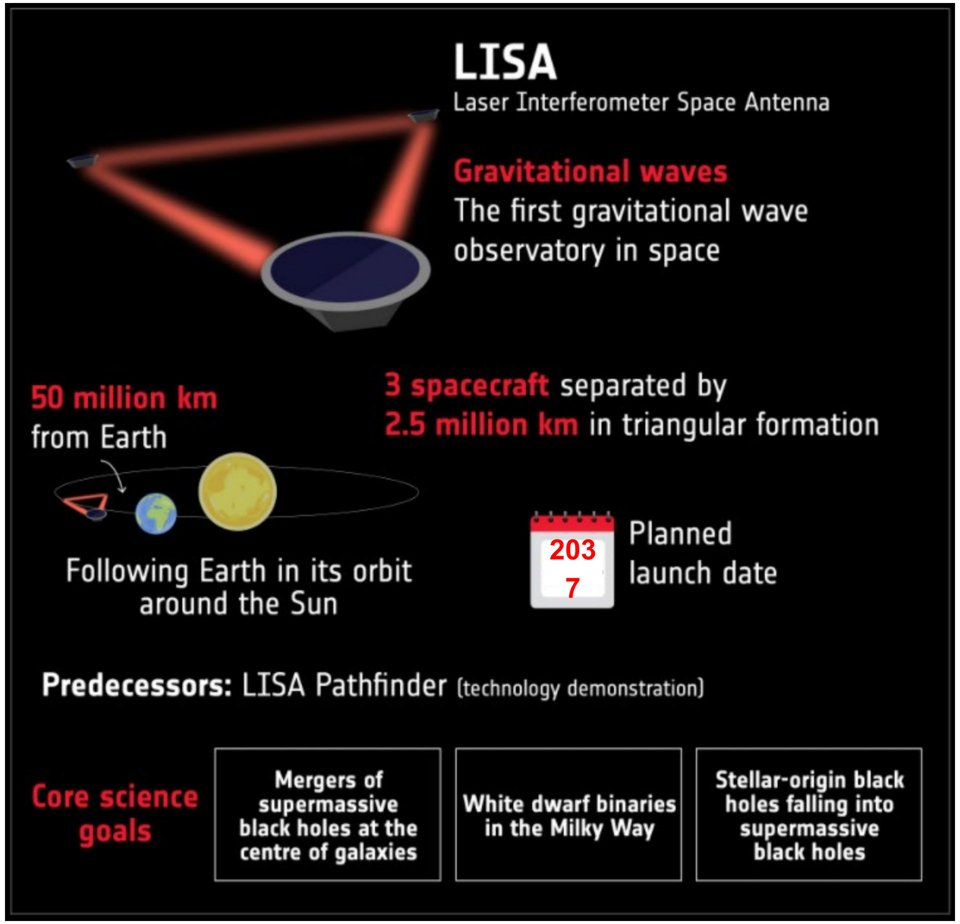
Agenda

- **Background**
- **Study History**
- **Objectives**
- **Preliminary Investigations and Main Trade-off**
- **Facility Design**
- **Facility Performance Demonstration**
- **Next Steps and Future Work**

Background

Background

- **Laser Interferometer Space Antenna (LISA) Mission**
  - LISA is designed to be the first ever gravitational wave observatory in space
  - The mission comprises three spacecraft that each contain two free-floating test masses (TMs)
  - Gravitational waves cause picometer changes in the distances between the TMs, measured interferometrically across a distance of approximately 2.5 million km between spacecraft
  - Most gravitational waves are expected to be visible at frequencies between 10^{-4} Hz and 1 Hz, driving the need for low frequency verification methods
  - Despite nominally non-magnetic TMs (a gold-platinum alloy), the interferometer is very sensitive, meaning even small magnetic field variations can result in an acceleration force
  - Studied in great detail on LISA Pathfinder (LPF)!



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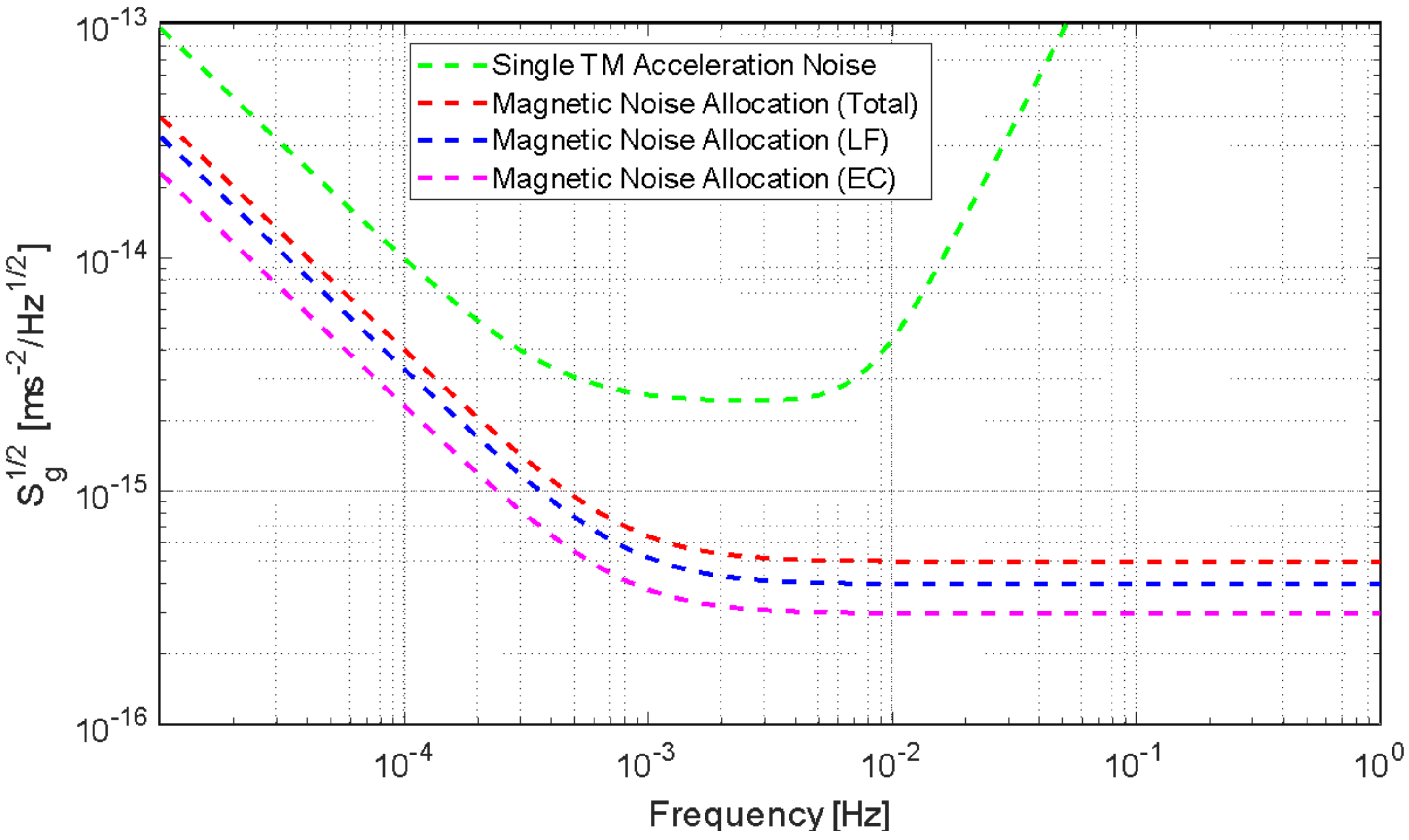
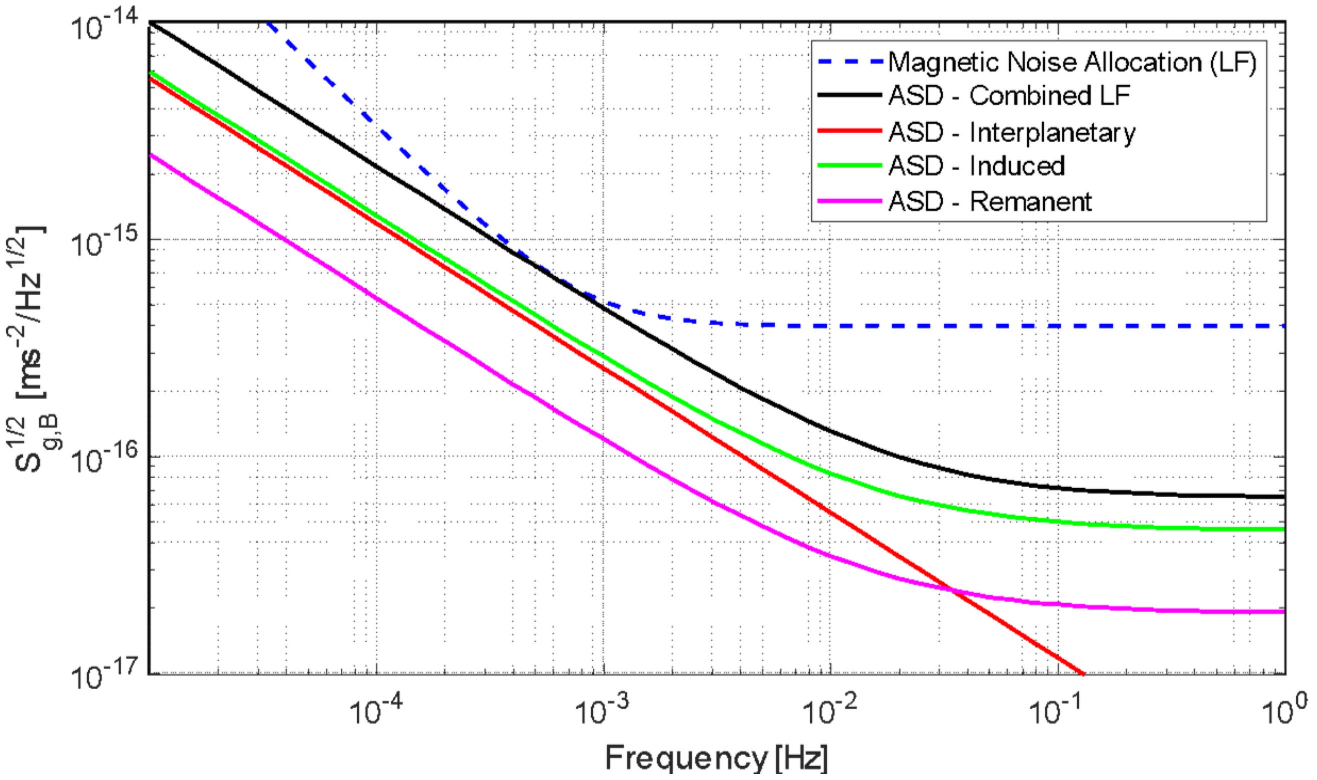
Background

- **LISA Requirements**
  - Magnetic noise is one part of the total TM acceleration noise, with contributions from low frequency (LF) sources directly in the measurement band
  - High frequency continuous magnetic spectral density as well as amplitude modulated narrowband sources will generate acceleration noise in the measurement band (labelled Eddy Current or EC)



Background

- **LISA Requirements**
  - The LF allocation can be further split into:
    - Interplanetary magnetic field (IMF) fluctuations coupling to the TM induced magnetic moment and a local field gradient
    - Local (on-board) field fluctuations coupling to the TM induced magnetic moment and a local field gradient
    - Field gradient fluctuations coupling to the TM remanent magnetic moment
  - On LPF, the in-flight observed magnetic acceleration noise was dominated by the first effect
  - … and overall much lower than worst-case expectations!



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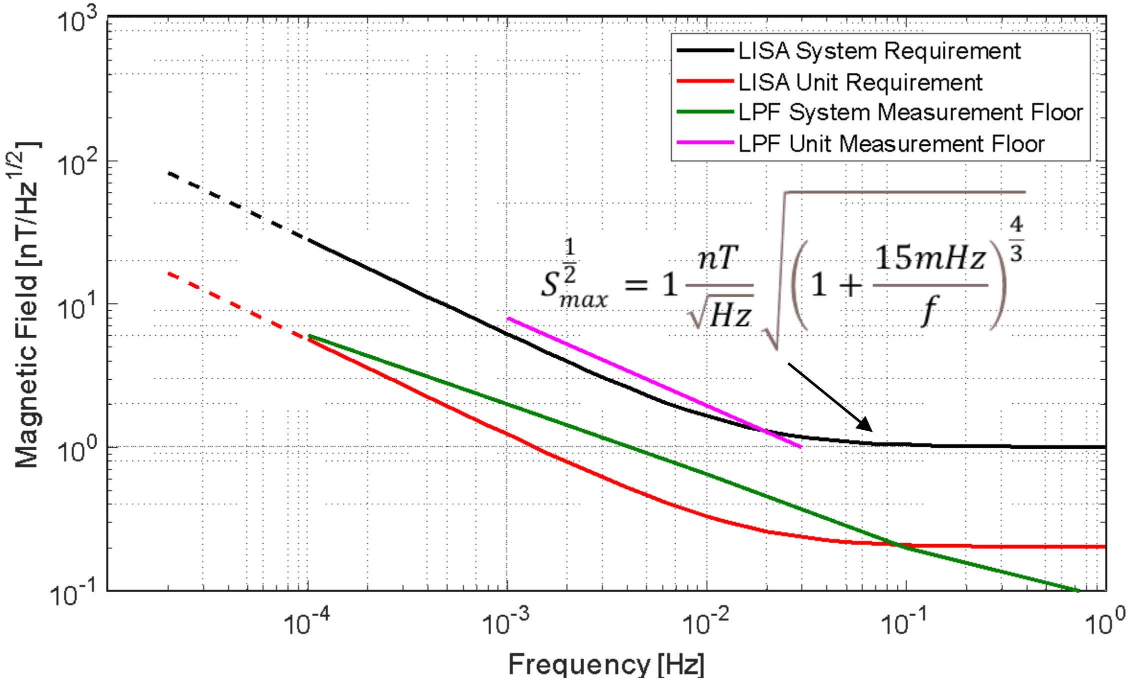
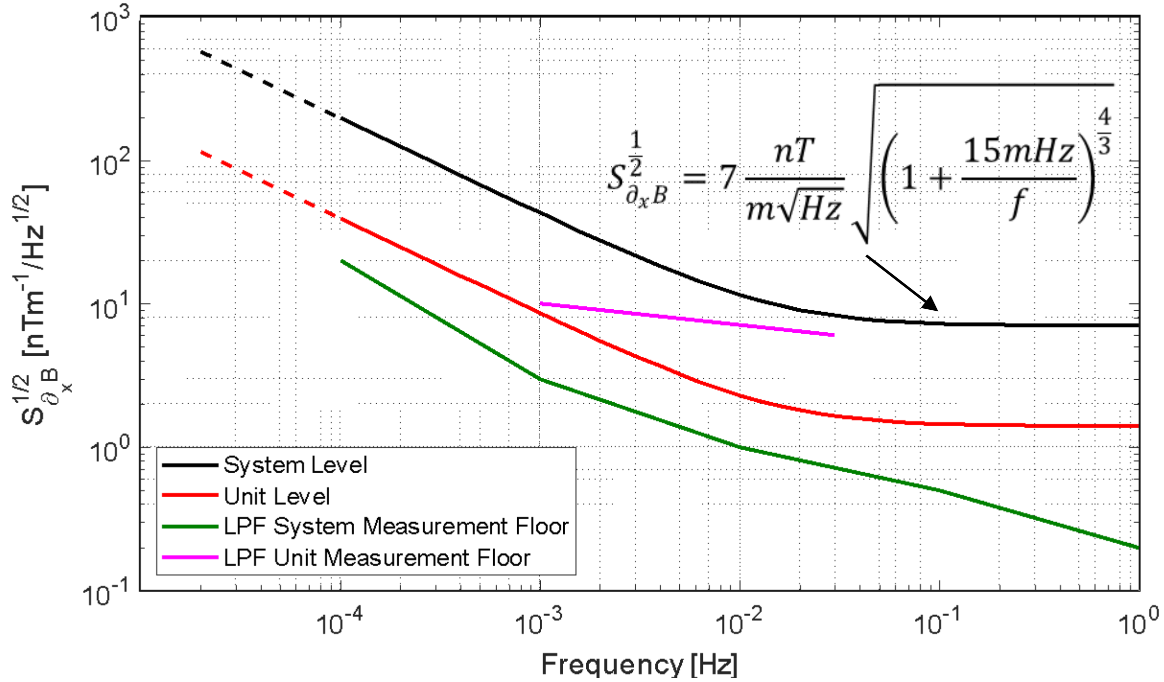
Background

- **LISA Requirements**
  - The resulting system level magnetic amplitude spectral density (ASD) can be directly measured at system level, but once allocated into unit level (assuming 25 units of equal contribution), the levels are challenging to meet due to the smaller unit contribution compared to the expected background environmental noise

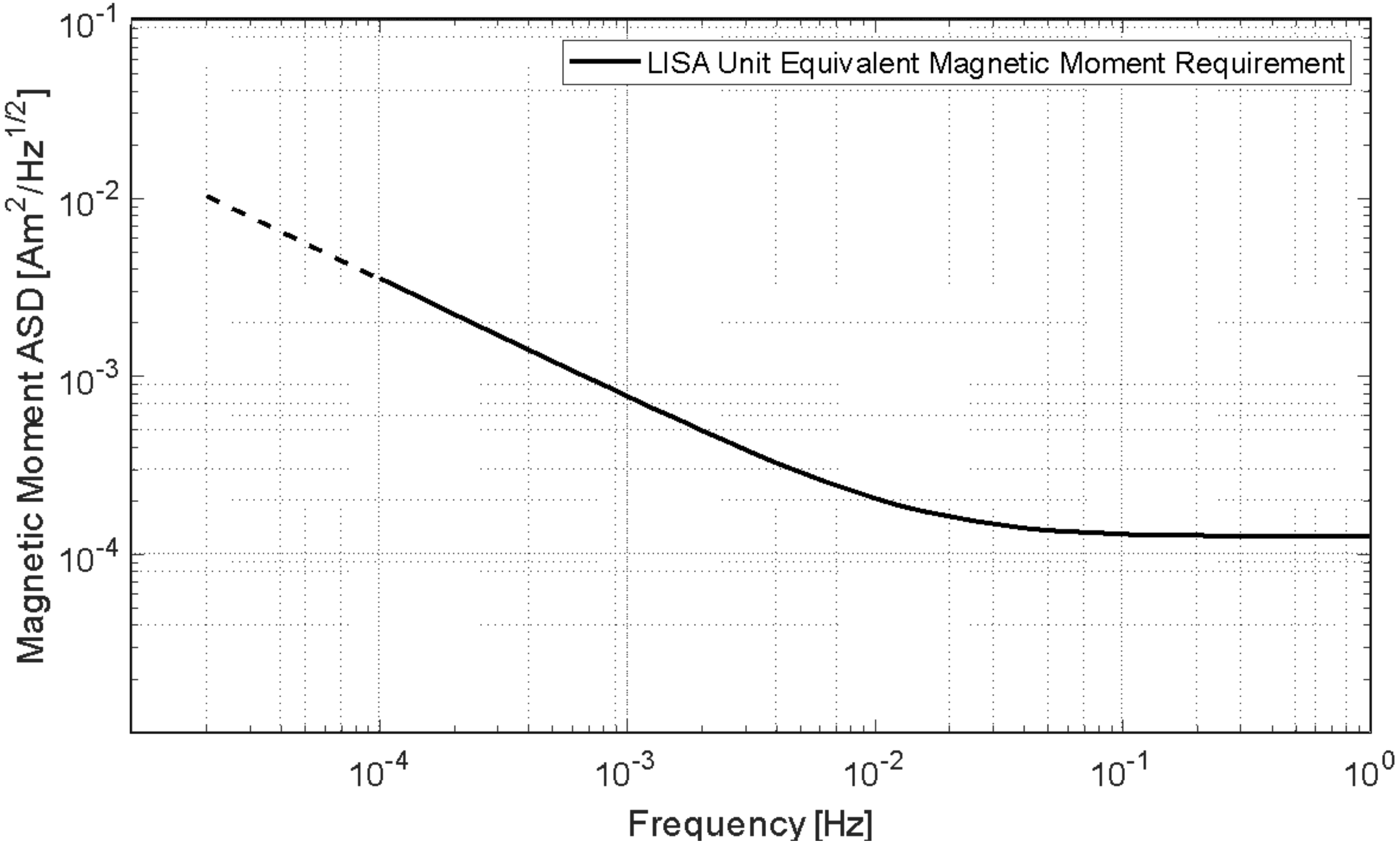




- Unit level test requirements considerably more challenging than for LPF!

Background

- **LISA Requirements**
  - The magnetic field ASD can be converted into an equivalent magnetic moment (at a given frequency), assuming the distance from a unit to the closest TM is 0.5 m
  - From experience, most units behave like a magnetic dipole at sufficient distance
  - Useful metric if unit is characterised in terms of magnetic multipoles



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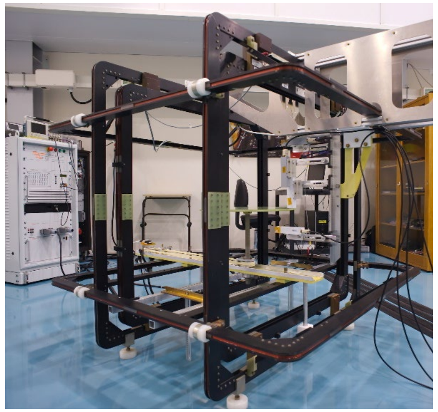
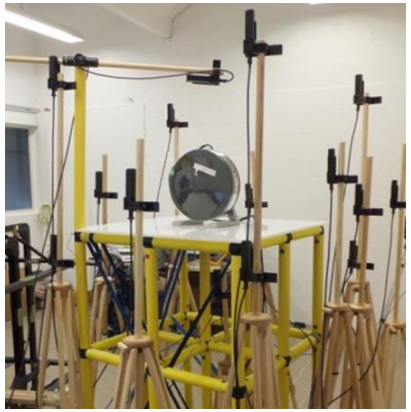
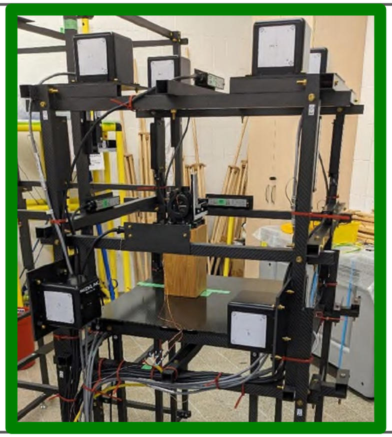
Study History

Study history

- **As performed**
  - ITT issued in April 2021
  - Proposal submitted in June 2021
  - Invitation to negotiation received in July 2021
  - Negotiation in September 2021
  - Study kick-off in October 2021
  - Preliminary concept review (PCR) October 2022
  - Demonstration frame constructed Summer 2022
  - Design review (DR) May 2023
  - Final frames constructed Summer 2023
  - Test readiness review (TRR) September 2023
  - Test review board (TRB) February 2024
  - Final presentation (FP) April 2024
- **Scheduled**
  - Final software/hardware delivery May 2024

Objectives

- **Current ESA Magnetic Test Facilities and ADAM**

Mobile Coil Facility (MCF)	Multi-Magnetometer Facility (MMF)	AC Magnetic Facility	Advanced DC and AC Magnetic Facility (ADAM)
			

• DC frequencies
• Earth field compensation using Helmholtz coils
• Turntable used to measure around device under test (DUT)
	• DC frequencies
	• Multiple sensors on mechanical slide to measure around DUT
		• AC frequencies
		• Multiple sensors on tripods surrounding DUT
		• Takes advantage of signal space separation techniques
			• Quasi-DC to AC frequencies
			• Multiple sensors on ultra-stable CFRP frames
			• Takes advantage of:
			  • signal space separation
			  • correlated noise removal

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Objectives

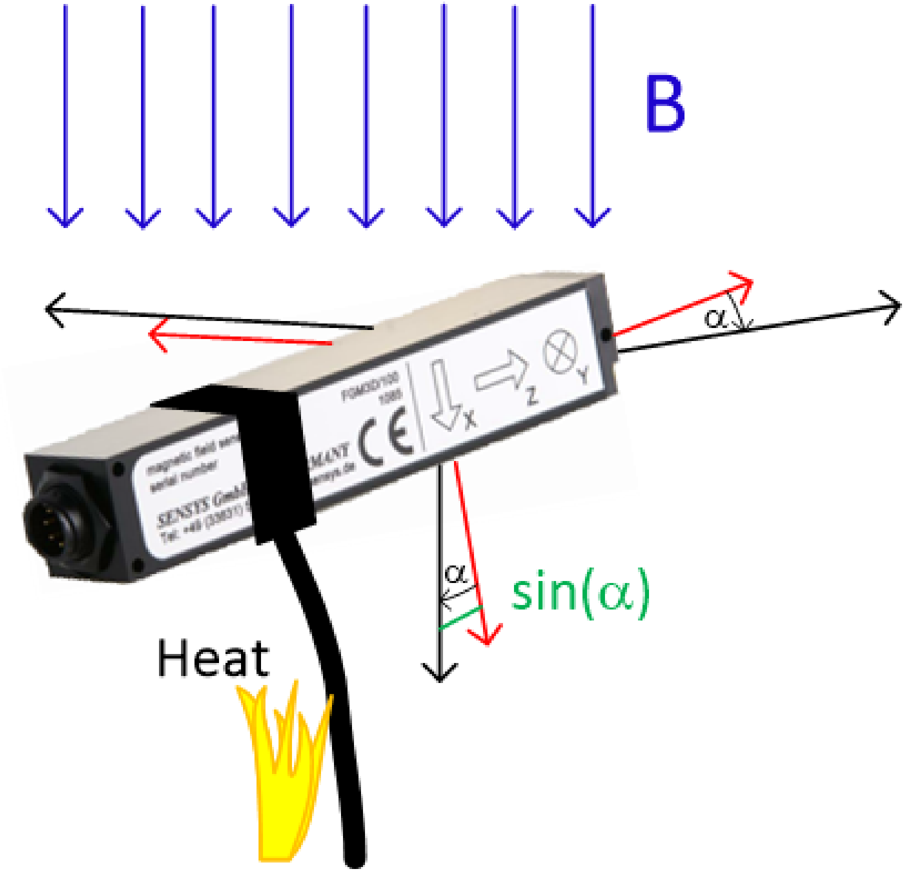
Objectives

- **Scheme of Work**
  - Develop efficient unit level verification and characterisation methods combining quasi-DC [0.1 mHz – 1 Hz] fluctuations and AC magnetic emissions, and covering the special needs of LISA, while constituting a step further applicable to all future science missions requiring magnetic cleanliness control.
  - Build on previous AC magnetic work, but focussing on the detailed characterisation, identification and mitigation of very low frequency (≈ mHz) noise contributions:
    - Thermal couplings
      - Sensor frame TED
      - Sensor thermal sensitivity
      - DAQ
    - Intrinsic Sensor noise
    - Intrinsic DAQ noise
    - Environmental noise

Preliminary Investigations and Trade-off Outcomes

Preliminary Investigations

- **Identification of main disturbance sources at low frequencies**
  - To assist the main trades, a systematic approach was taken to identify all possible disturbance sources and their relevant impacts, including:
    - Sensor scaling with temperature
    - Sensor offset
    - Sensor rotation and translation
    - Thermoelastic distortion of the sensor mechanical support
    - Floor tilt
    - Local field changes and distortions
  - Demonstration measurements and analysis showed the main disturbance sources of relevance are **temperature induced sensor rotation and translation**, driven mainly from the sensor mechanical support distortion



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Preliminary Investigations

- **Mitigating against temperature induced sensor rotation and translation**
  - Three options were investigated to mitigate this effect:

(1) The use of compensation coils in order to minimise ambient field pick-up during sensor rotation & translation

(2) The generation of a pilot tone of known signature in order to track the sensor rotation and translation, with post test correction in data analysis

(3) Minimisation of sensor rotation and translation by manufacturing an ultra-stable sensor array support frame

Mitigating noise due to sensor rotation & translation – Option 1

- **Compensation Coils**
  - To determine the effectiveness of placing the sensor array inside a set of magnetic compensation coils, some trial measurements were performed with an array of sensors inside and outside the MCF
  - It was shown that the impact of thermal patterns e.g. from ambient heating cycles could be improved through the use of compensation coils
  - Unfortunately the current source used to drive the coils actually introduces additional low frequency noise (10 mHz – 1 Hz)
  - Without active compensation, external field variations are not compensated for, only the DC component will be compensated
  - Active compensation was considered, but the complexity and increase in current noise does not justify its adoption

FDH MCF compensation coil trade-off measurements

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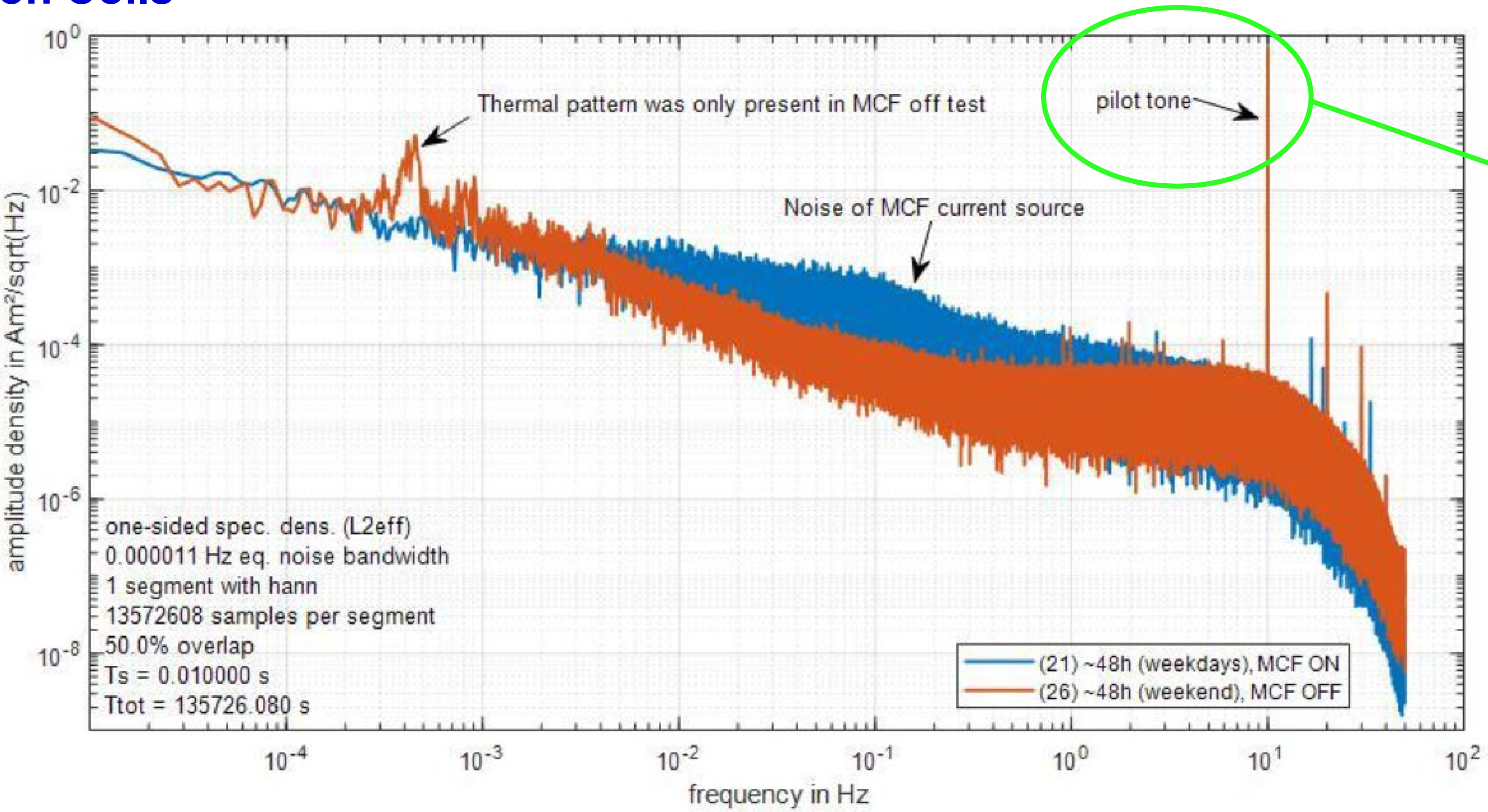
Mitigating noise due to sensor rotation & translation – Option 1

- **Compensation Coils**



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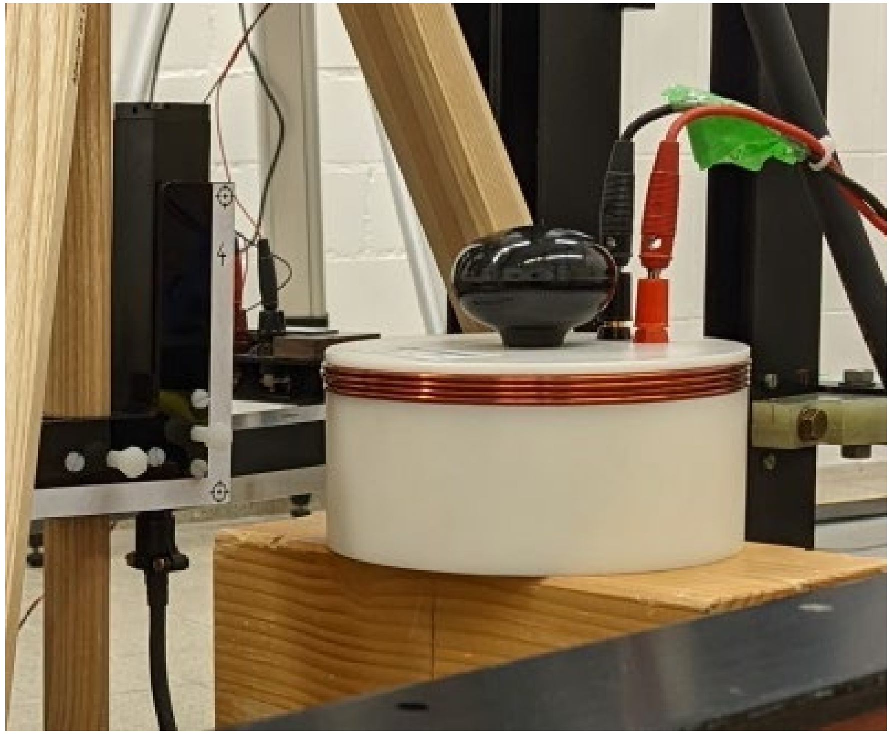
Mitigating noise due to sensor rotation & translation – Option 2

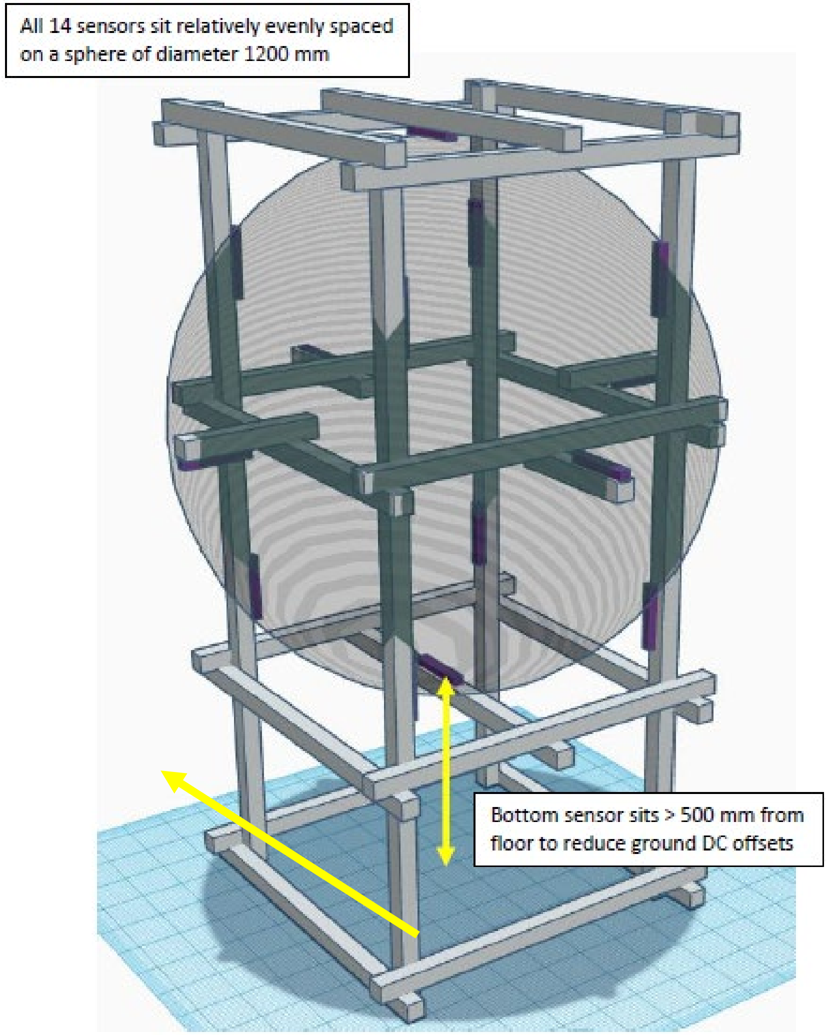
- **Pilot Tone**
  - One way to track the movement of sensors with temperature would be to use a pilot tone signal
  - Several demonstration measurements were performed to determine the merits of such an approach
  - One major drawback of the method is that to generate a large enough signal at all sensors in the frame would require either one strong pilot tone coil in the centre (generating a large field at the DUT) or multiple pilot tone coils outside the sensor array, resulting in higher complexity
  - The pilot tone coil itself would need mounting onto a stable mechanical support, and in the end it was deemed not necessary to use such a signal if the sensors could themselves be mounted onto a sufficiently stable platform



Mitigating noise due to sensor rotation & translation – Option 3

Prototype demonstration frame design

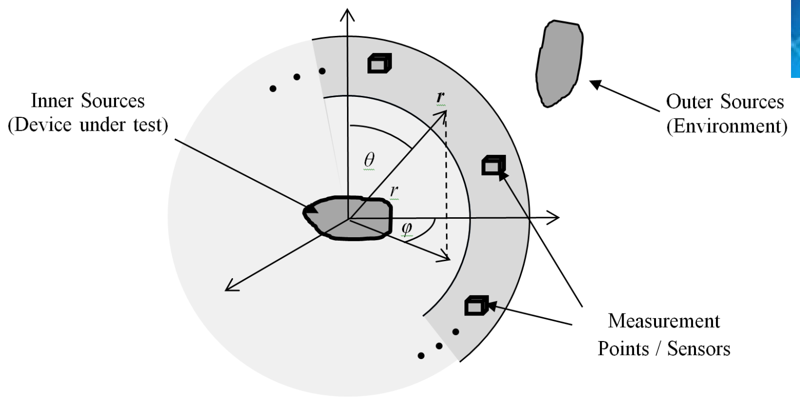
- **Ultra-Stable Sensor Array Support Frame**
  - Wooden tripods as used for previous study were suspected to be responsible for thermally induced sensor translation / rotation
    - Relatively high CTE and potentially CME
  - Replaced by frame made from CFRP
    - Very low CTE
    - Non-magnetic / non-metallic
    - Relatively stiff
  - A demonstration frame with an equal distance to all FGMs of 600 mm was used, which resulted in performance close to but still above the requirement



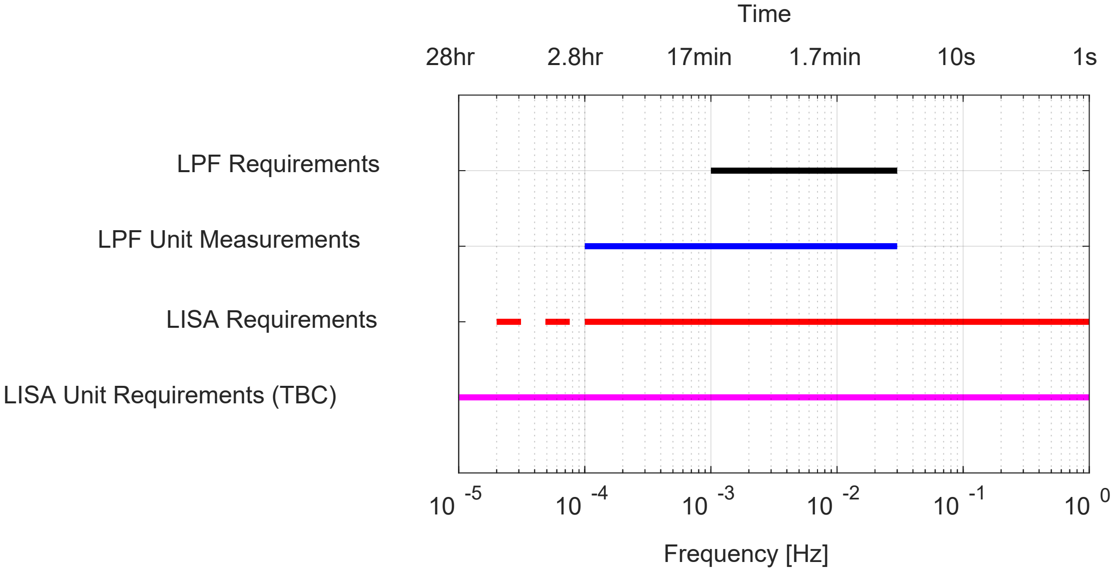
Mitigating noise due to sensor rotation & translation – Trade-off Outcome

- **Preferred Option**
  - Based on the above tests, an Ultra-Stable Sensor Array Frame was selected for subsequent test facility implementation
  - Best 'out-of-the-box' performance (of the three options)
  - Low cost
    - Relative to large set of compensation coils (even without active compensation)
  - No added complexity in terms of control or data analysis
  - Potential concern
    - Uncompensated environment can generate field-induced effects (soft magnetic materials)
    - Thought to be tractable via correlated noise removal

Additional Investigations



- **Signal Space Separation**
  - The use of this technique was already established from the previous AC magnetics study, but its effectiveness at sub-Hz frequencies was proven during the trade-offs
- **Test Time**
  - For LPF testing, a test duration was selected equivalent to 1/10th the lowest frequency range of interest, which for LISA would translate into ~30 hours
  - Demonstration measurements show that the required sensitivity at the lowest frequencies can still be achieved within a day of testing, even during a day shift
  - A direct test approach is therefore recommended, with a minimum measurement time of 3 hours, although the impact, risk and proposed mitigation for an accelerated test option is also considered in the documentation



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Facility Design – Hardware

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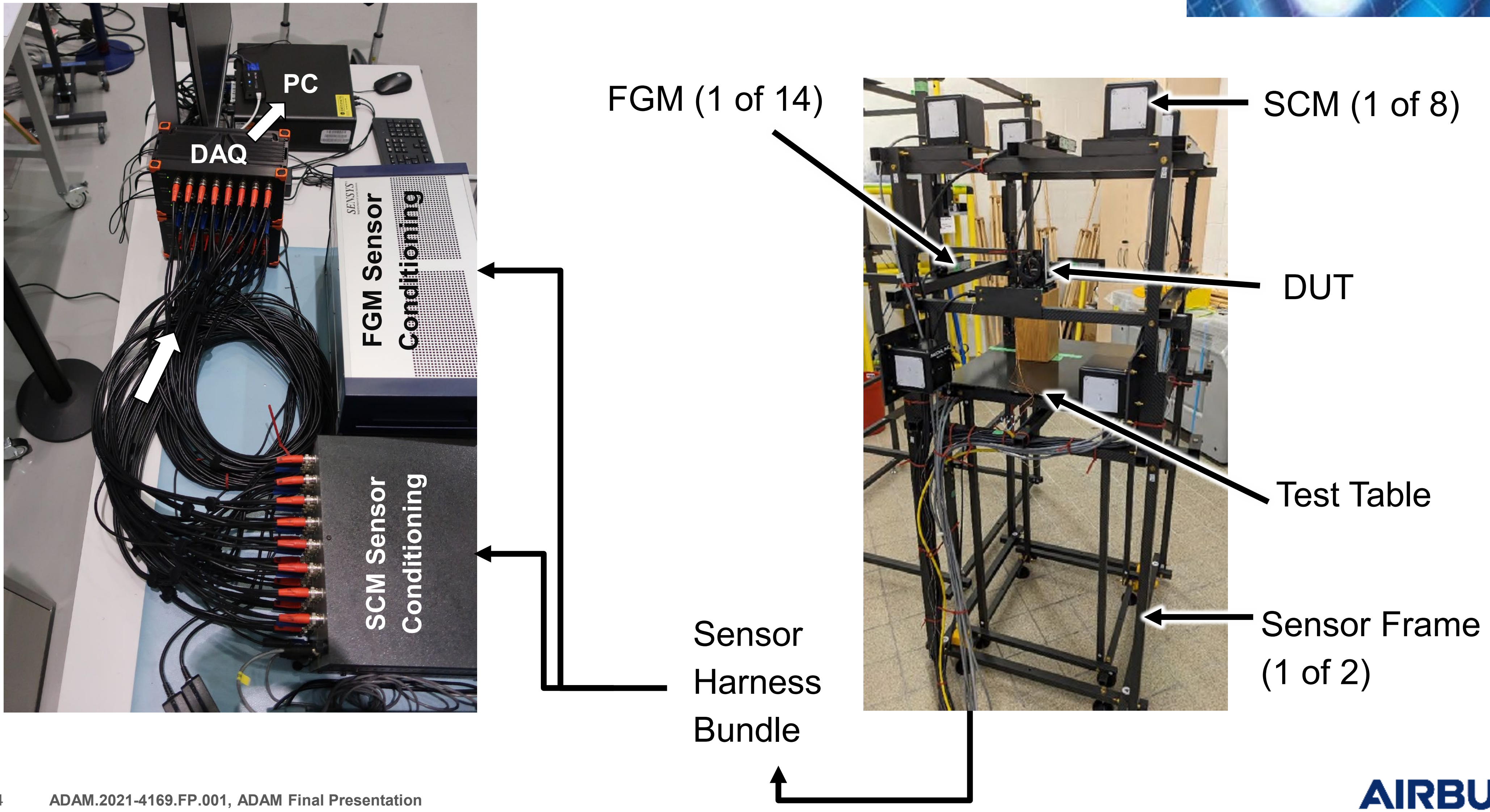
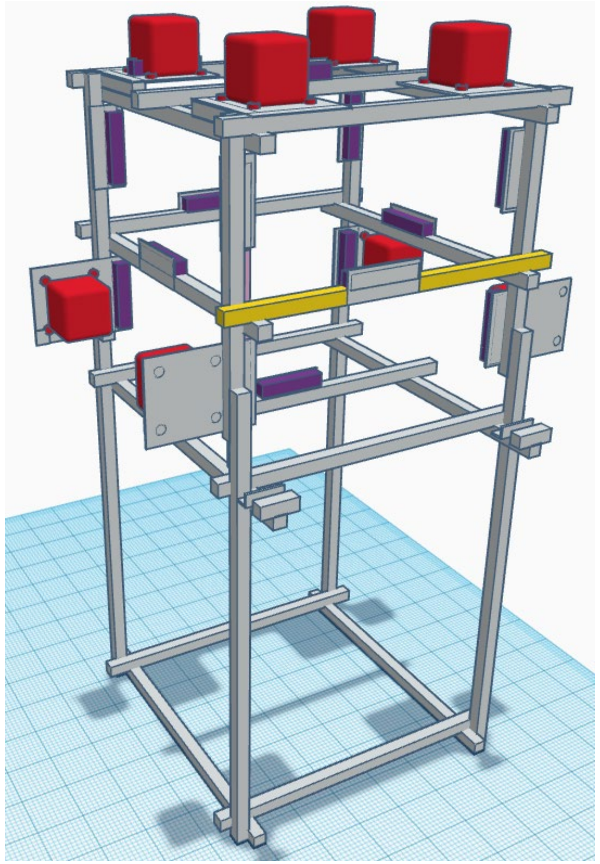
Facility Design

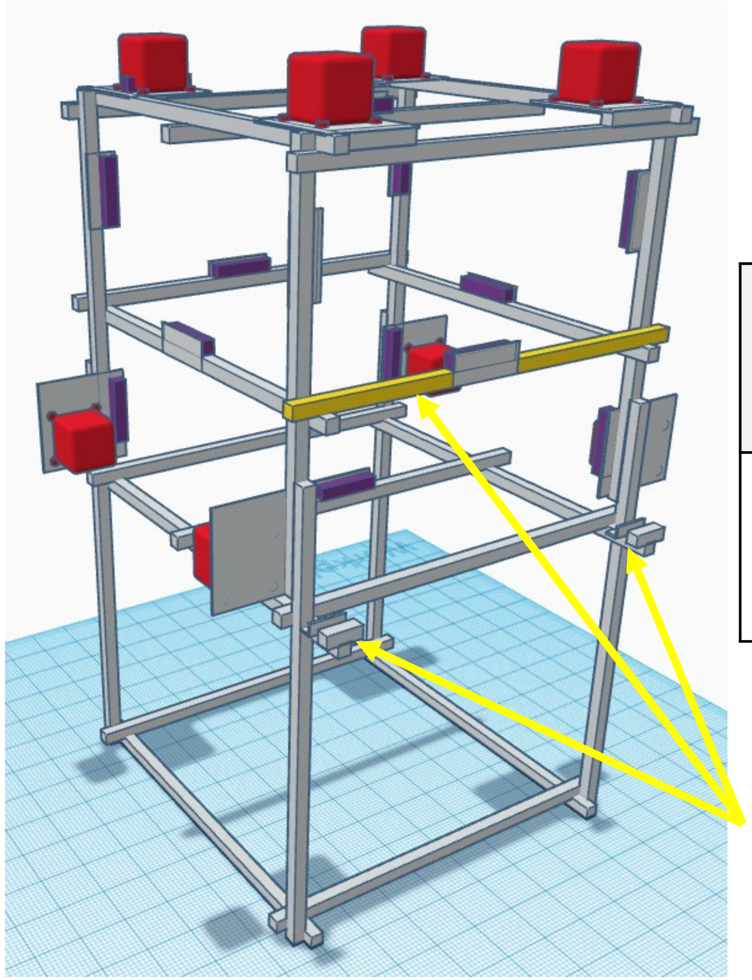


Facility Design

- Two final CFRP frames were constructed to cover a range of DUT sizes / distances

Small sensor frame: DUT centre to sensor distance	6x sensors at 300 mm 8x sensors at 450 mm
Small sensor frame: Internal accessible volume	(depth) 520 mm (width) 520 mm (height) 480 mm



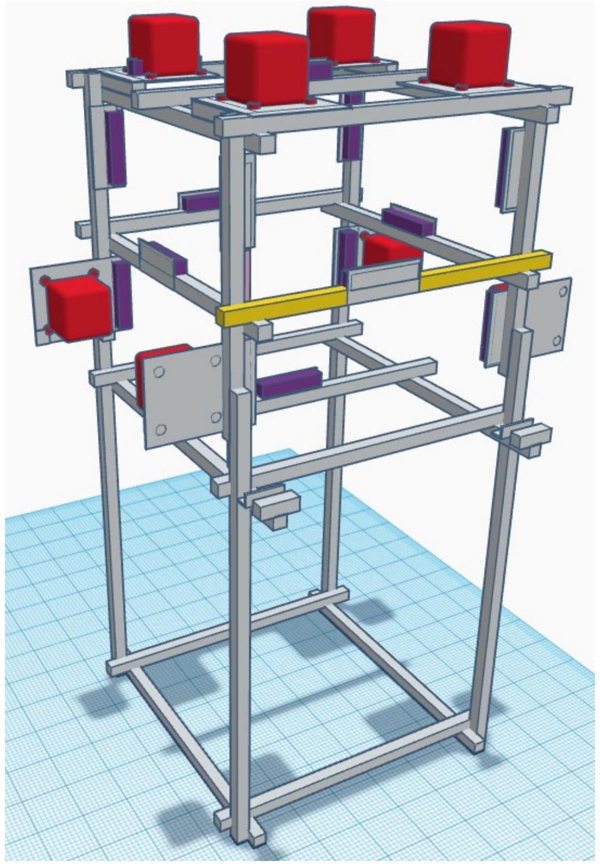


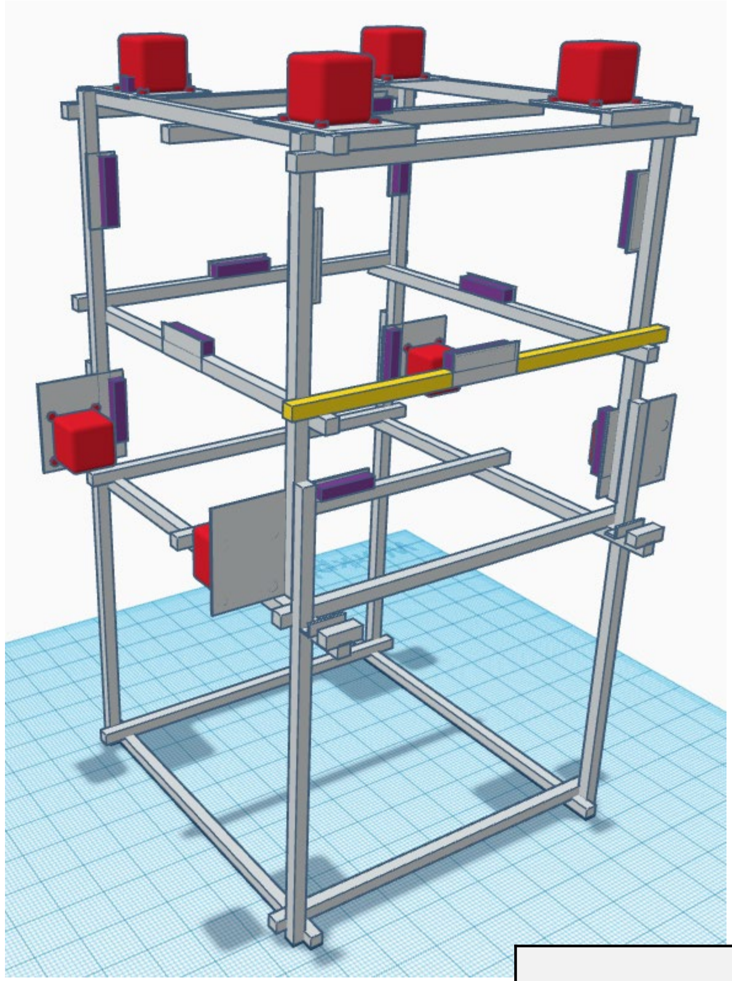
Removeable bar and rest

Medium sensor frame: DUT centre to sensor distance	6x sensors at 400 mm 8x sensors at 600 mm
Medium sensor frame: Internal accessible volume	(depth) 720 mm (width) 720 mm (height) 600 mm

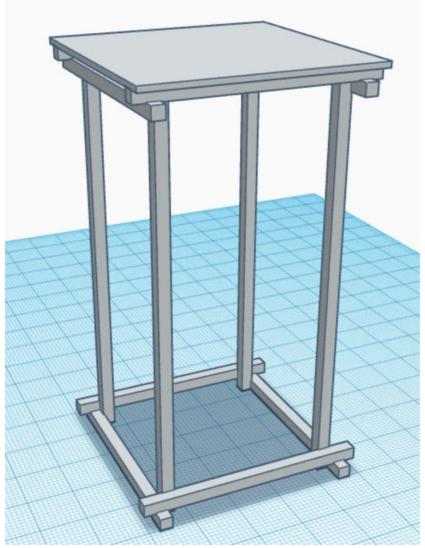
Facility Design

Small sensor frame: Overall size	(depth) 700 mm (width) 925 mm (height) 1557 mm





Medium sensor frame: Overall size	(depth) 900 mm (width) 1135 mm (height) 1682 mm



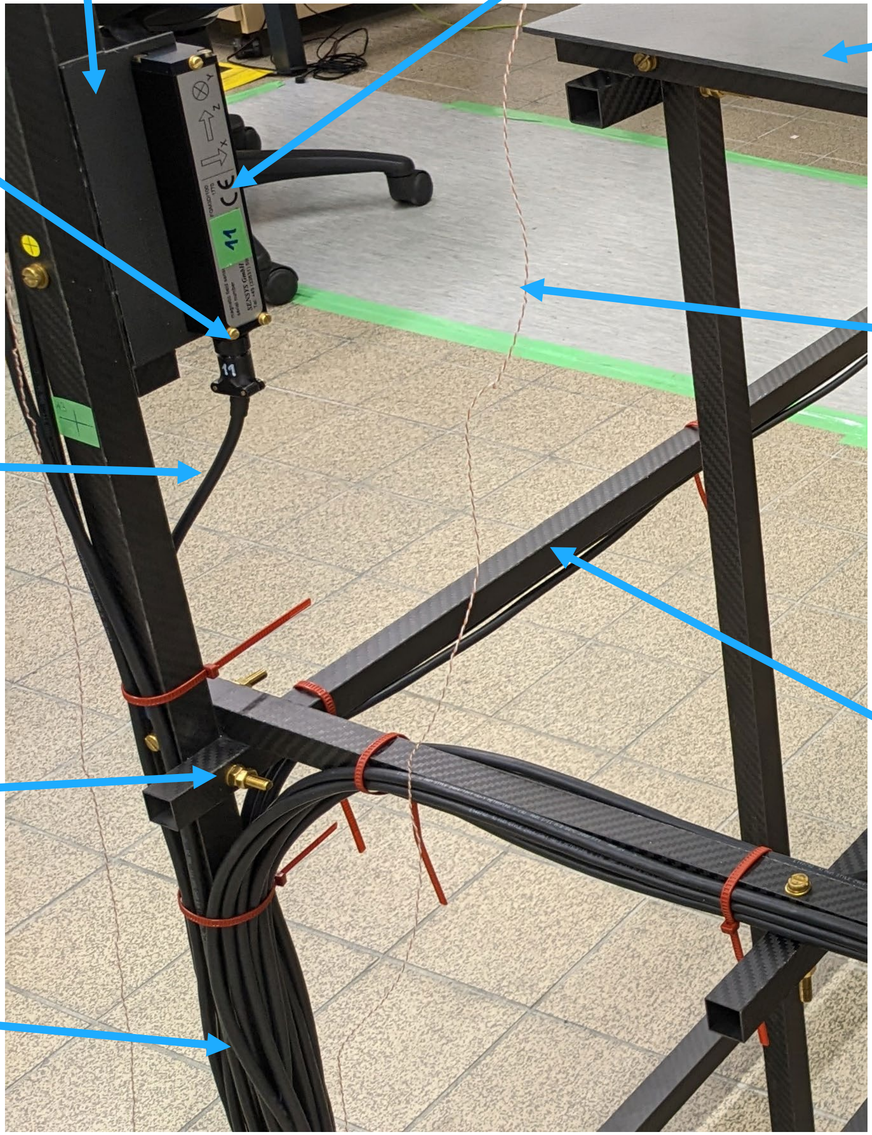
Test table dimensions	(depth) 500 mm (width) 500 mm (height) 910 mm

Facility Design

Small frame with test table and synthetic DUT

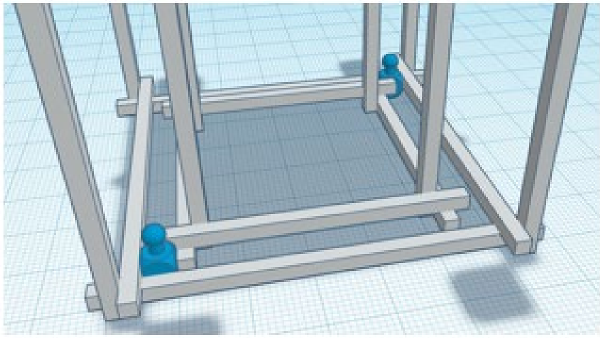
Medium frame with test table and synthetic DUT

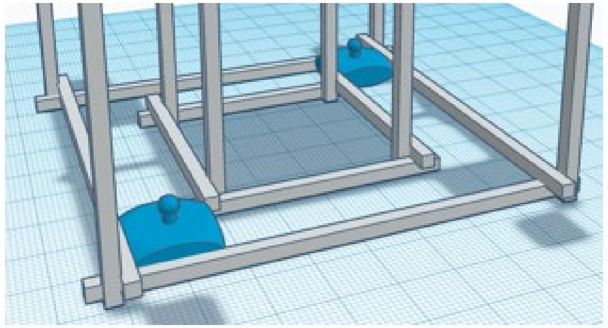
Facility Design

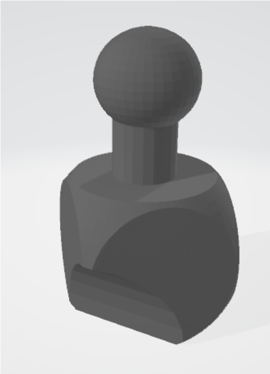


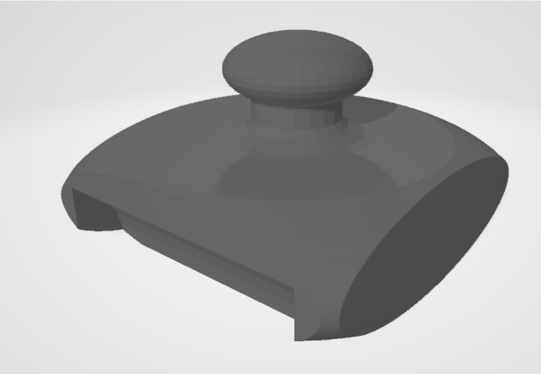
Facility Design

Levelling capability







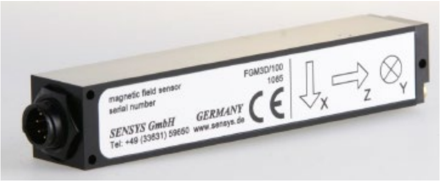


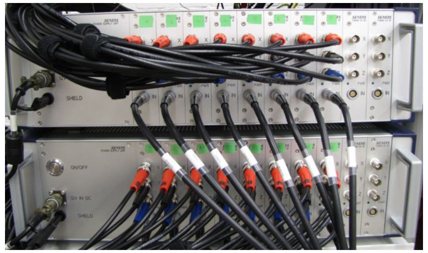
Centering capability

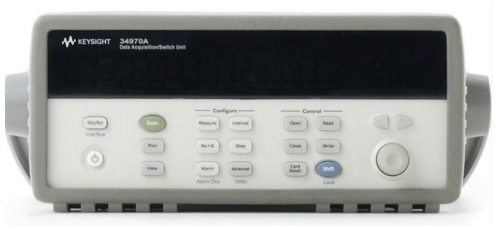
Sturdy transport case

Facility Design

FGM x 16







Thermal hardware monitoring system

SCM x 8

8 Channel DAQ x 6

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Facility Design – Software Processing

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Verification Methods
Model Based Verification

Measurement

DUT Model

Assembly of S/C model

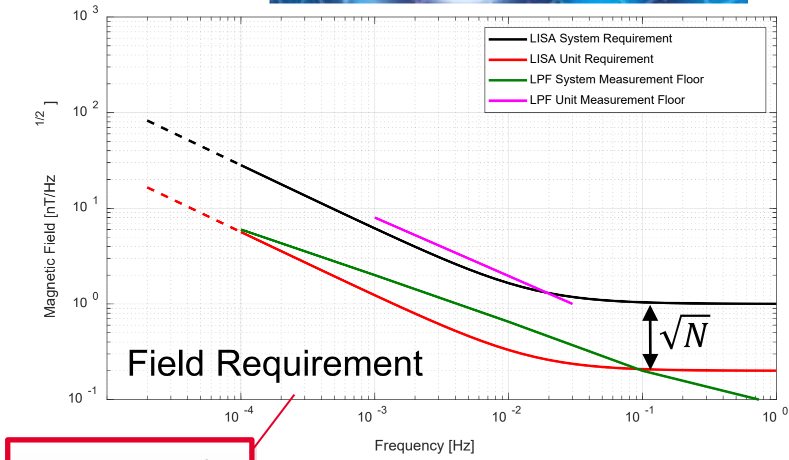
Prediction of field at PoS

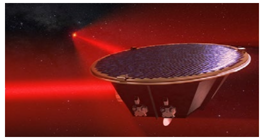
Prediction

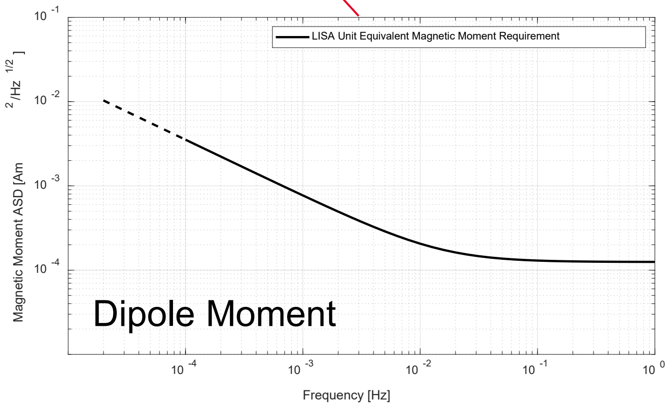
AC Magnetic Field Verification

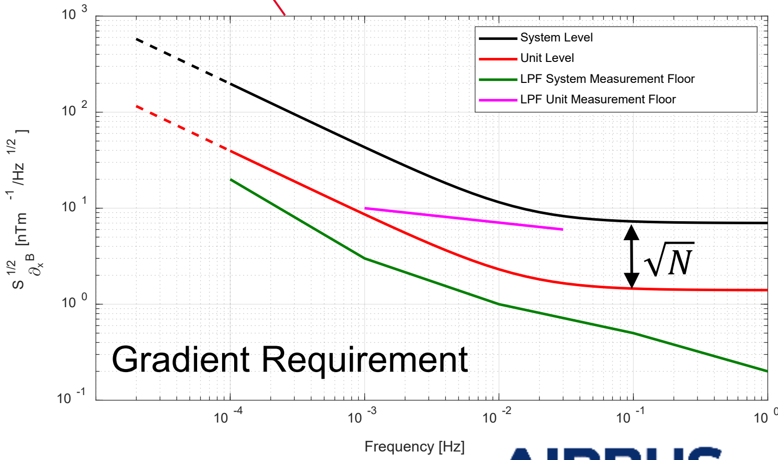
Knowledge

Case Specific Parameters / Timlines









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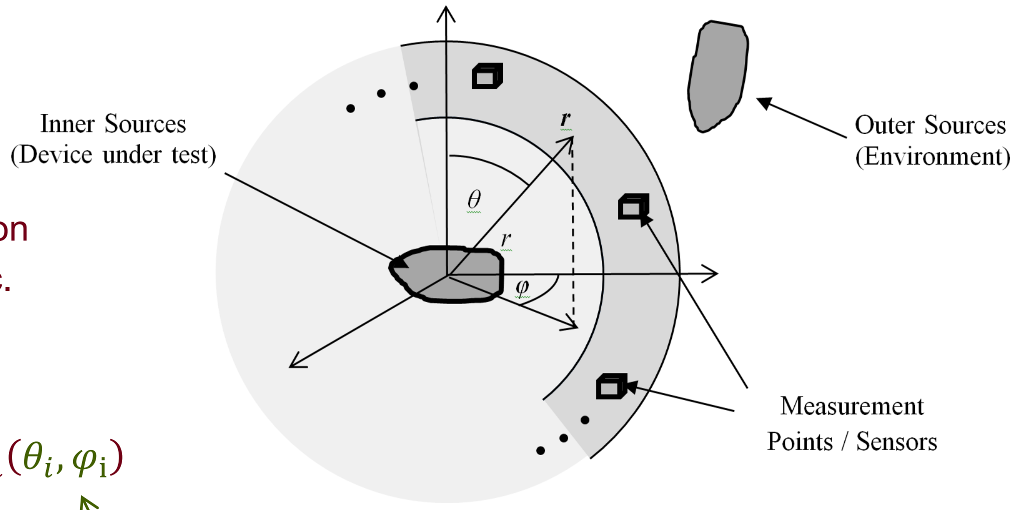
Verification Methods
Fitting Model: Multipole Expansion based on Sperical Harmonics

Expansion by Orthogonal Functions

- **Vectorial basis functions** (field vectors)
- with **vectorial arguments** (evaluation points)



$$\boldsymbol{B}(\boldsymbol{r}_i) = -\mu_0 \sum_{l=1}^{L_{\text{inner}}} \sum_{m=-l}^{l} \alpha_{lm} \frac{\boldsymbol{v}_{lm}(\theta_i, \varphi_i)}{R_{ij}^{l+2}} - \mu_0 \sum_{l=1}^{L_{\text{outer}}} \sum_{m=-l}^{l} \beta_{lm} R_{ij}^{l-1} \boldsymbol{w}_{lm}(\theta_i, \varphi_i)$$

Basis function of inner src. → $\boldsymbol{v}_{lm}$

Spherical coordinates → (θ_i, φ_i)

Basis function of outer src. → $\boldsymbol{w}_{lm}$

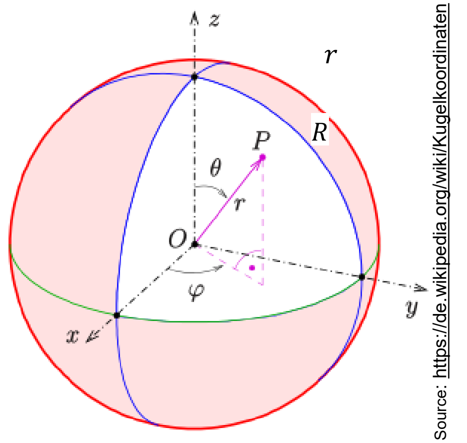
"Inner" coefficient describe dipole, quadrupole, etc. moments of the sources concentrated at the expansion center → α_{lm}

Well defined distance law depending on order → R_{ij}^{l+2}

"Outer" coefficient describe the moments of the sources infinitely far away → β_{lm}

Well defined distance law depending on order → R_{ij}^{l-1}

Spherical coordinates → (θ_i, φ_i)



Source: https://de.wikipedia.org/wiki/Kugelkoordinaten

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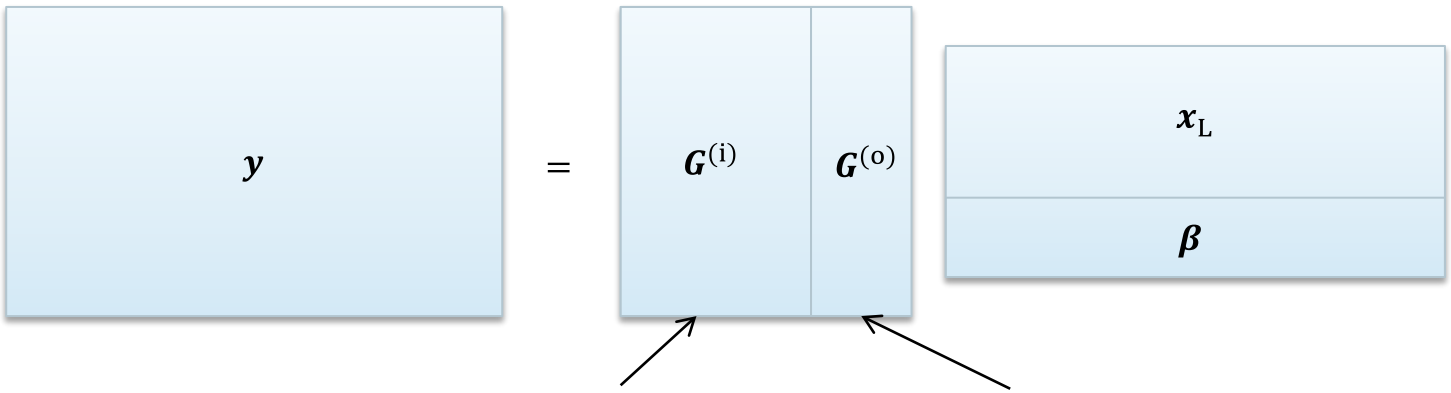
Verification Methods
Signal Space Separation

Principle: Include model of environmental disturbance in the model fitting

Vector of sensor values



Vector of linear parameters (excluding outer spherical harmonics)

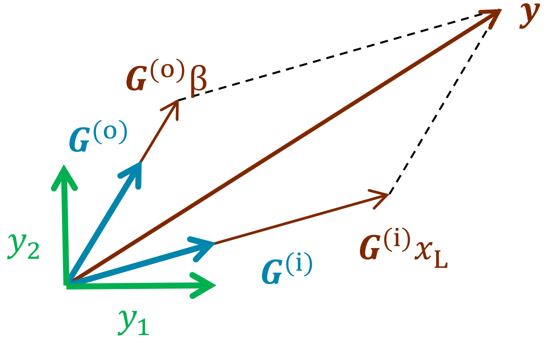
Vector of coefficients for outer spherical harmonics

Geometry matrix of inner sources

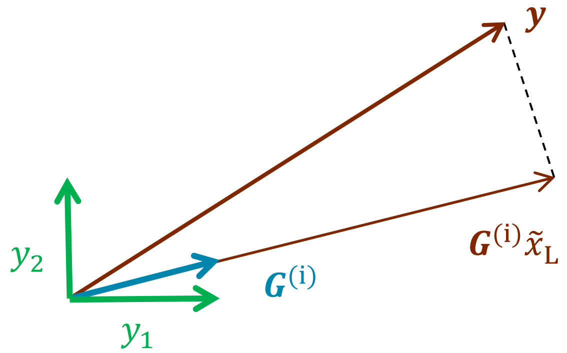
Geometry matrix of outer sources

Geometrically, Signal Space Separation (SSS) is a oblique projection:

with SSS:

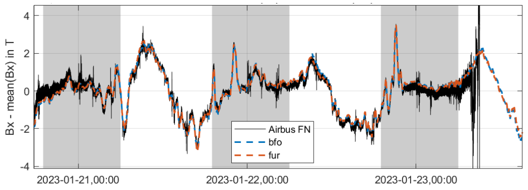


without SSS:



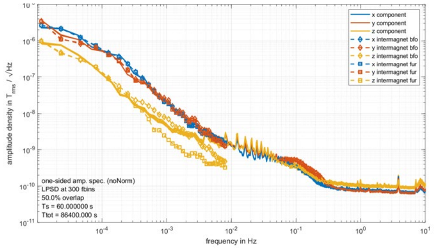
Verification Methods
Processing Scheme

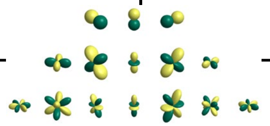
Magnetic Test

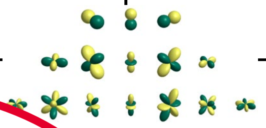


Measurement Data in Time Domain

Measurement Data in Frequency Domain







Multipole Coefficients of **Outer Sources** in Time Domain

Multipole Coefficients of **Inner Sources** in Time Domain

Multipole Coefficients of **Inner Sources** in Frequency Domain

Multipole Coefficients of **Outer Sources** in Frequency Domain

Performance metric

Field Prediction at **Point of Spec.** in Time Domain

Field Prediction at **Point of Spec.** in Frequency Domain

Verification of field and gradient requirement

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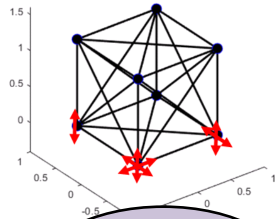
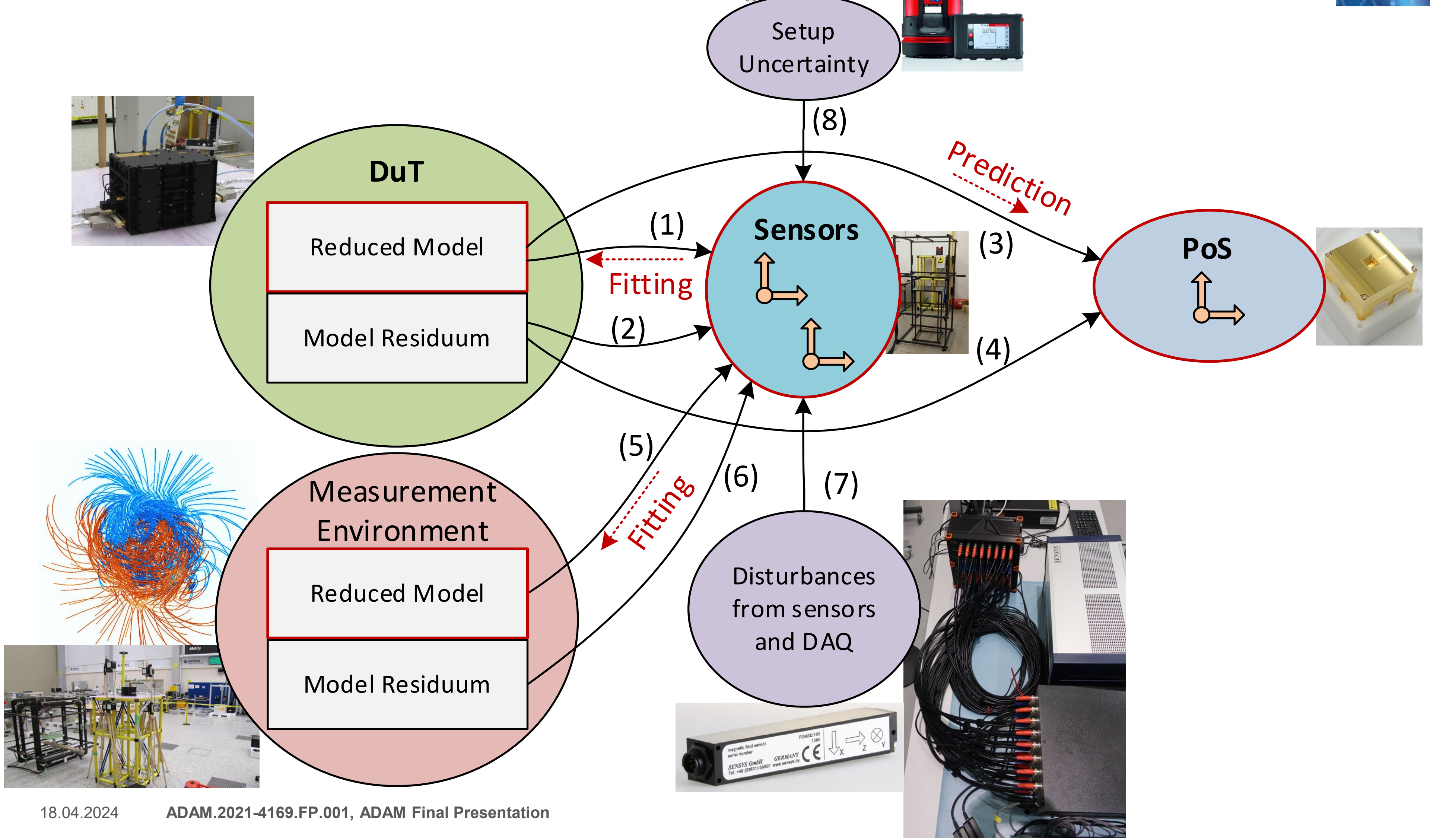
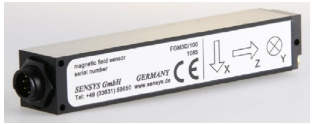
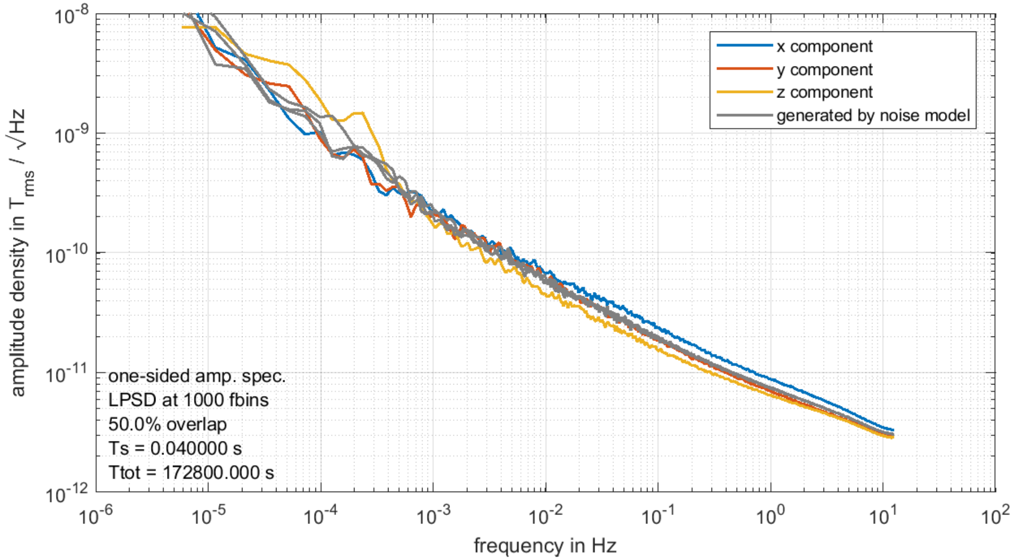
Verification Methods
Disturbance Sources





Performance Tests
Sensor Noise

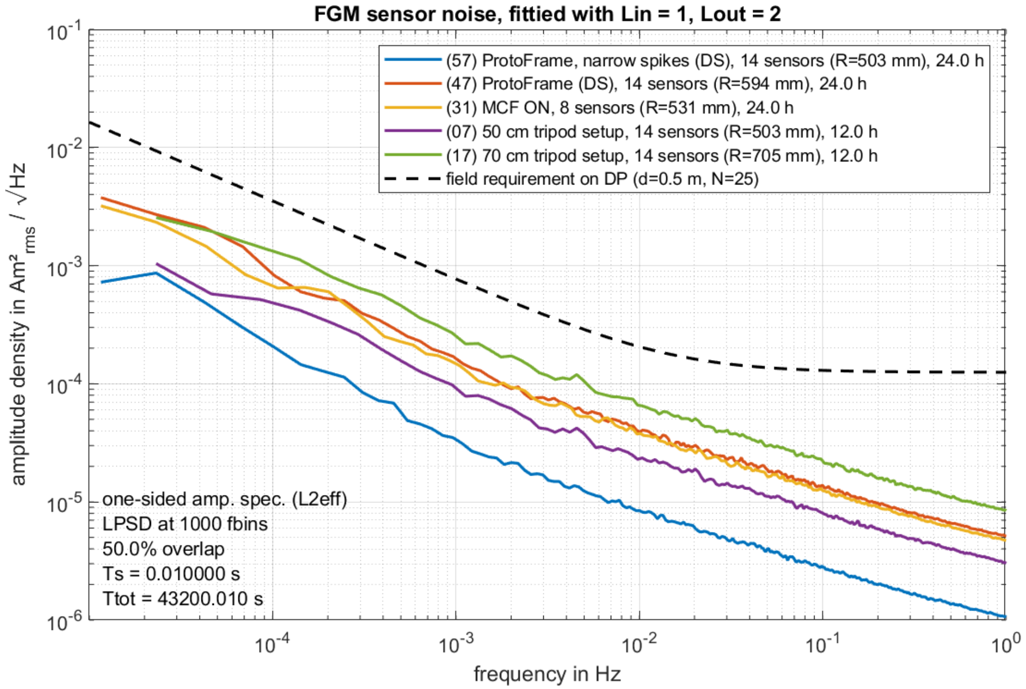




- Noise floor of measured by sensor supplier Sensys:
  - 1x Sensys FGM3D/100 Sensor (4 kHz variant)
  - 4-layered Mu-metal box for shielding
  - DAQ: Keithley Digital multimeter DMM6500.
  - +/-100 mV voltage range (+/-1 µT)
  - Sampling rate: 25 Hz
  - Total sampling time: 48 hours

- Extraction of noise model.
- Random sequence generator with pseudo white noise and shaping filter to reproduce same noise model.
- Simulation of virtual test with uncorrelated sensor noise on each sensor channel followed by fitting DuT model.

⇨ Sensor noise below requirement but also not negligible



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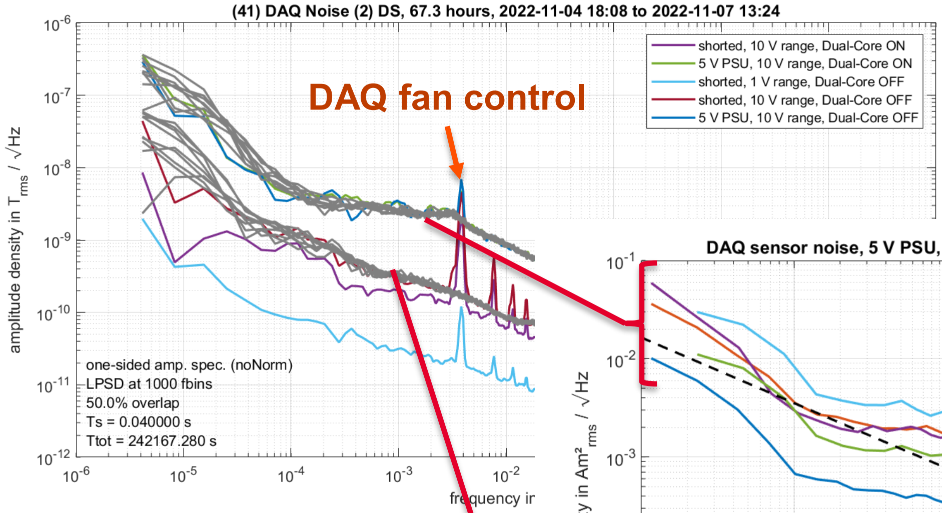
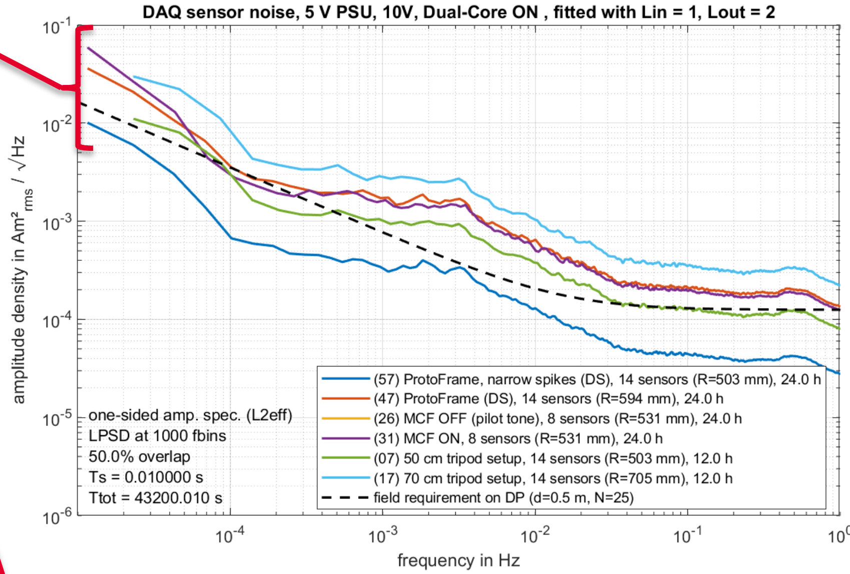
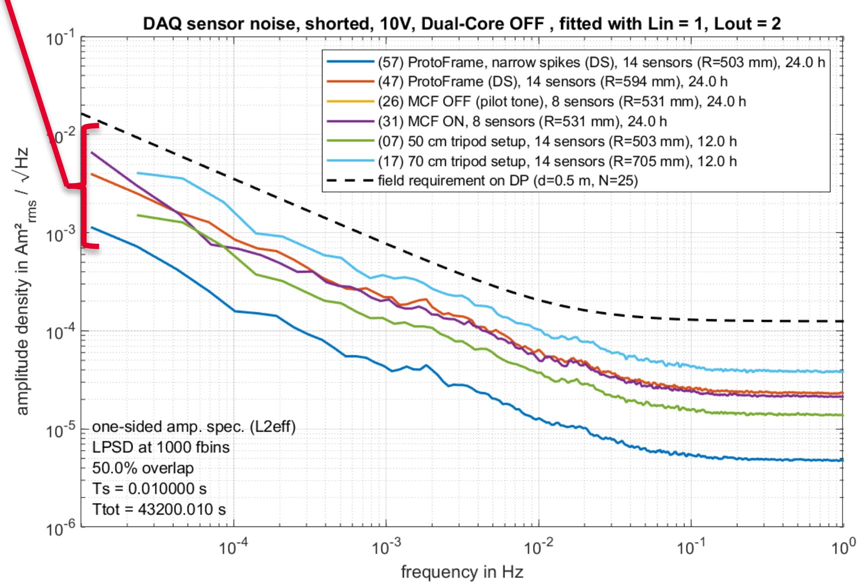
Performance Tests
DAQ Noise



- DEWESoft Sirius modules tested by
  - **5V PSU (=50 µT), +/-10V input range, Dual-Core**
  - 5V PSU (=50 µT), +/-10V input range, Single-Core
  - Channel shorted, +/-10V input range, Dual-Core
  - **Channel shorted, +/-10V input range, Single-Core**
  - Channel shorted, +/-1V input range, Dual-Core
- ***Automatic fan control generates disturbance at 3.8 mHz (~4.4 min period)***
- Extraction of noise model by sampling average amplitude density.
- Random sequence generator with pseudo white noise and shaping filter to reproduce same amplitude density spectrum.
- Simulation of virtual test with uncorrelated sensor noise on each sensor channel followed by fitting DuT model



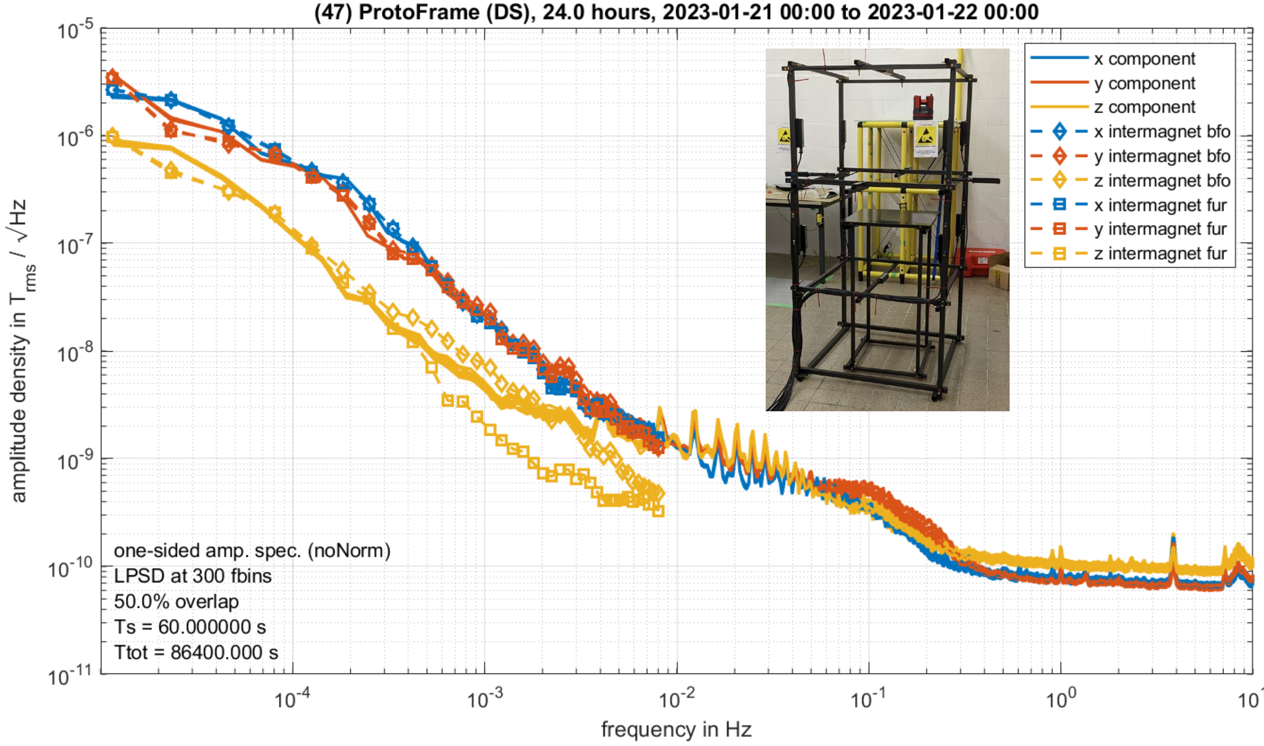


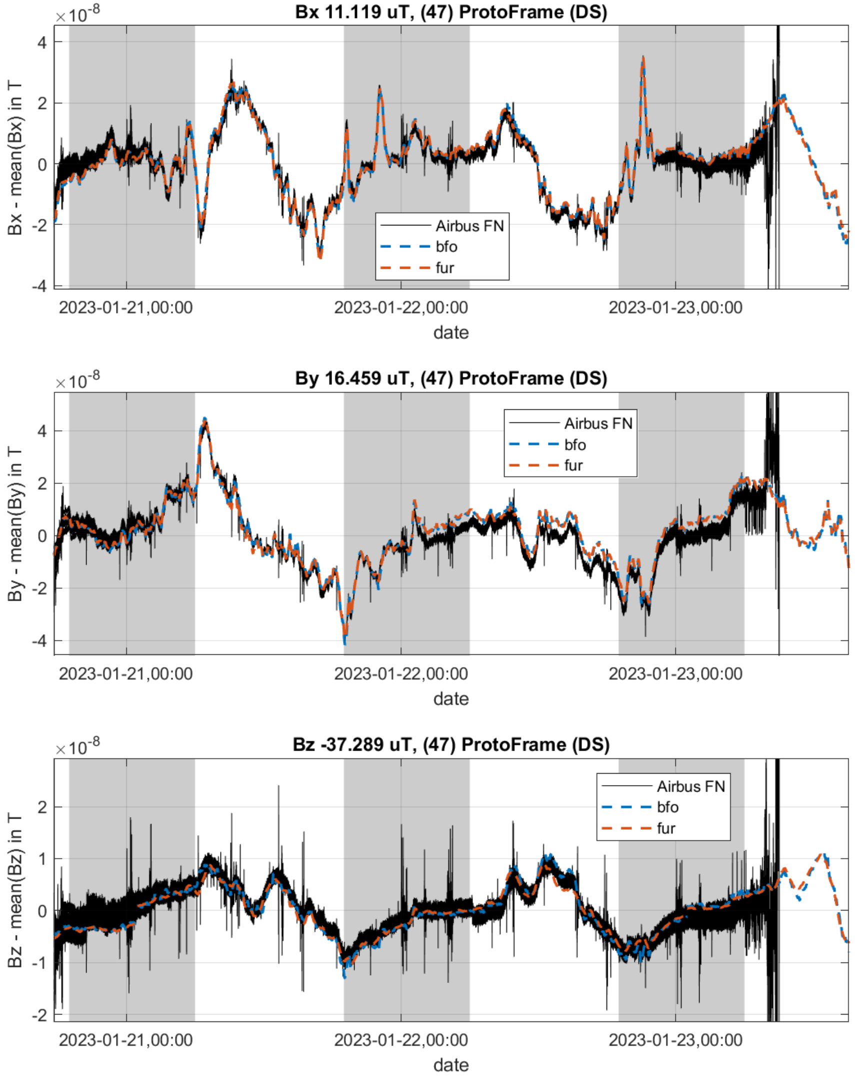
⇨ Noise floor of the DAQ is in the range of requirement.

⇨ Contribution of the 5V PSU unclear at the moment. Performance of software shielding (see following slide about software shielding) indicates that DAQ noise is lower than measured here with 5V PSU.

Performance Tests
Consistency with Intermagnet Data

Comparison of ambient test with Intermagnet observatories:
- Black Forest Observatory (**BFO**)
- Fürstenfeldbruck (**FUR**)
- Airbus FN, with demonstrator frame, all sensor channels overlayed



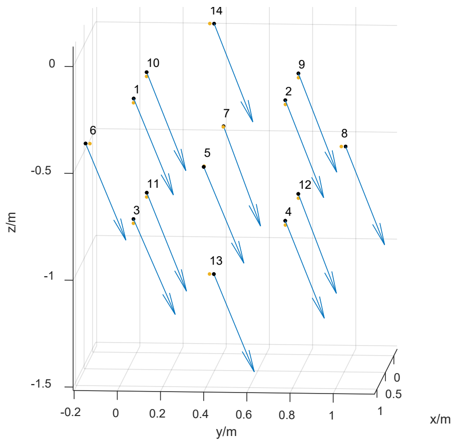


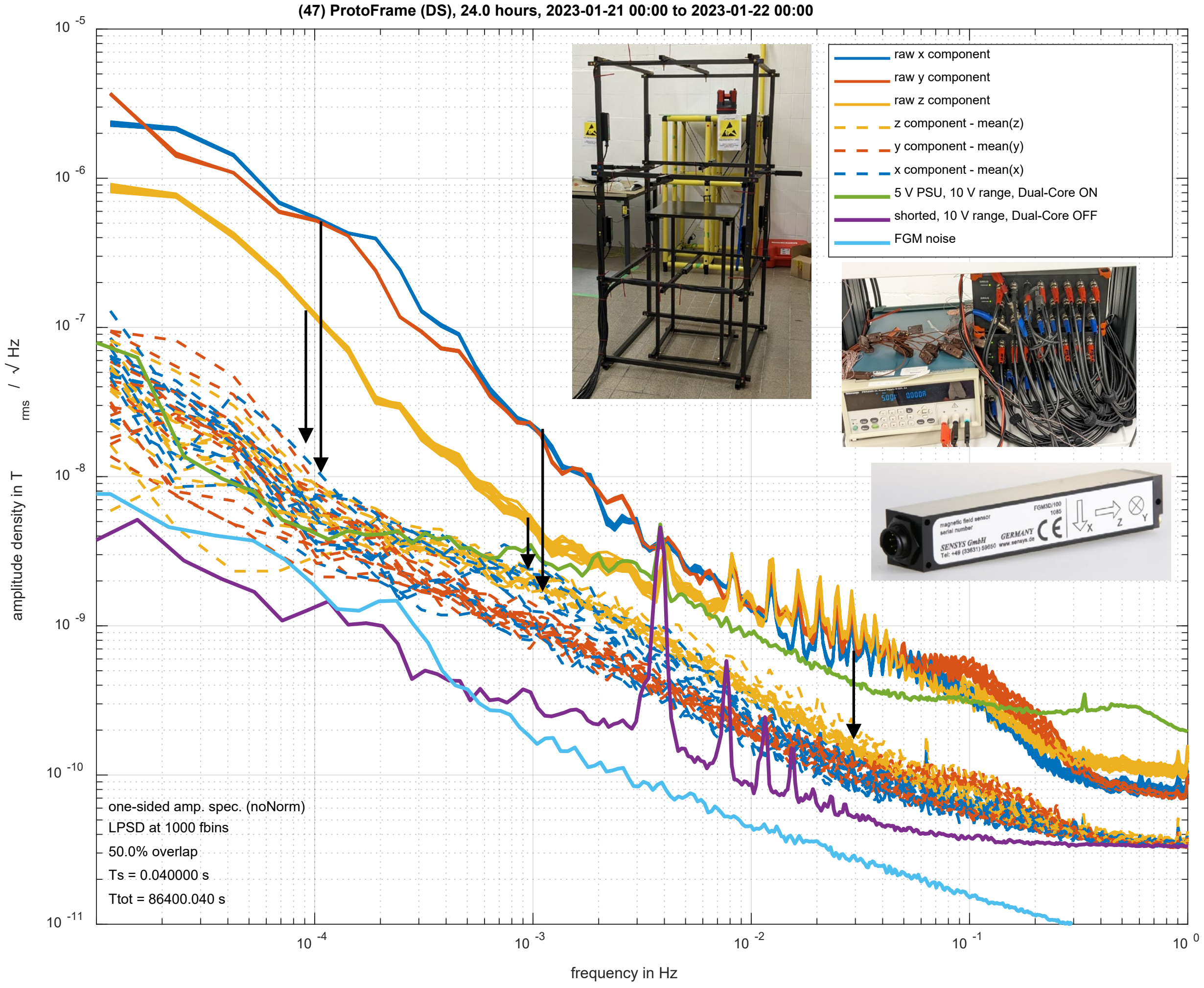
Performance Tests
‘Software Shielding’

Simplest software shielding (independent of fitting):

1. Estimate homogeneous field component by averaging over all 14 sensors.
2. Remove homogenous field component from each sensor.

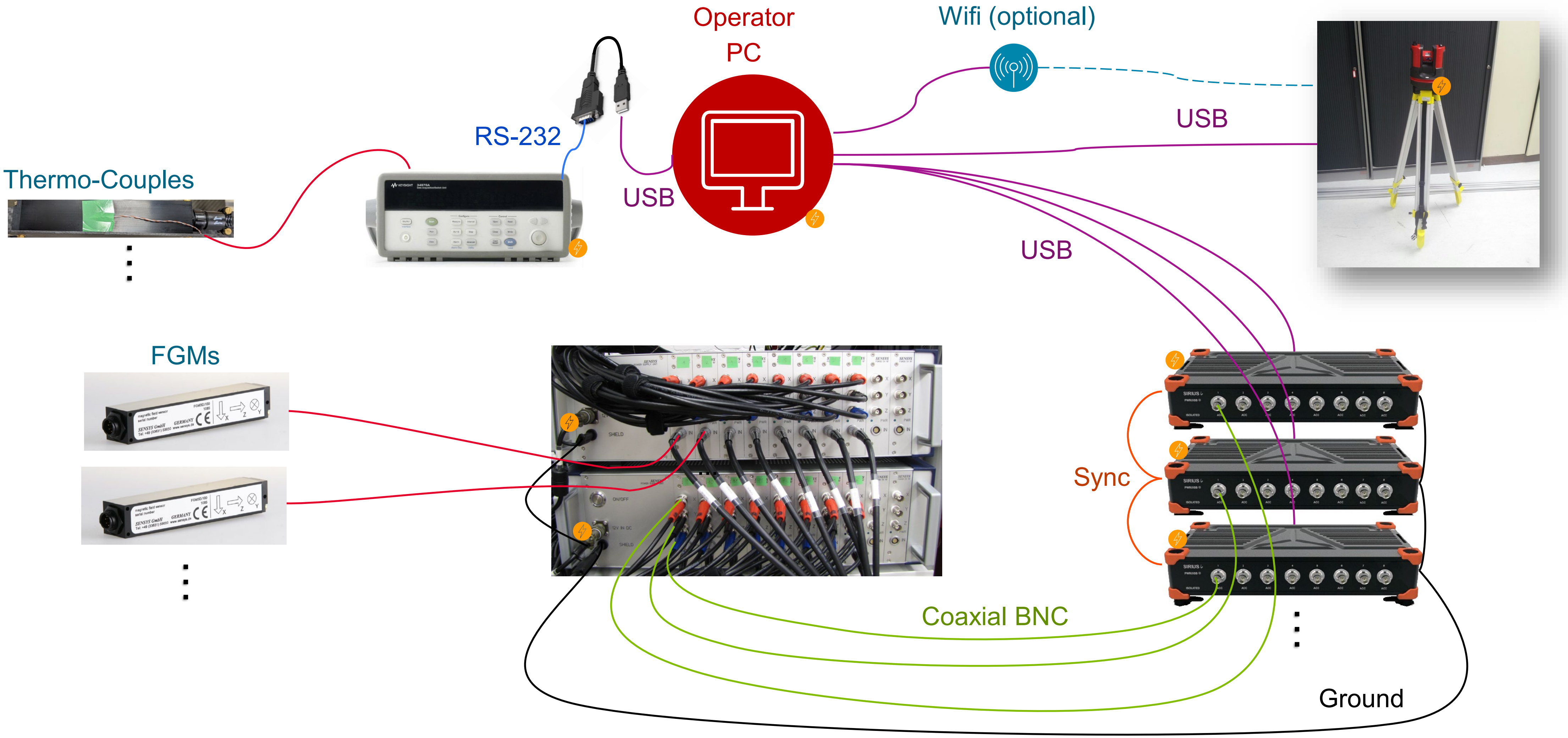
- ‘Software shielding’ efficiency by factor of up to 50
- Pre-processing step has no impact on fitting.
- Noise floor is significantly reduced, close to sensor and DAQ noise. For comparison, at IABG the field noise level is at $2\ \mathrm{nT}/\sqrt{Hz}$ at $1\ \mathrm{mHz}$.





Facility Design

Electrical Setup



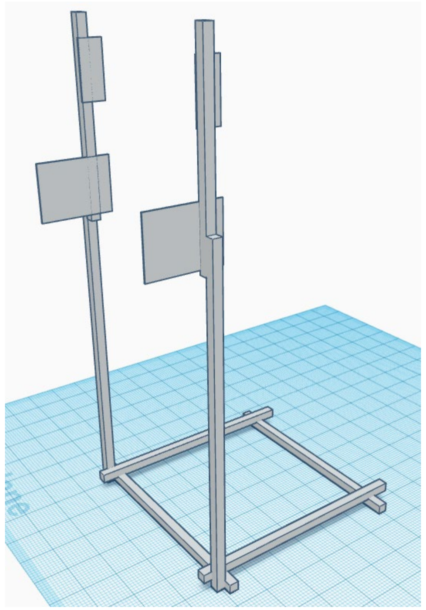
Facility Design

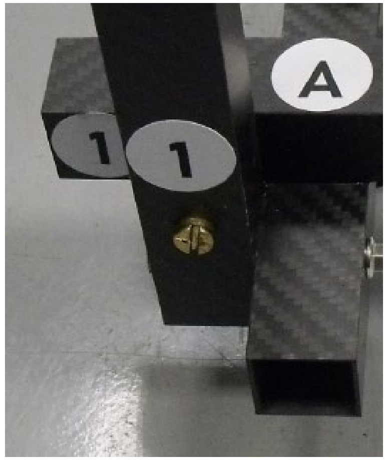
- **Software description**
  - The latest design includes:
  - DEWESoft 2023.1
    - Configures DAQ hardware in preparation for the test (input voltage range, coupling, anti-aliasing, etc.), manages sensor sensitivities, provides live preview of TD and FD data, data recording and export
  - Leica 3D Disto
    - Used for laser positioning system, control of laser with virtual view finder, acquisition of 3D position of targeted points, export of point cloud
  - MATLAB / Octave
    - Signal processing toolbox and optional distributed computing toolbox for improved processing speed
    - Functionality packed into a custom ADAM library, used for:
      - Thermal data logger control, template project folders, DUT definition, individual measurements and log test characteristics, test data processing vs requirements, export of plots for test reports

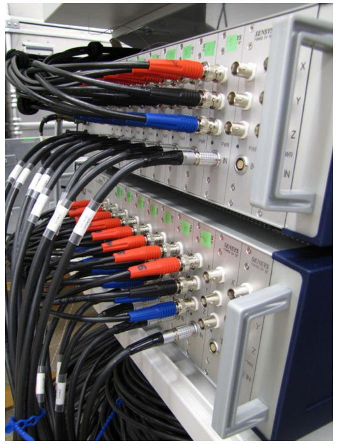
Facility Operation

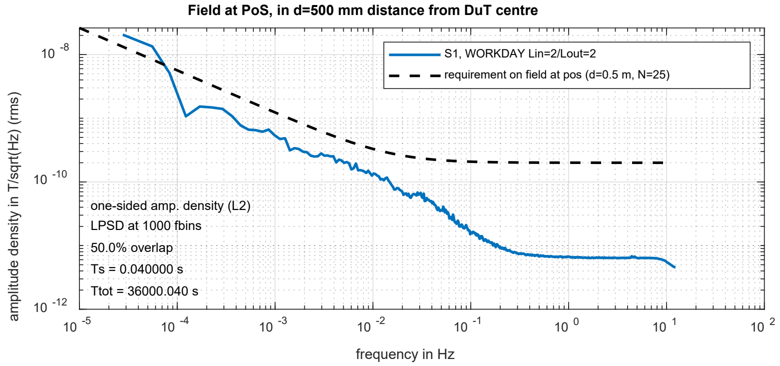
- ## Setup and Test Preparation

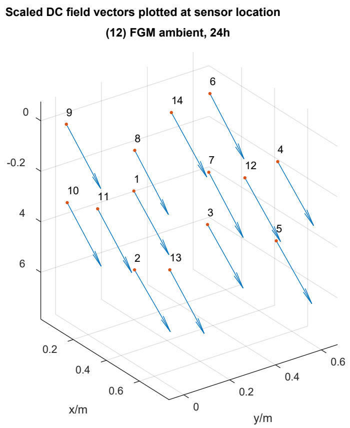
P1	**Hardware Preparation** • Assemble sensor frame and test table • Mount sensors
P2	**Electrical Preparation** • Setup DAQ and sensor conditioning • Connect sensors
P3	**Positional Calibration** • Scan markers on frame and all sensor • Use additional environment markers to merge different views
P4	**Test Measurement / Ambient Characterization** • Measure ambient field without DuT • Check data consistency and noise floor to be below requirement











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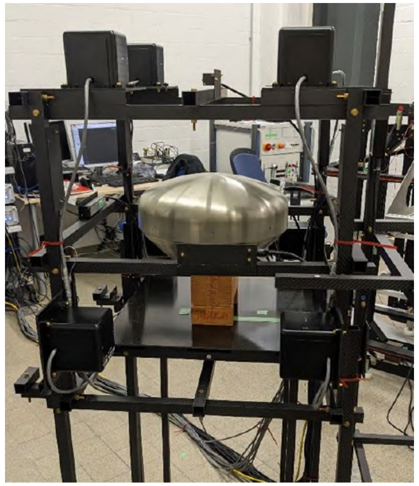
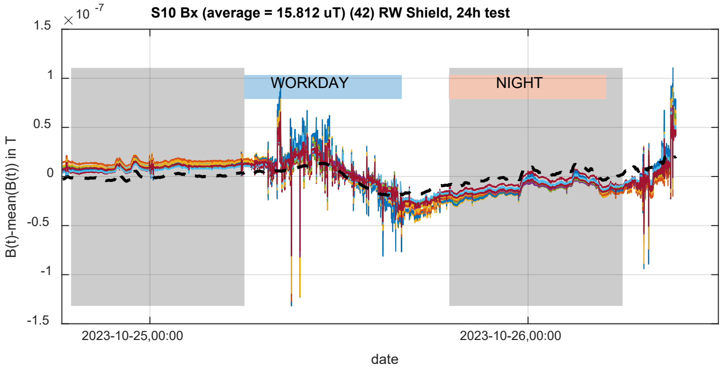
Facility Operation

```
function settings = config_settings()
% This config file stores general settings for a given test. A template is
% provided in the test template folder.

%% Intermagnet Network
% Intermagnet observatory closest to the magnetic facility of this test.
% See https://imag-data.bgs.ac.uk/GIN_V1/GINServices?Request=GetCapabilities&format=html
% for a list of available observatories.
settings.intermagnet.observatory = 'bfo'; % << Select closest observatory
% Subfolder to store data files pulled from the Intermagnet observatory
% network. Use pwd for to refer relative to the current working folder.
settings.intermagnet.local_folder = [pwd,'/../Intermagnet/'];
% Offset between UTC and local time for converting intermagnet time
% axis. t_local_days = t_utc_days + UTC_to_local_hour_offset/24
settings.intermagnet.UTC_to_local_hour_offset = 1; % << Set UTC time offset
% Note that the rotation between the intermagnet coordinate frame and
% the current test frame is specified for each test independently in
% the config_testDefinition. There is also a processing script to
% identify the corresponding matrix.

%% Sensor calibration
% Defines a map of sensor calibrations to be applied during import of
% data in the post processing. Use empty array if no calibration
```

- **Unit Level Test**

T1	**Preparation** • Prepare test folder on test PC from template. • Preconfigure general settings, DuT definition, list of tests, req.
T2	**DuT Setup** • Place DuT on test table. • Setup EGSE and test harness.
T3	**Small Positional Calibration** • Scan markers on frame (one side only) and on DuT. • If front bar was removed, also scan marker on this sensor.
T4	**Start testing** • For each measurement: – Export test data and make entry in list of tests. – Run processing script.





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Facility Performance Demonstration

Facility Performance Demonstration

- **Test configurations**
  - Small frame, medium frame, and large tripod configuration (the latter for comparison only)

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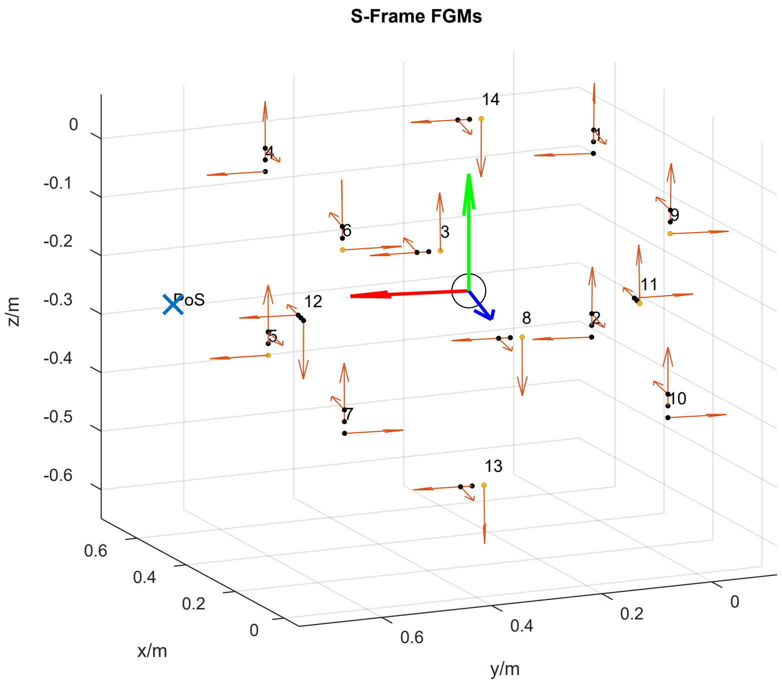
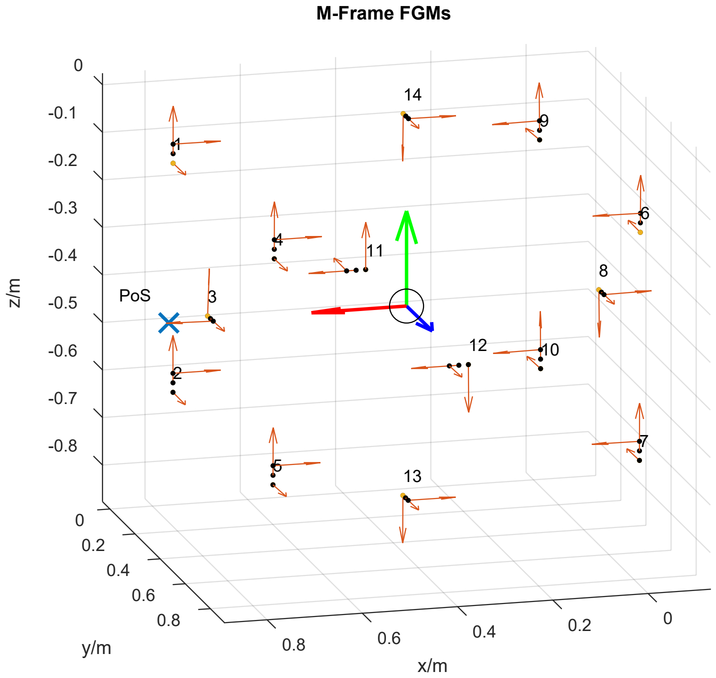
Facility Performance Evaluation

- **Test Performance in Terms of Noise Leakage**
  1. Measuring ambient field without DuT
  2. Fitting of multipole model at assumed DuT position.
  3. Prediction of field and field gradient at PoS with model of inner sources (and for information purpose also with model of ambient outer sources).
  4. Computation of Amplitude Spectral Density (ASD) and comparison with requirement at PoS.

- **Test Performance in Terms of Model Capability**
  1. Same test as above but with synthetic DuT.
  2. Comparison between predicted emission as computed with identified model and expected emission based on simulation model of the DuT.





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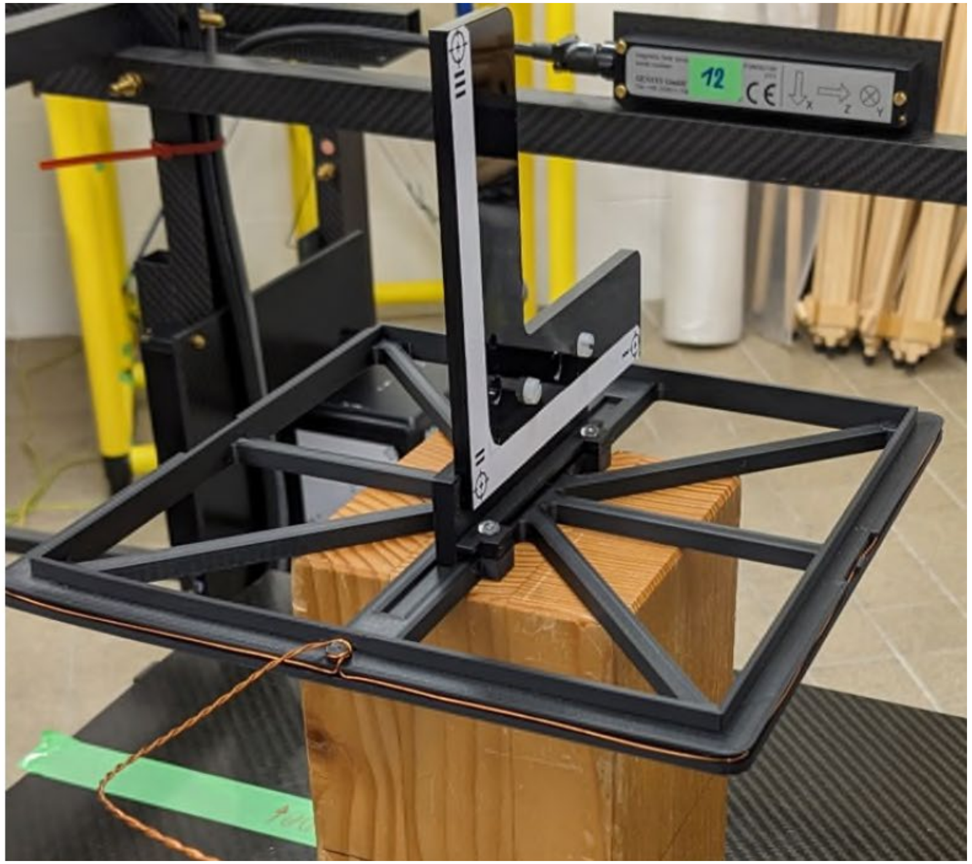
Facility Performance Demonstration

- **Test configurations**
  - Without DUT, or with synthetic DUT (dipole, quadrupole, loop)



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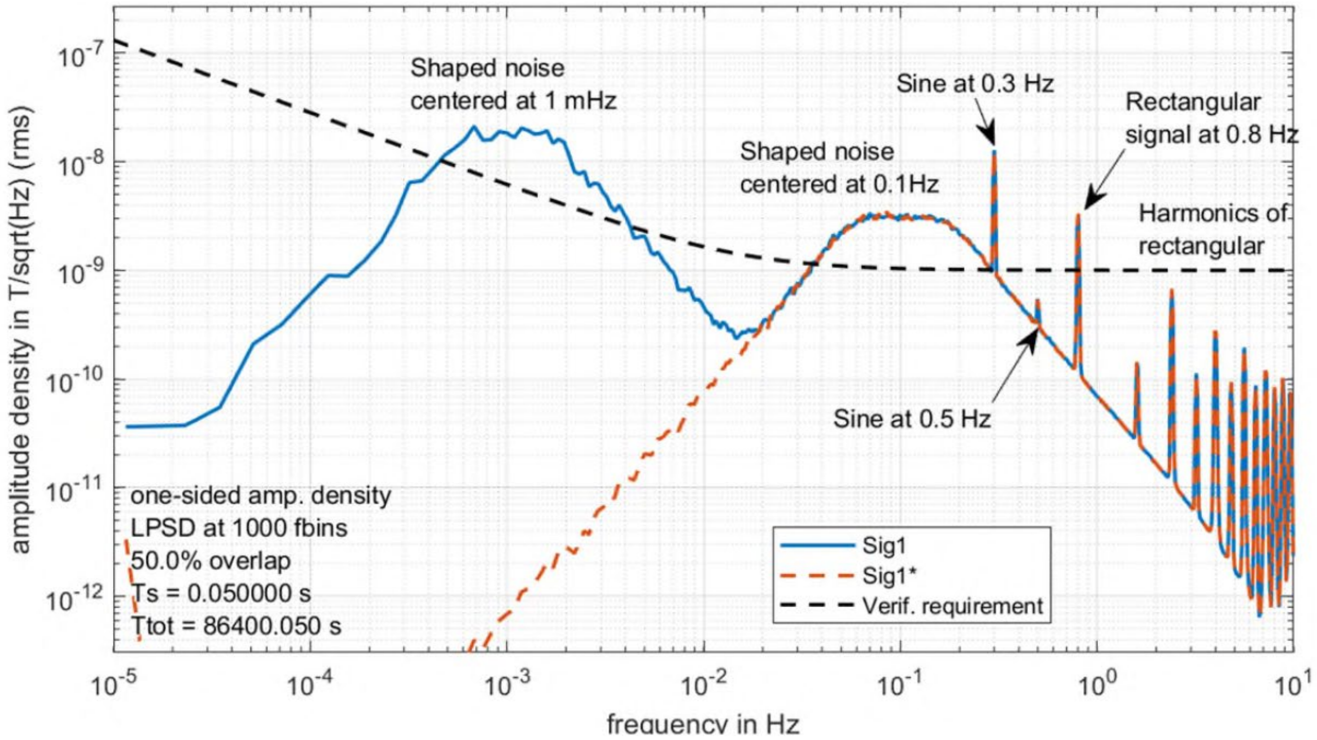
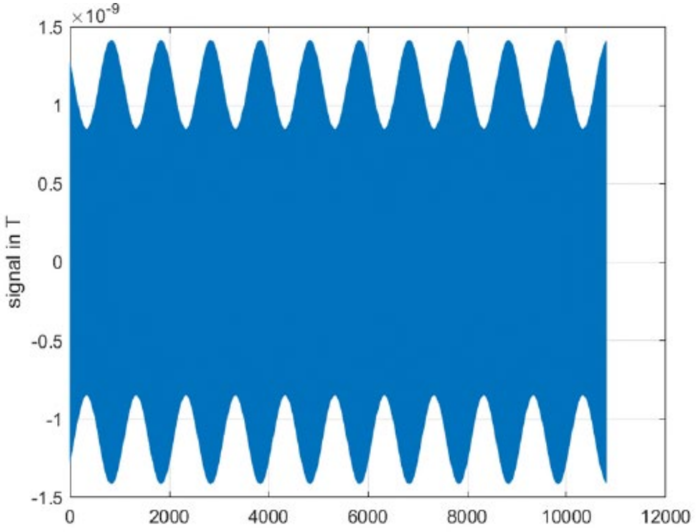
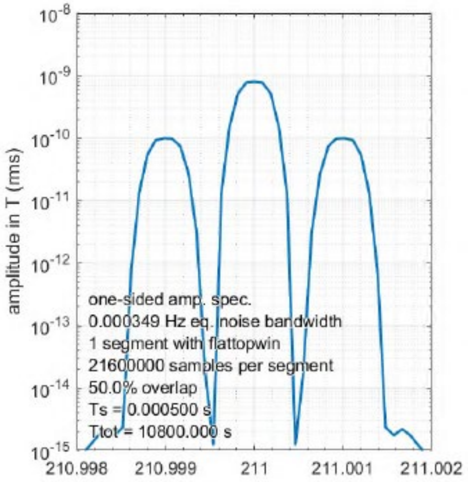
Facility Performance Demonstration

- **Test configurations**
  - Driving signal with broadband and narrowband noise, or an amplitude modulated signal

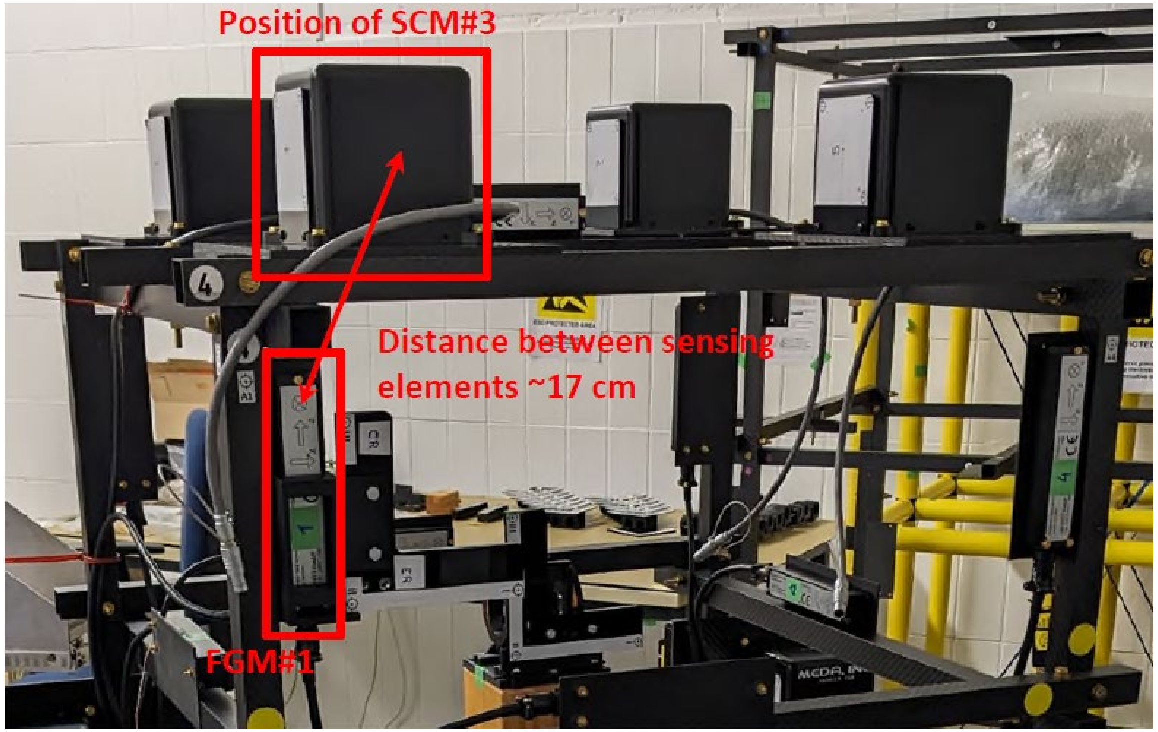






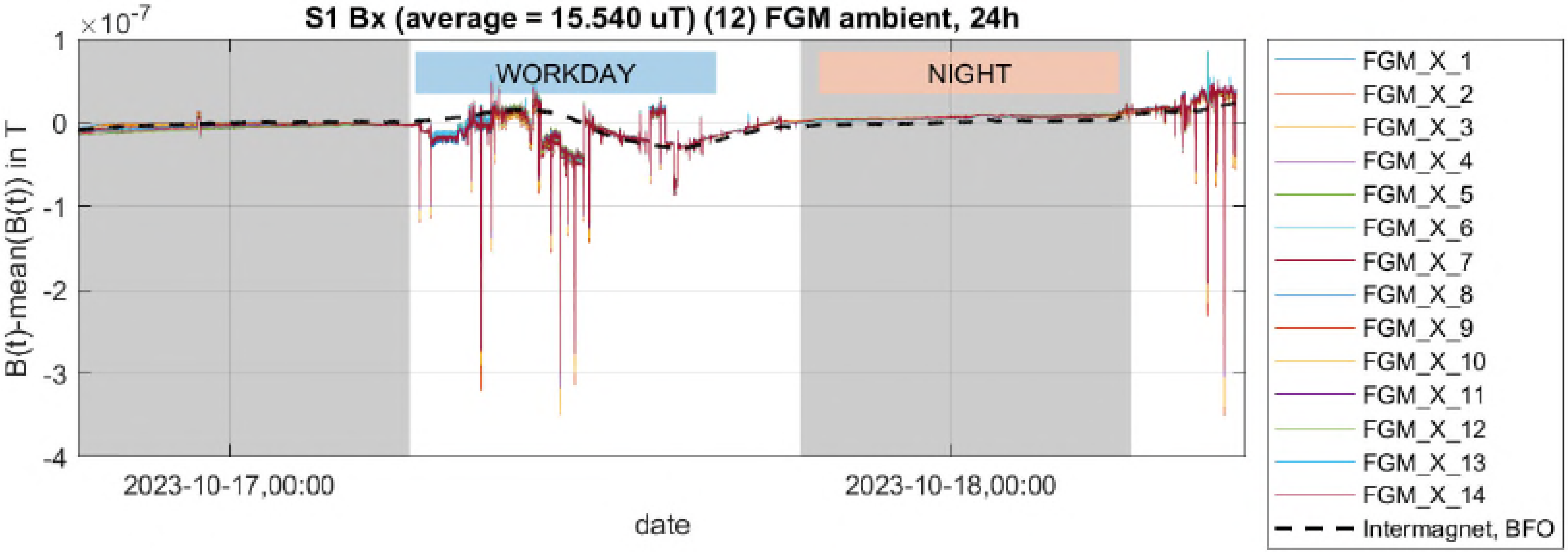
Facility Performance Demonstration

- **Test configurations**
  - With or without SCMs and FGMs installed simultaneously
  - Result: the field bias generated by the SCMs has no visible impact on the FGM test performance



Facility Performance Demonstration

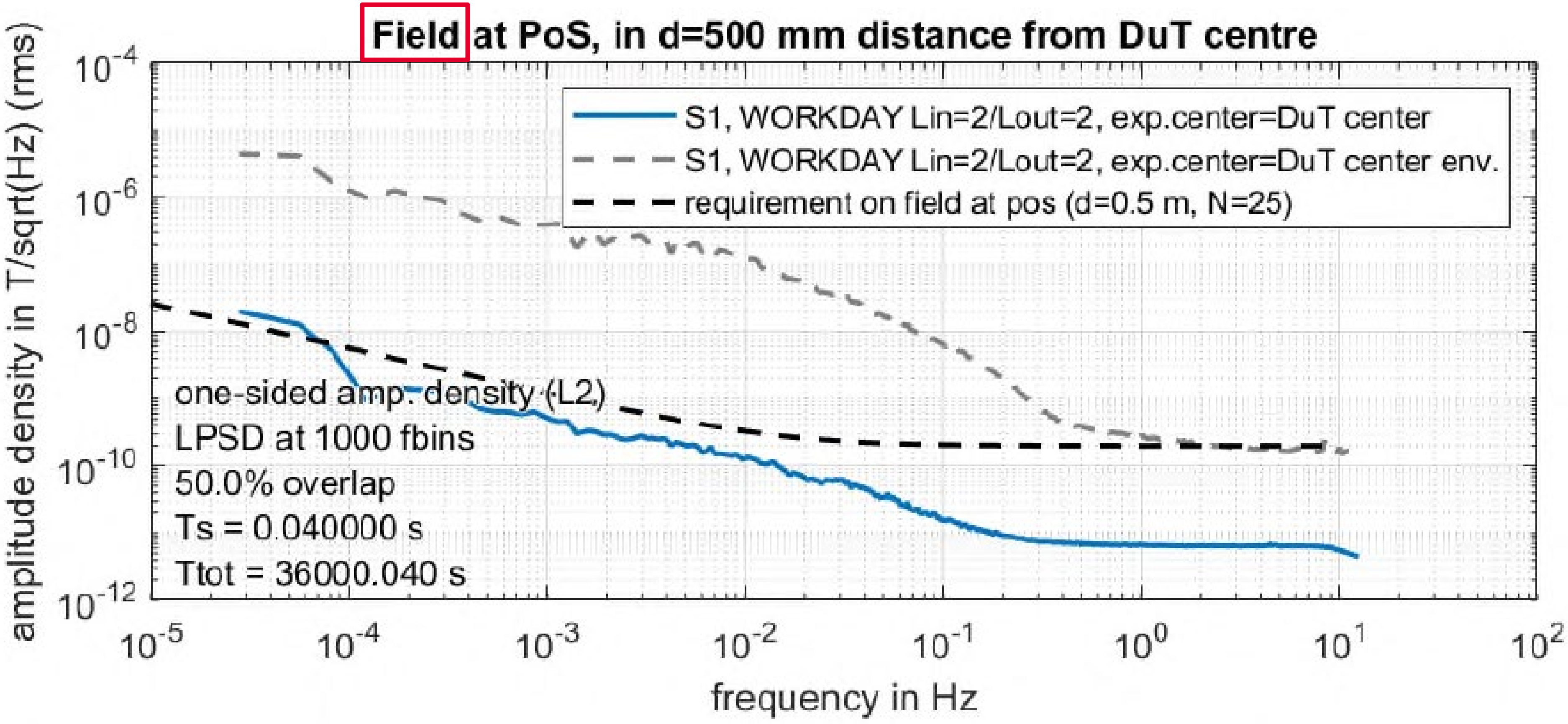
- **Test result: small frame**



x-component time domain example

Facility Performance Demonstration

- **Test result: small frame noise floor**



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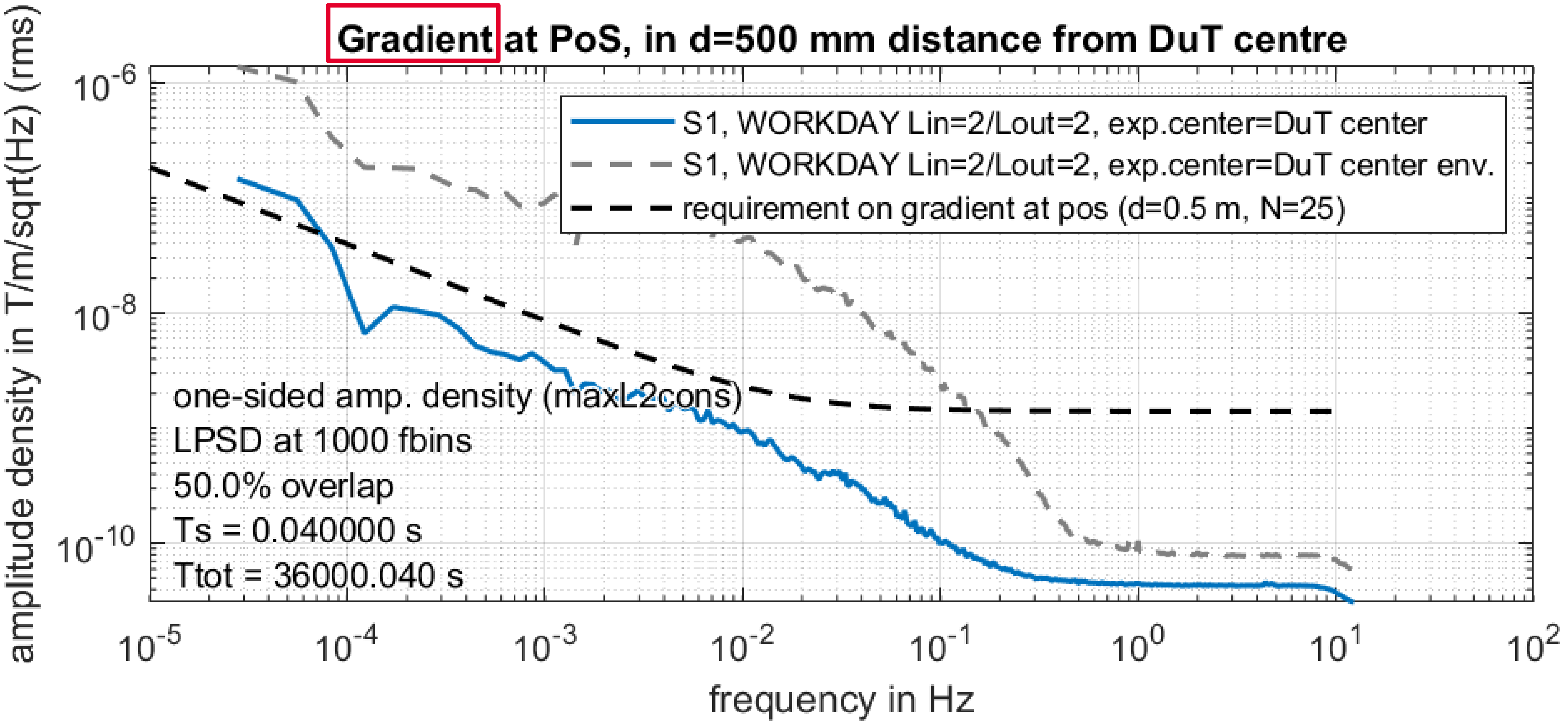
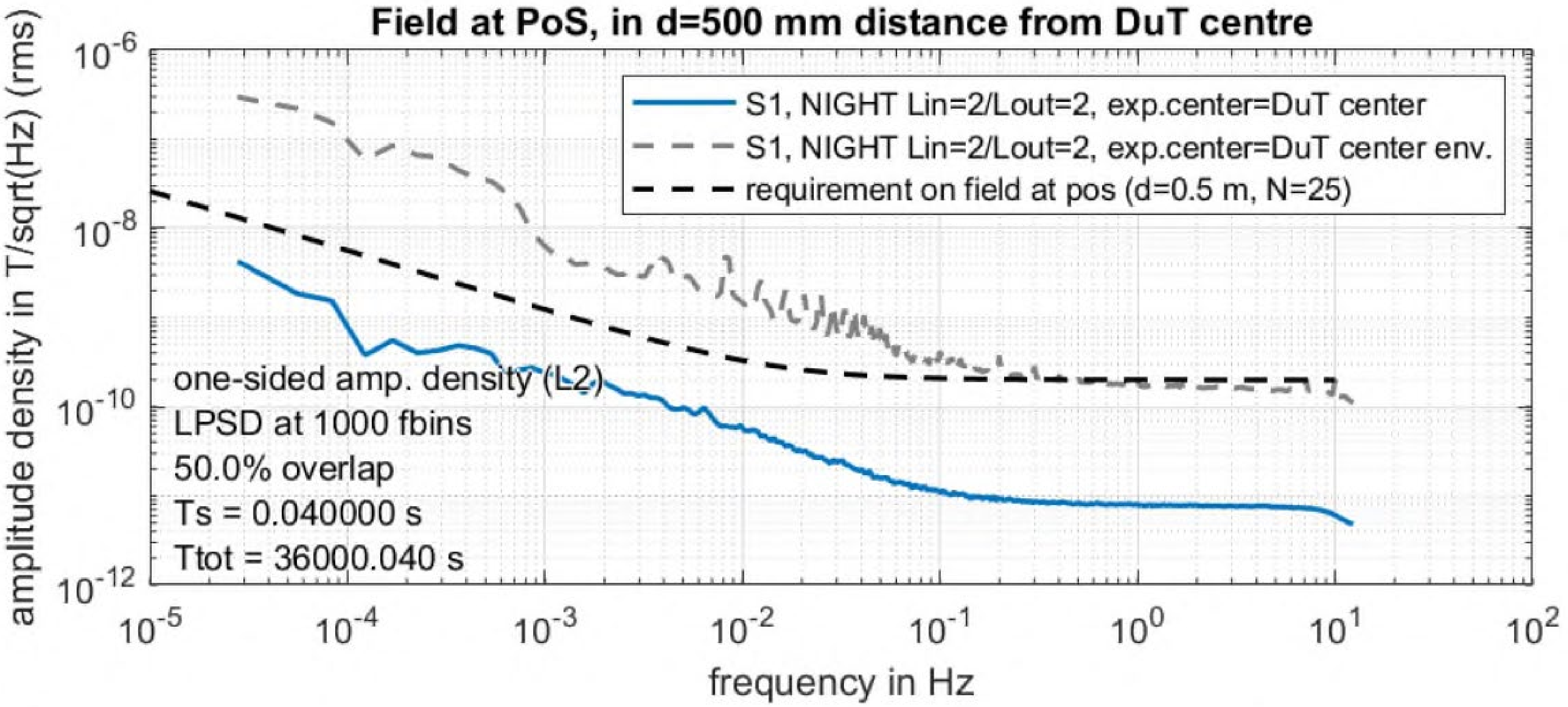
Facility Performance Demonstration

- **Test result: small frame noise floor**



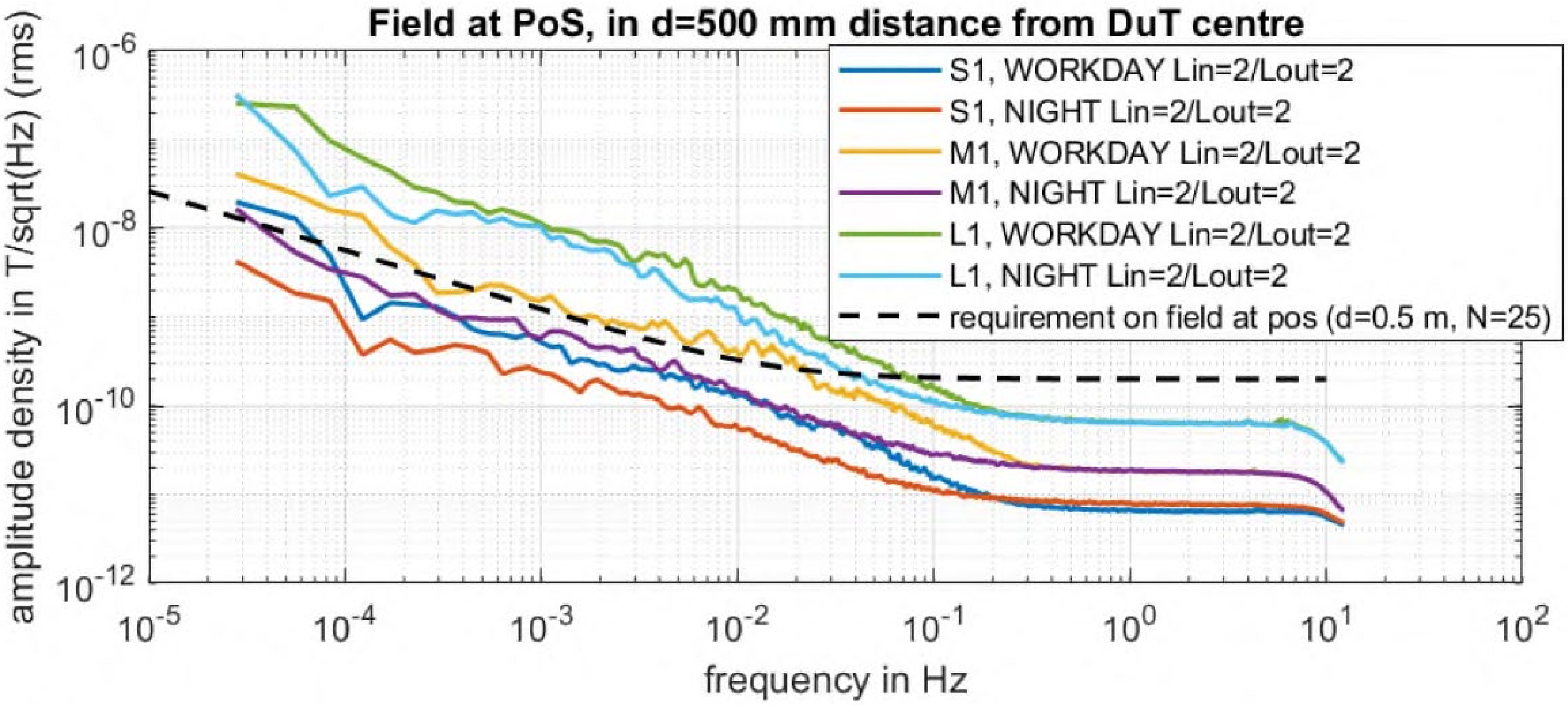
Facility Performance Demonstration

- **Test result: small frame noise floor**



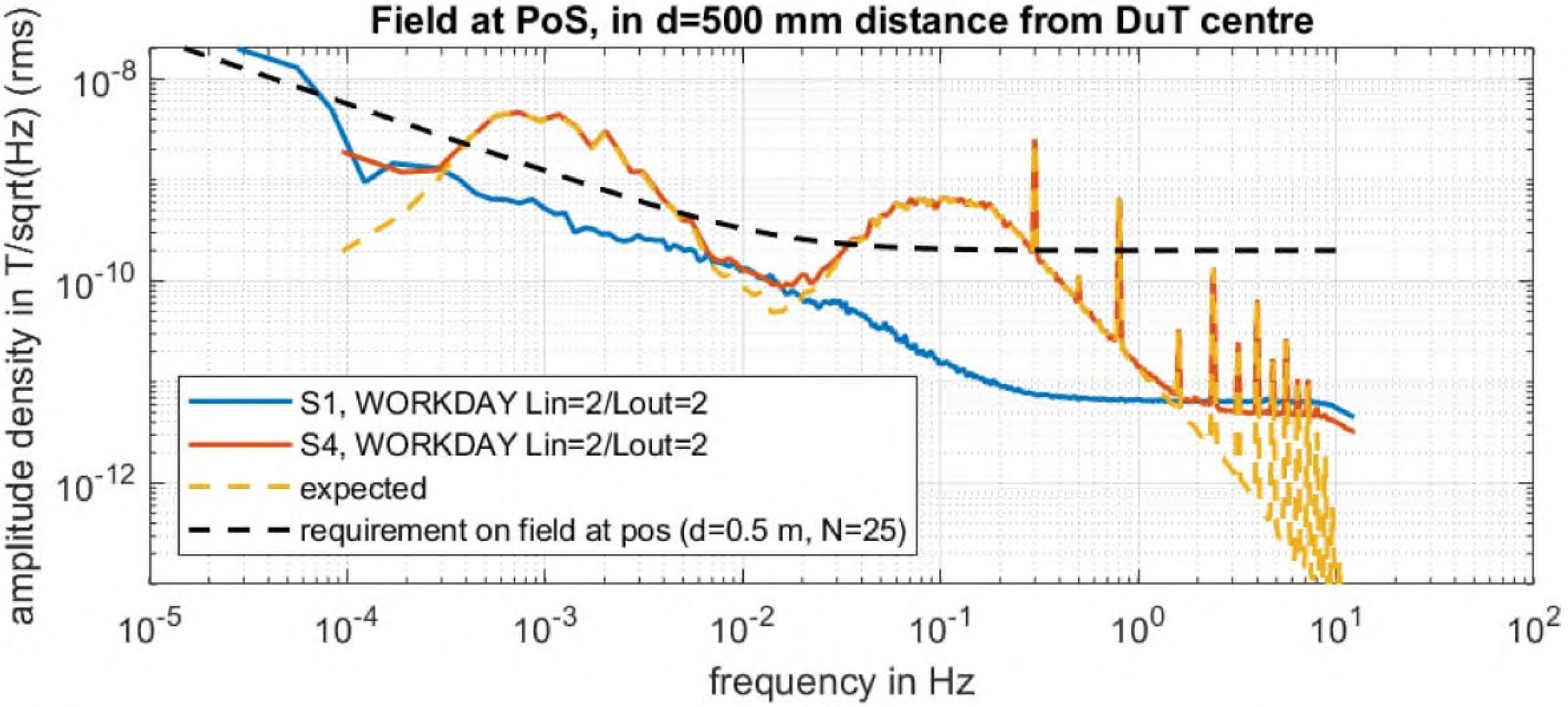
Facility Performance Demonstration

- **Test result: all frames noise floor**



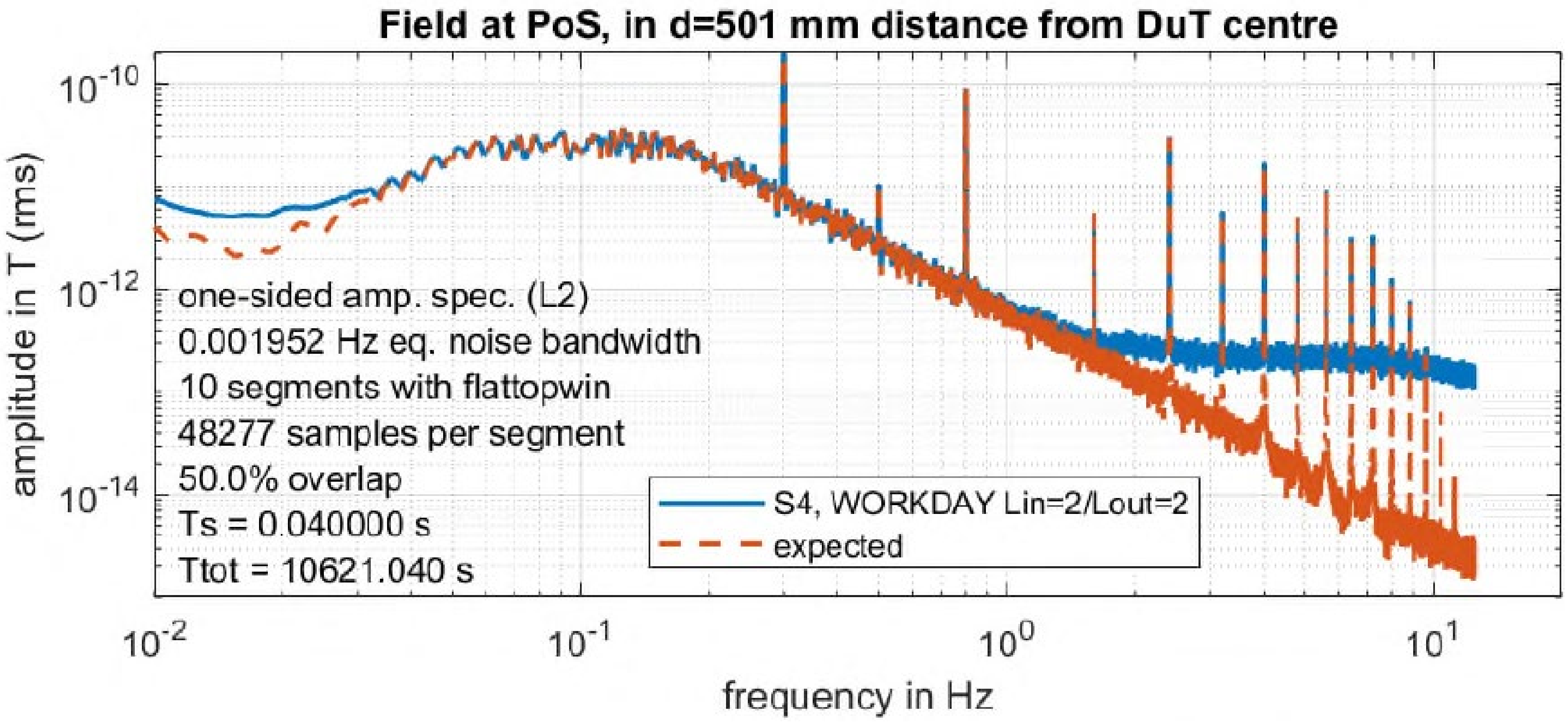
Facility Performance Demonstration

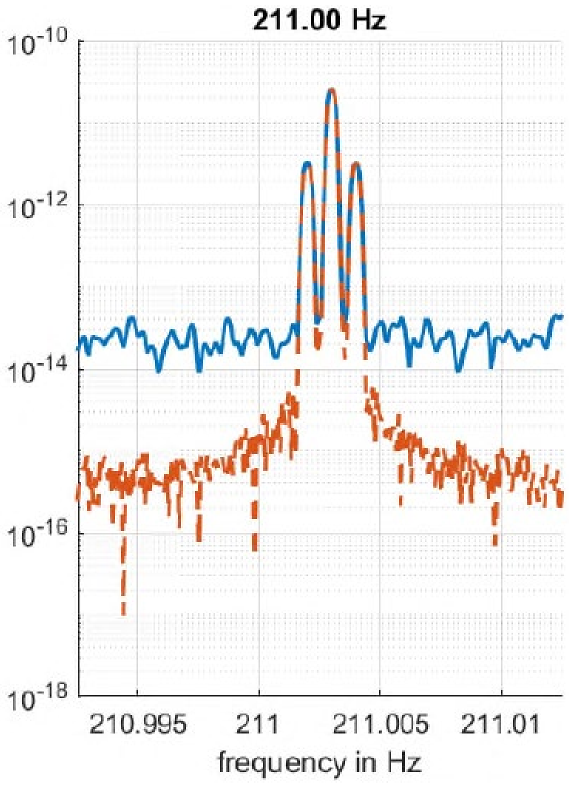
- **Test result: small frame with DUT**



Facility Performance Demonstration

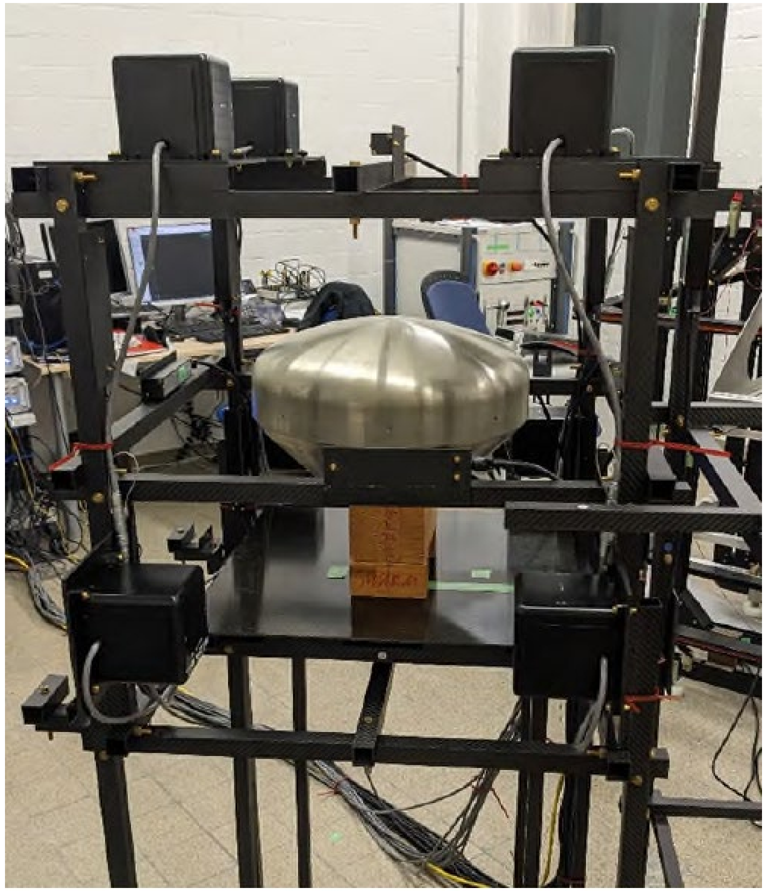
- **Test result: small frame with DUT – amplitude modulation**

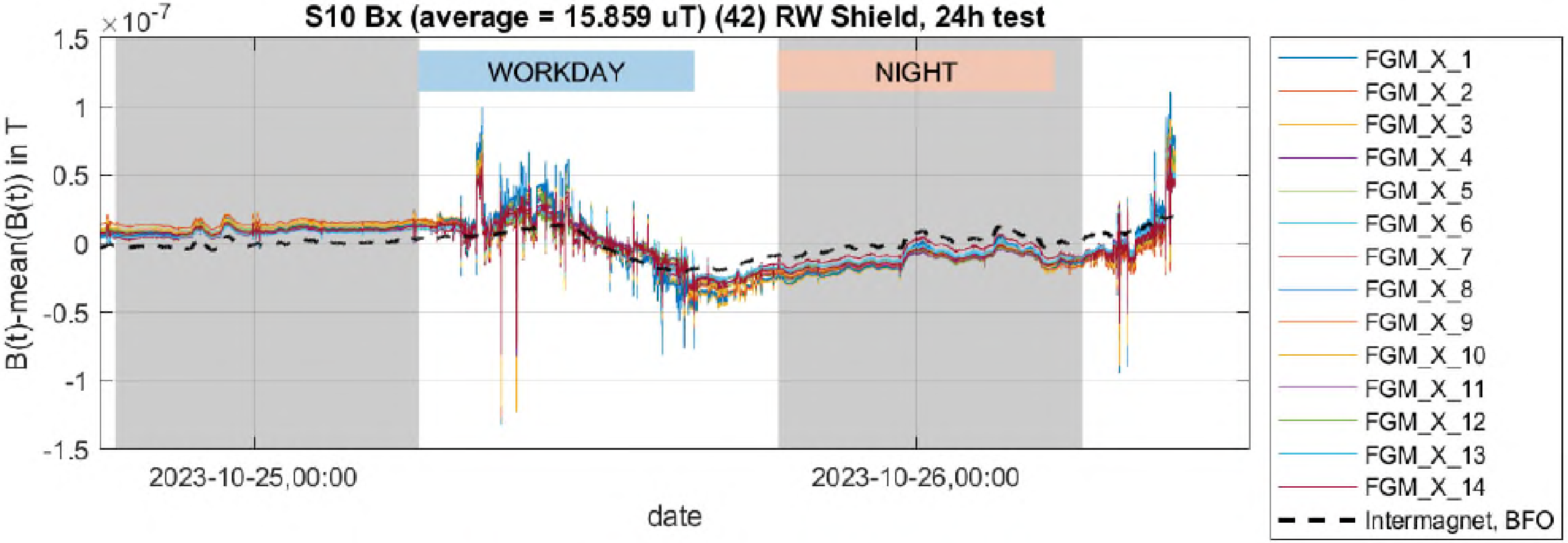




Facility Performance Demonstration

- **Test result: induced field effects – large mu-metal RW shield (‘worst case’)**





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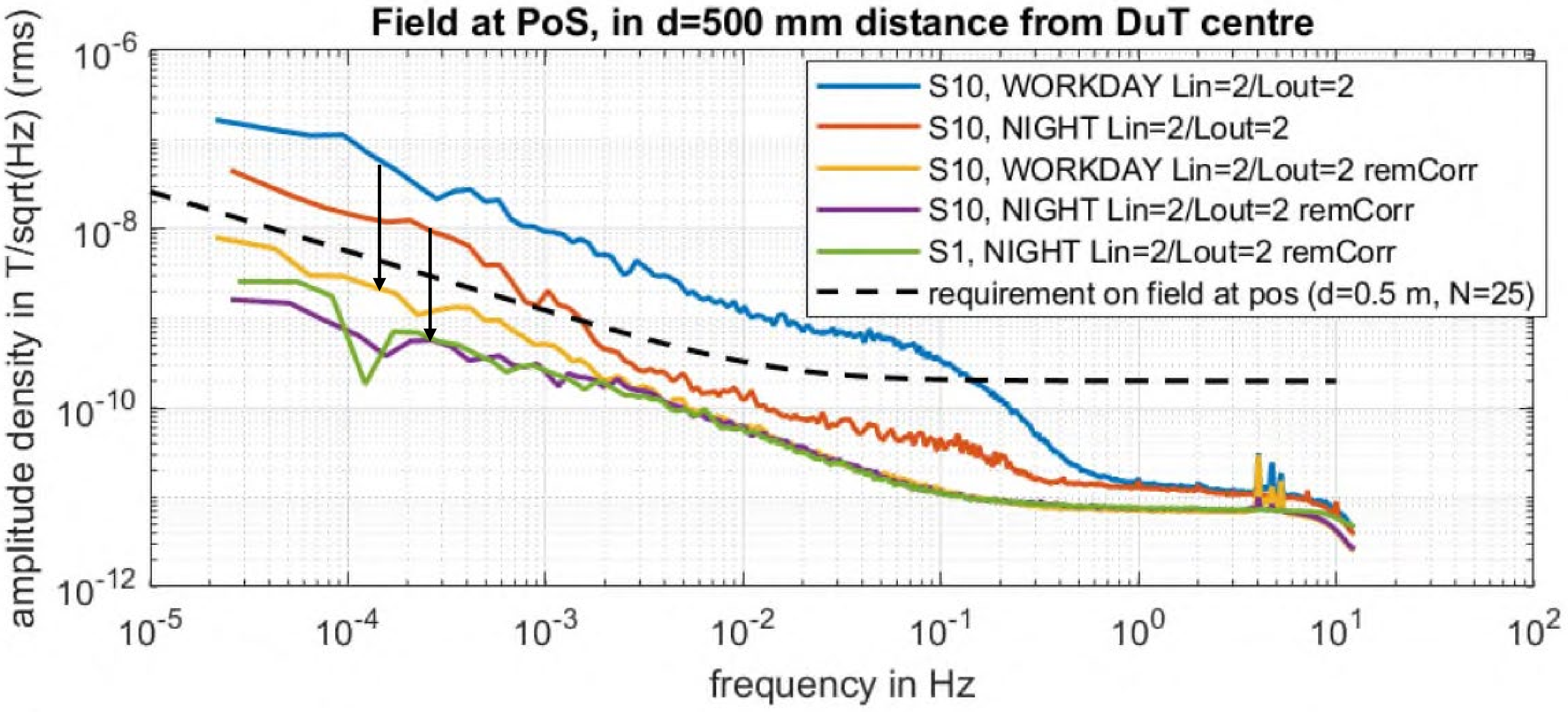
Facility Performance Demonstration

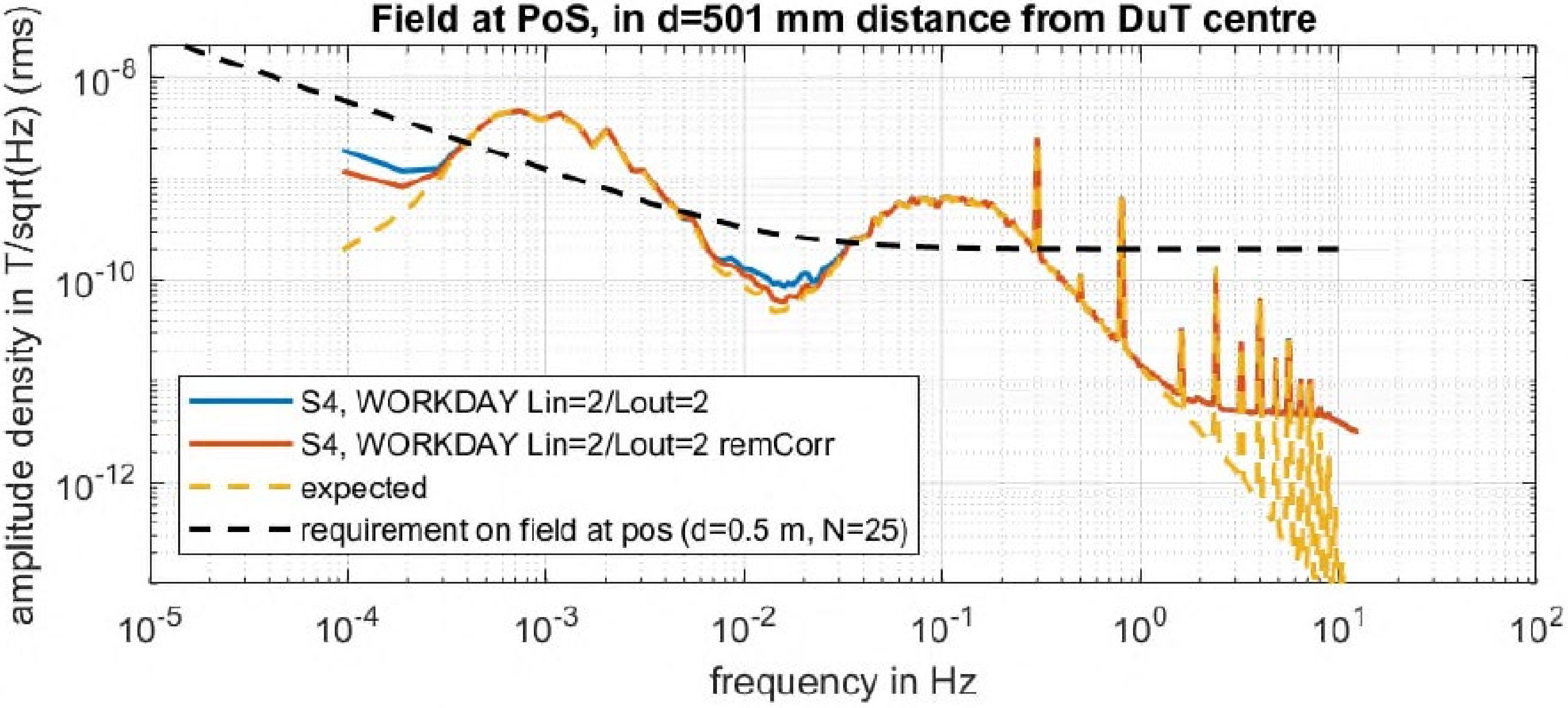
- **Test result: induced field effects – large mu-metal RW shield (‘worst case’)**



  - Correlated noise removal works very well – RW induced magnetism perfectly correlated with environment

Facility Performance Demonstration

- **Test result: correlation technique applied to synthetic DUT data**



Conclusions and Next Steps

Conclusions

- Major progress has been made on understanding (and mitigating against!) low frequency noise contributions, best results were achieved by:
    - Ultra-stable sensor array CFRP support frame – minimising thermally-induced sensor rotation and translation and environmental magnetic field pick-up at source
    - Discovery of DAQ thermal sensitivity and link to internal fan control
- This meant that more costly and more complicated solutions, such as large (active) compensation coils or ultra-stable pilot tone generators, were not necessary to meet the LISA requirements
- Test performance in terms of minimum noise floor predicted at the PoS in 0.5 m distance from the DuT with an equivalent DuT model fitted inside the facility representing the ambient noise leakage into the DuT model:
    - Noise floor of the S-frame is verified to be comfortably below the LISA requirement
    - Noise floor of the M-frame is verified to be in the same range as the LISA requirement

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Conclusions

- Optimal crossover when switching from FGM to SCM confirmed to be approximately 3 kHz
  - Potentially, due to GRS shielding, LISA unit level tests might require FGM measurements only
- A Synthetic DuT has been tested as a dipole, quadrupole and large loop with excellent results of the fitted model compared to the expected field at the PoS as simulated based on the measured current
  - Both broadband and narrowband emissions
- Test hardware and processing scheme is verified to be able to resolve amplitude modulated signals with a carrier frequency around 200 Hz and a modulation frequency of 1 mHz
  - Excellent agreement even for carrier frequency amplitudes of order 50pT
- Extended processing technique to remove correlated signatures very successful
  - Necessary to handle field-induced effects in unshielded environment
  - Confirmed that it has no impact on intrinsic DUT emissions (not correlated with external field)
  - Correlated component could in principle be used to quantify field-induced contributions

Next Steps and Future Improvements

- **Next steps**
  - Complete remaining final report documentation
  - Deliver software/hardware and install at ESA premises in May 2024
- **Future potential improvements**
  - One outcome of the testing was that the DAQ noise could be reduced by using a lower field limit
    - If the facility magnetometers were placed onto an adjustable bracket, such that the orientation would result in two sensor axes being < 1 V, technically a lower noise limit could be achieved
  - Having understood the fundamental contributions to the low frequency noise floor, another logical step would be to scale the same technique up to a larger number of sensors
    - This would allow to:
      - Fit higher order spherical multipoles to handle more complex sources
      - Fit the same order of multipoles but with lower noise through averaging
    - Systems with several hundred measurement channels (!) can be found in the literature

Thank you!

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Any Questions?

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