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ADAM

Advanced DC and AC Magnetic Verification (ADAM)

Executive Summary

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None.

Table of Contents

1 Executive Summary

1.1 Introduction and motivation

The main objective of the Laser Interferometer Space Antenna (LISA) mission is to observe gravitational waves emitted by a multitude of stellar, galactic and possibly cosmic sources. Most sources of gravitational waves are expected to be visible at frequencies between 10^{-4} Hz and 1 Hz, meaning any verification strategy needs to be able to cover long time periods of magnetic field measurement or analysis.

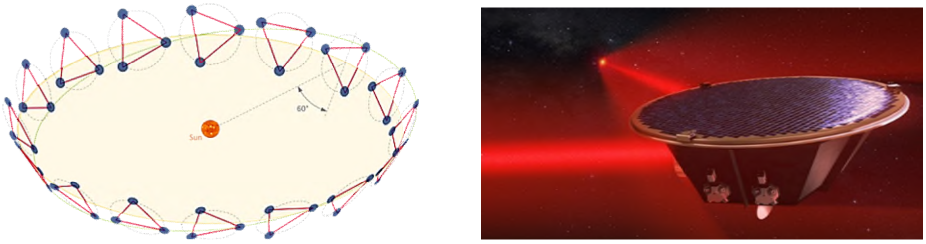


Figure 1-1: (left) Illustration of the LISA constellation (right) Artist's impression of a LISA mission concept spacecraft (one of three identical spacecraft in the constellation).

One of the driving performance requirements for LISA is the test mass (TM) acceleration noise, which has many contributions, including magnetic forces. When converting the system level magnetic allocation into an equivalent unit test level, the resulting amplitudes cannot be directly measured at the equivalent TM distance from the unit. The magnetic field amplitude spectral density (ASD) requirement is shown in Figure 1-2, with the unit level amplitude less than even the dedicated IABG MFSA facility can provide (labelled “LPF System Measurement Floor” in the figure).

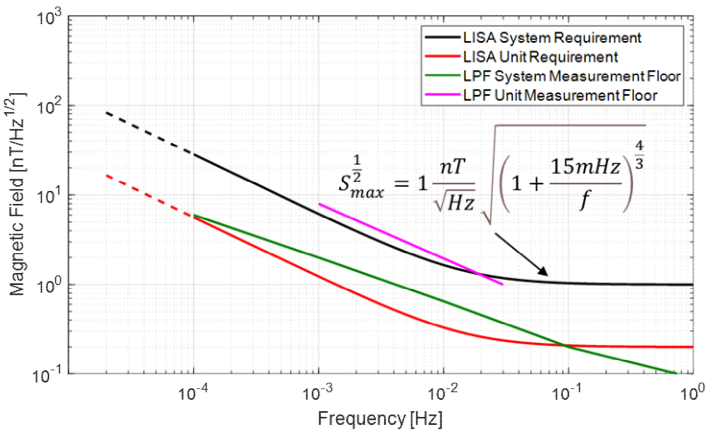
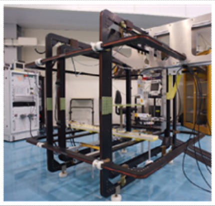
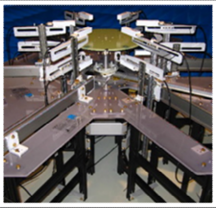


Figure 1-2: ASD system level to unit level apportionment, compared to LPF facilities performance

This drives the need for a new magnetic test facility, which we call ADAM (Advanced DC and AC Magnetic Verification facility). A summary snapshot of how ADAM fits in with other existing magnetic test facilities is shown in Figure 1-3. While the Mobile Coil Facility (MCF) and Multi-Magnetometer Facility (MMF) are well placed to perform static DC magnetic moment measurements, and the AC Magnetic Facility has focused on testing at frequencies higher than LISA, ADAM expands the frequency range to the lowest frequencies while taking advantage of many techniques developed in the AC Magnetic Facility.

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

Figure 1-3: Magnetic test facility comparison chart

1.2 Verification methods at sub-Hz

The initial starting point on ADAM was to re-use the same techniques adopted for the AC Magnetic facility – namely to use multiple magnetometers around the device under test (DuT) and then take advantage of the signal space separation technique based on the spherical harmonic decomposition of the magnetic field to distinguish between internal and external sources.

Instead of measuring the quantities specified in the requirement directly at the point of specification (PoS), a model-based approach is proposed as shown in the following figure. In order to verify a requirement at the PoS, a model of the DuT is identified and parameterized from measurements based on the knowledge of the underlying physics. Then the model is used to predict the field characteristics at the PoS, where it is checked against the requirement.

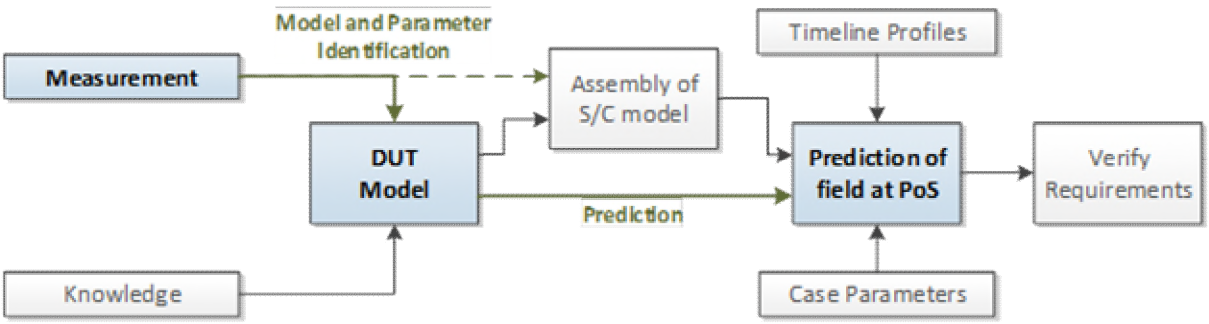


Figure 1-4: Structure and Objective of Data Processing Methods

The fitting model for the DuT then takes advantage of a multipole expansion based on spherical harmonics. The method of signal space separation (SSS) utilizes the fact, that all terms of the multipole expansion are orthogonal to each other w.r.t a surface integral of the field, which contains the centre of the expansion. In particular, all terms of the inner sources (which can be thought to be concentrated at the expansion centre) are orthogonal to the terms of the outer sources (which can be thought of being infinitely far away).

The main formula that determines the magnetic field modelled is shown below, with the various parameters explained.

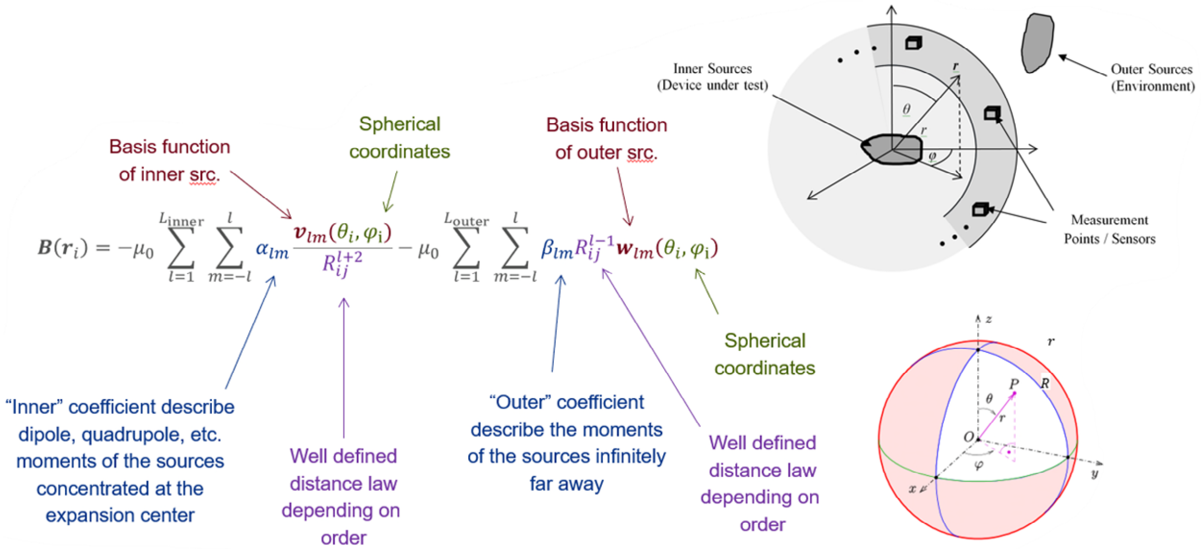


Figure 1-5: Spherical harmonics multipole expansion.

1.3 Driving disturbance sources

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

Analysis of demonstration measurements showed the main disturbance sources are temperature induced sensor rotation and translation, driven by distortion of the sensor mechanical support.

1.4 Mitigation measure trade-off

To mitigate the driving disturbance mechanism, a number of options were considered and tested:

- **Compensation coils**
  - To minimise the ambient field pick-up during sensor rotation and translation
- **Pilot tone**
  - The generation of a pilot tone with a known signature to track the sensor rotation and translation, correcting the data with post-processing to re-align the field vectors
- **Ultra-stable mechanical support**
  - To reduce the sensor rotation and translation in the first place and eliminate at source, through the manufacture of a thermally stable sensor array support frame

Dedicated tests were carried out to assess the pros and cons of each option.

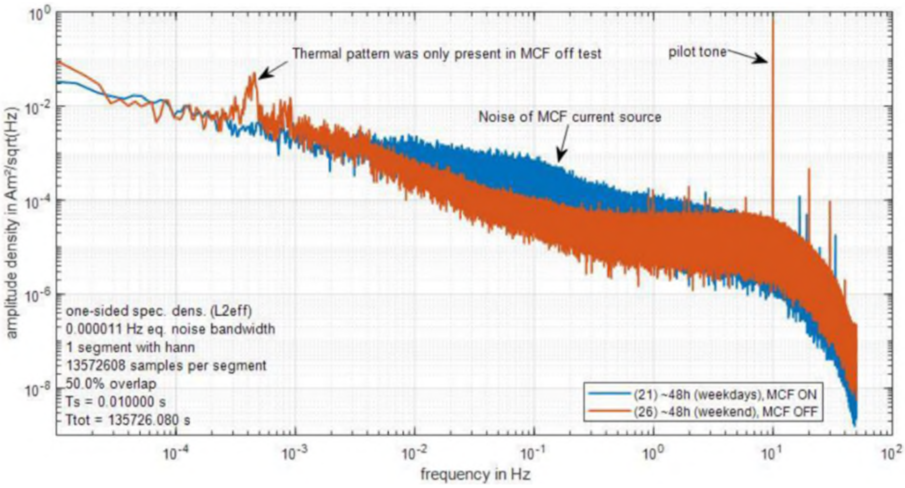


Figure 1-6: Comparison between compensation coils ON (blue) and OFF (red), with pilot tone.

In a test with the MCF, compensating for the ambient field showed a reduction in thermally induced noise patterns. However, controlling the thermo-elastic distortion of the compensation coils proved to be just as challenging as managing the thermo-elastic distortion of the sensor setup in the first place. Furthermore, it was found that using compensation coils generated additional noise in the frequency range from 10 mHz to 10 Hz, due to the injected current noise. (Figure 1-6).

While using the pilot tone method showed some merits, to generate a large enough signal at all the sensors in the frame requires either one strong coil in the centre of the array or multiple coils spread around the perimeter, and requiring a highly stable support. Finally, a demonstration frame made from CFRP was designed, manufactured and tested in order to investigate the third option.

Using an average sensor distance of 600 mm from the DuT, the results from the demonstration frame measurements were sufficiently close to the requirement to given confidence that the design would meet the necessary levels once the sensors were mounted at a closer distance.

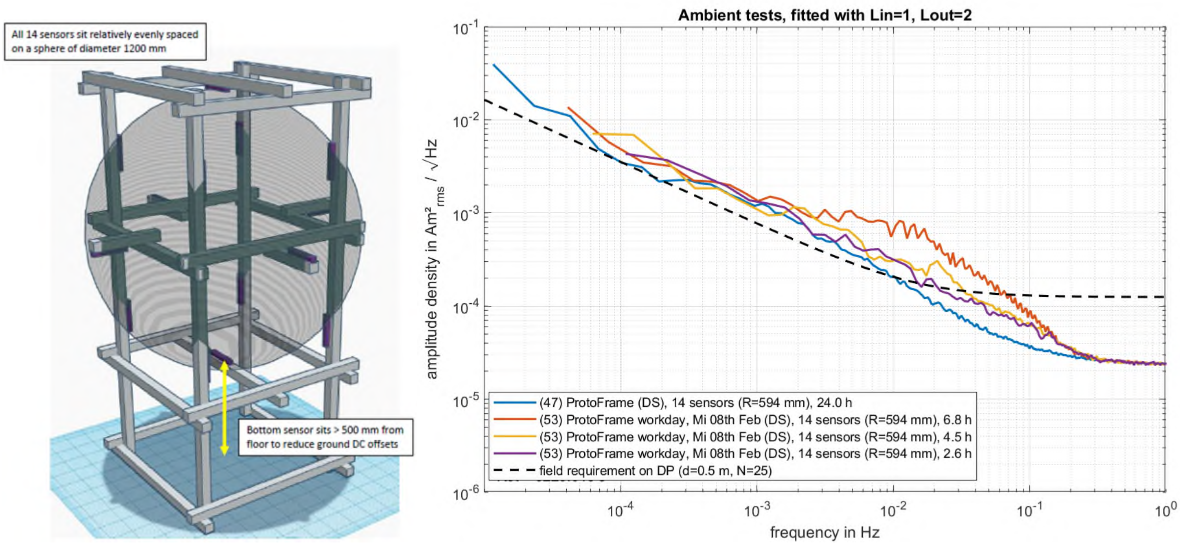


Figure 1-7: (left) Model of the demonstration frame (right) ASD of fitted dipole moment into ambient test data with demonstrator frame measured on a weekday, fitted with Lin=1, Lout=2.

Once it was proved that the limits could be achieved with the proposed Sensys fluxgate magnetometers (FGMs) and data acquisition system (DAQ), a final shape for the sensor frames was designed and manufactured at Airbus UK, before being shipped to Airbus FDH for testing.

1.5 Test Facility Design

The facility uses multiple magnetometers distributed in space around the DuT, namely 14x fluxgate magnetometers (FGMs) and 8x search coil magnetometers (SCMs), to record the magnetic field over long time periods sufficient to cover the LISA requirements range down to 0.1 mHz. A summary of some of the test facility components shown together is presented in Figure 1-8.

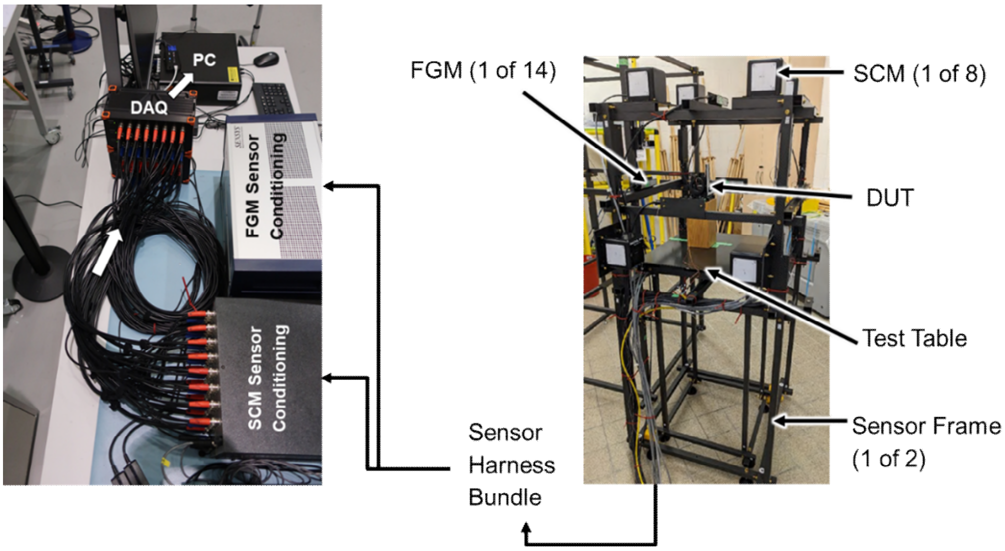


Figure 1-8: ADAM test facility overview.

Two sizes of frame were constructed, named "small" and "medium":

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
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

Figure 1-9: ADAM carbon fibre mechanical sensor frames (left) small (right) medium sized.

Focusing on the elements close up, the various parts that make up the frame become clear. In addition, the facility is adjustable in many ways, such as having a removable bar to allow DuT access, levelling feet to allow the height of the frames and test table to be adjusted, and a flight transport case that can be used to move or store all frames when dismantled.

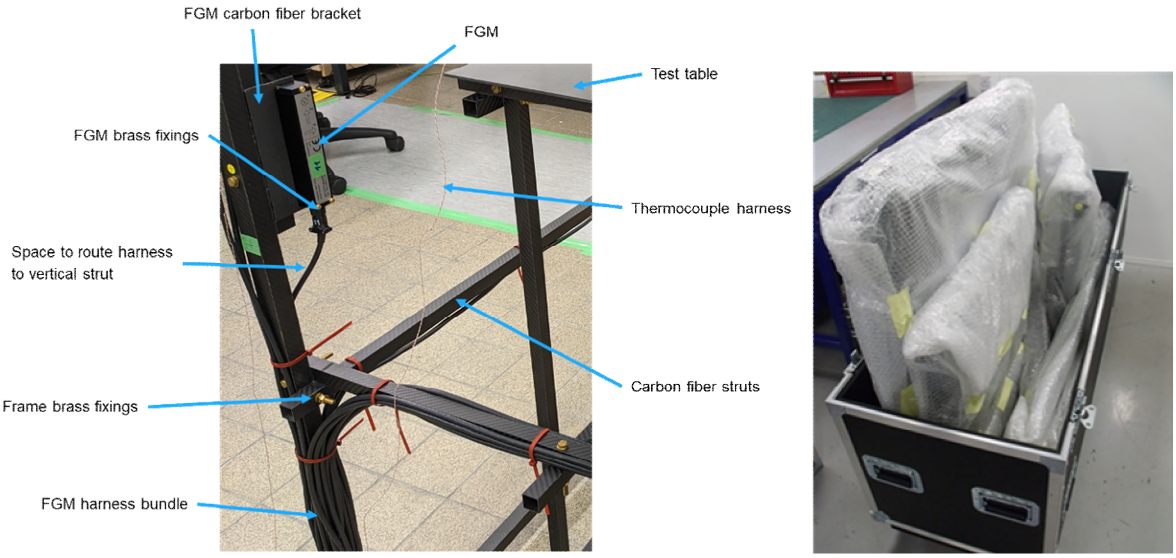


Figure 1-10: (left) sensor frame elements (right) transportation case.

The following drawing shows the connections between the sensors to the DAQ and desktop.

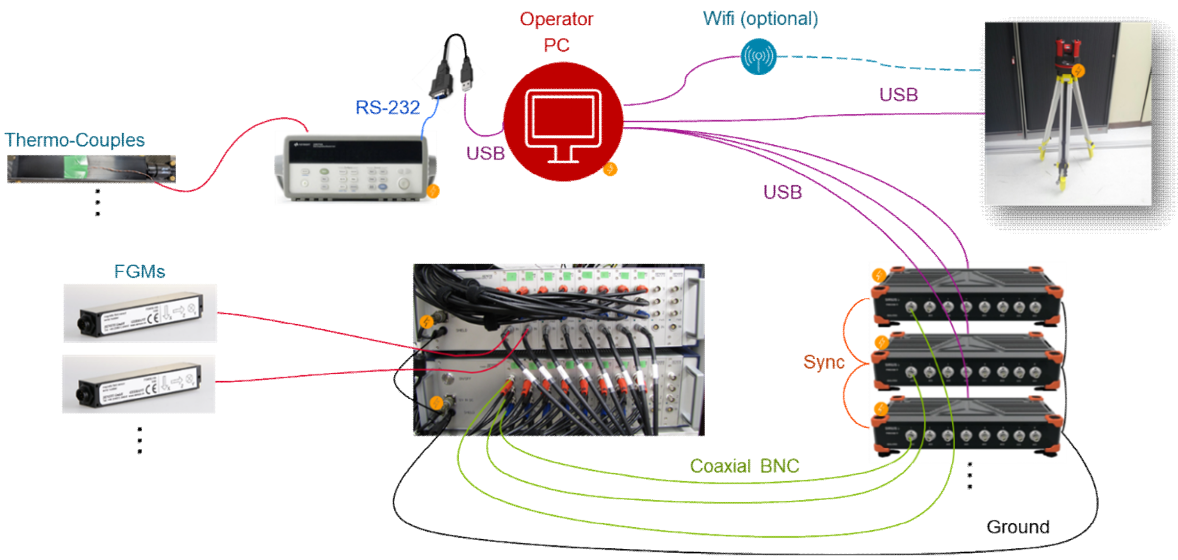


Figure 1-11: Electrical interfaces.

The software uses DEWESoft 2023.1 for the DAQ hardware configuration, Leica 3D Disto for the laser positioning system, and MATLAB/Octave for the custom ADAM library, used for many things, including thermal data logger control, DuT definition, individual measurements and log test characteristics, test data processing vs requirements, etc.

A full user guide has been provided including installation instructions and an end-to-end test flow.

1.6 Validation testing

A synthetic DuT was manufactured to generate a known signature for validation of the test facility. It was driven by a complex signal that combined low frequency shaped noise broadband signatures as well as higher frequency peaks with harmonics.

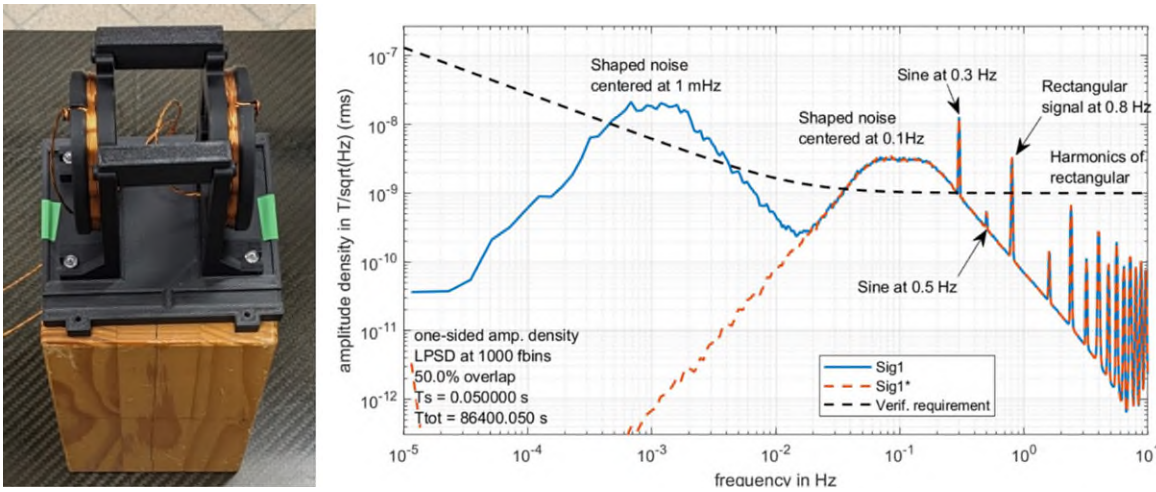


Figure 1-12: Synthetic DuT models (left) Quadrupole and Large Loop (right) shaped noise signal.

The small frame (S), medium frame (M) and a larger tripod configuration for information (L) were all tested. The performance of the facility in ambient conditions of the small frame was compliant even during a workday environment, while the medium frame was compliant at night and hovering at the requirement limit line during the day.

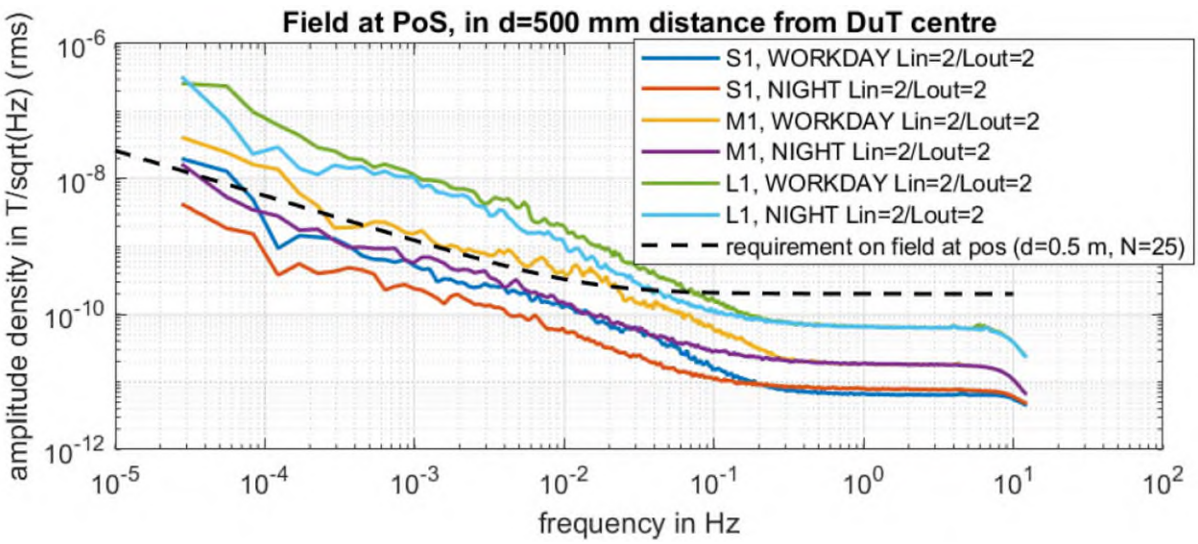


Figure 1-13: ASD ambient performance for all sensor frame scale sizes, during different times.

The tests using the synthetic DuT showed that it was possible to recover both the broadband and narrowband behaviour accurately, as modelled in a DuT simulator prior to the measurement.

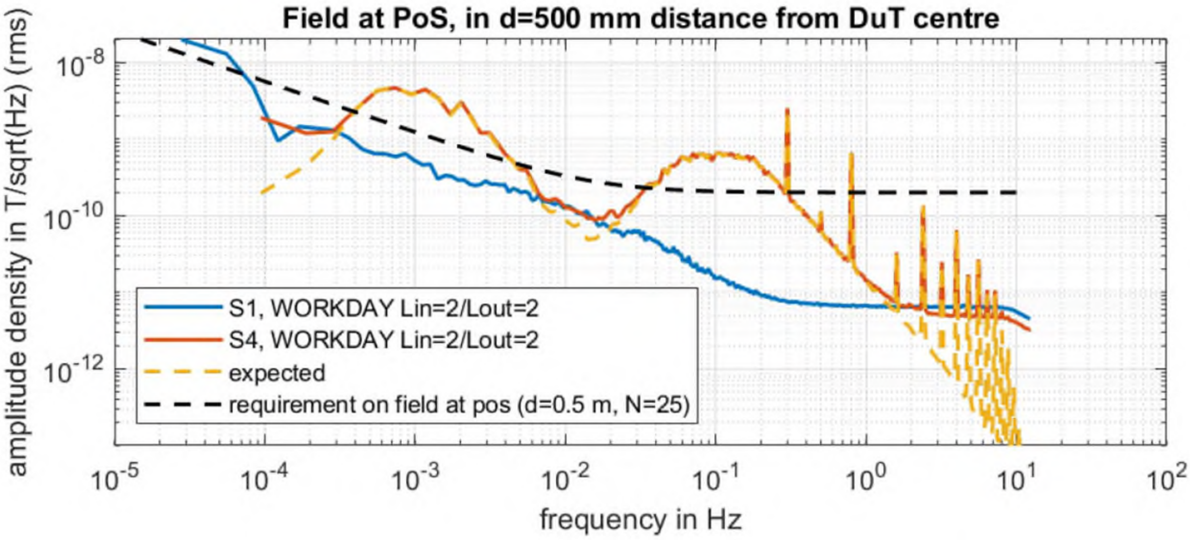


Figure 1-14: Recovered DuT contribution matching predicted field closely.

Additional testing also pushed the capabilities of the facility further, for example demonstrating the ability to measure higher frequency amplitude modulated signals, which can result in TM accelerations at low frequency.

ADAM is designed to operate in an unshielded environment, and this carries the risk that emissions from DuTs including soft magnetic materials could be contaminated by field-induced effects. For this reason, a correlation technique was developed and applied to the data analysis, whereby field induced contributions were identified as those highly correlated with the external environment. This method was applied to the characterisation of a large mu-metal shield and was shown to perform extremely well. When this technique was retrospectively also employed on the ambient data, it reduced the noise recorded with the medium frame sufficiently to ensure compliance with the requirements for most frequencies even during a day-shift.

1.7 Summary and conclusions

The ADAM facility developed within the frame of this TDA has been successfully designed, built and tested to the required levels for the LISA unit level verification programme.

A major trade-off was performed comparing the relative benefits of using a Helmholtz coil to provide a compensated field environment and a pilot tone for tracking sensor movements. It was ultimately possible to meet the requirements without adopting these mitigation measures by using an ultra-stable sensor array made from CFRP. This minimised the sensor rotations and reduced the impact of environmental field pick-up from sensor rotation caused by thermal drift in the sensor MGSE.

The overall test performance was exemplary, showing that the baseline small frame can meet the required performance during a standard working day-shift, using FGMs for the majority of the frequency range, while also being able to resolve amplitude modulated signals.

The extended processing technique to remove correlated signatures was also very successful, giving confidence that the impact of field-induced effects in an unshielded environment can be handled by ADAM.

Document Change Log

VERSION	DATE	MODIFICATIONS
1.0	12 June 2024	Initial version.