Document No: SEAFOM Measuring Sensor Performance Document – (SEAFOM MSP-02 V2.0)

DAS Parameter Definitions and Tests

Issue Date: February 2024

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1 Introduction

This document was written by and on the initiative of the SEAFOM Measurement Specifications Working Group. It is targeted specifically for “Distributed Acoustic Sensing” (DAS). The first version was published in August 2018. This updated and extended second version was written by and on the initiative of the SEAFOM DAS (MSP-02) Working Group. The extensions consist of a brief introduction to Distributed Acoustic Sensing in this section and two extra tests in Section 4; namely “Long-Range Self-Noise” and “Fading” tests.

It is intended to be used as a guide to enable the characterization of performance of DAS interrogator Units (IU) as defined by the measurement parameters and via the use of a recommended set of measurement practices – including definitions of key parameters, test setups, procedures, and calculation methods. Use cases of this document might include, for example, quantitative performance analysis of a single IU (e.g. to assess suitability for a particular application), or objective comparison of two or more IUs to support a procurement decision. The document is not intended to define any specific acceptance criteria for any given application, neither to limit the ability for any user to use any brand of DAS with any desired fiber and cable that is compatible with such system. The recommended equipment that is required to support these setups and test procedures does not require any particular class of performance; however, their performance parameters will limit the quality of the determination of the various fiber measurement parameters.

Further, it is intended to have an agreed definition set for the following:

1. Specification elements and parameters of interest.
2. Conventions to follow.
3. Vocabulary or metrics used when expressing performance parameters.
4. Measurements to be made to assist operators in determination of suitability of IU equipment for their requirements.

1.1 Objectives and scope of document

The objectives of this document are to:

1. Establish key requirement elements in consideration of operator needs.
2. Define these elements with standardized metrics.
3. Provide a recommended set of test approaches to evaluate the specification elements which are designed to be performed by non-SME personnel.

Whilst this document does provide a harmonized set of DAS performance testing procedures which are valid for any brand or model of a DAS system, it does not impose any requirements on the actual DAS system performance.

1.2 A brief introduction to Distributed Acoustic Sensing (DAS)

This section provides a high-level introduction to optical fiber-based Distributed Acoustic Sensing (DAS). It assumes the reader is familiar with the wave nature of light (the concept of *phase* in particular) and the concept of *mechanical strain*. It sacrifices detail and strict physical accuracy in the interests of brevity and clarity and is limited to single wavelength or *single carrier* operation. For a deeper understanding of DAS, the reader is directed to the following technical resources:

1. SEAFOM Primer, https://seafom.com/published-documents/, (release anticipated Q1, ‘24).
2. Hartog, A. H. (2017). An introduction to Distributed Optical Fibre Sensors (1st ed.) CRC Press

1.2.1 DAS physical principles

Optical fiber comprises a cylindrical *core*, normally of fused silica glass, surrounded by a concentric *cladding* layer with a lower *index of refraction* (Figure 1a). The combined cylinder is only a few tens of microns in diameter but potentially many tens of kilometres in length; hence “fiber”. The fragile fiber is normally enclosed within strength members and a protective outer layer to yield a practical, deployable fiber optic *cable*.

Light rays injected into one end of the fiber core within a certain critical angle of its axis or *Numerical Aperture* (NA) are repeatedly internally reflected or guided at the core-cladding boundary as they advance, thereby being constrained to remain within the core along its length (Figure 1b).

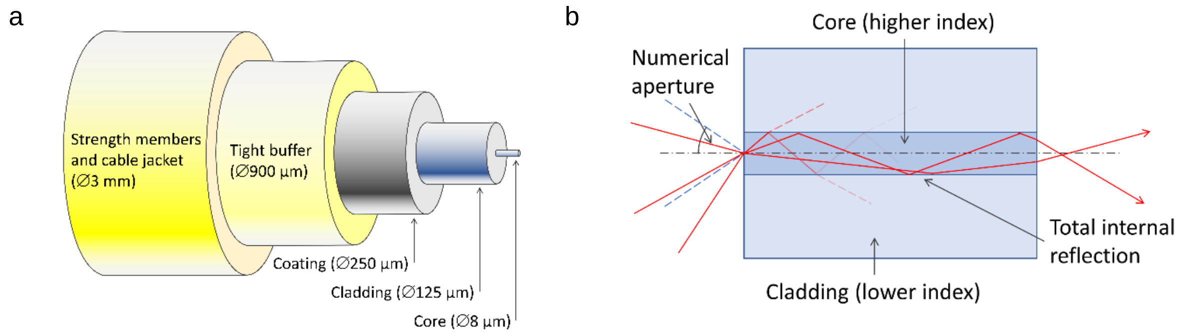

Figure 1: a. Example fiber optic cable construction (not to scale). A wide variety of alternative cable constructions are in use. b. Ray schematic of optical fiber guiding action (not to scale). Rays within the NA are constrained to remain within the core by total internal reflection at the interface between the higher index of refraction core and lower index cladding. Rays outside the NA only partially reflect at the interface, progressively escaping the core on each reflection and rapidly attenuating with distance. The NA guiding condition is illustrated at the entry facet in this schematic. It is equally applicable at any scatter site within the core.

Modern fiber achieves extremely high reflection efficiency at the core-cladding boundary for rays within the NA and extremely low attenuation in the core so that optical losses with propagation distance are very low. (One way loss in silica fiber is typically around 0.2 dB km^{-1}; a loss of only 5% optical power per kilometre.)

In any given short section of fiber, most of the light therefore propagates in the forward direction but, owing to sub-wavelength inhomogeneities in the core index of refraction frozen in at time of manufacture, a small proportion of light is scattered out of the forward NA cone. The range of scatter angles is sufficiently large that some of the scattered light is captured by the *backward* NA leading to a very weak source of counter-propagating light.

Consider then a short pulse of light launched into such a fiber by an *Interrogator Unit (IU)* Figure 2.

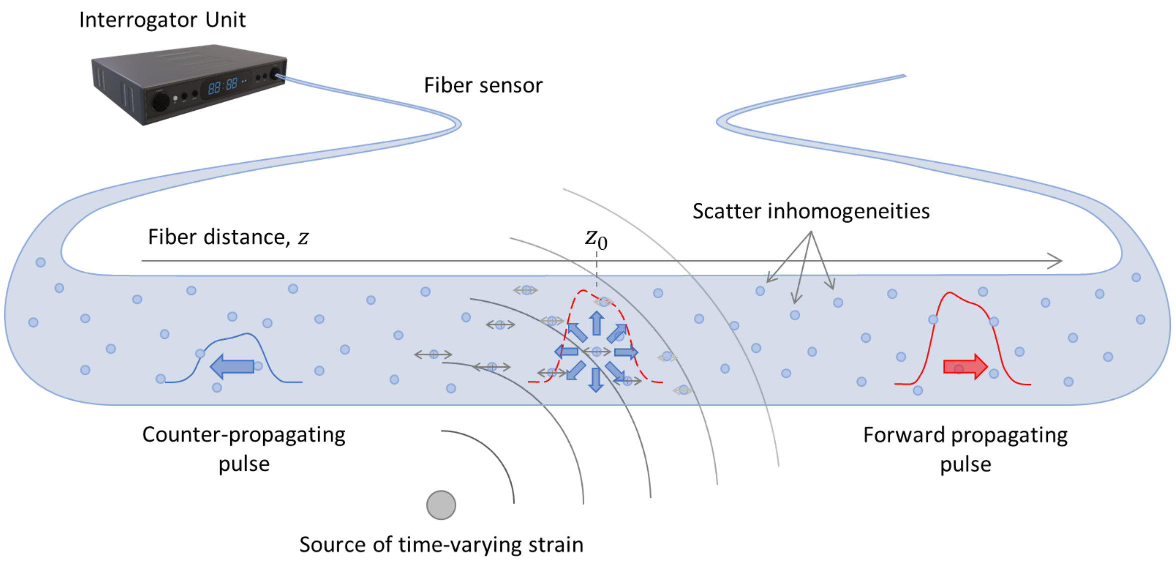

Figure 2: Schematic of the DAS measurement principle (conventional short, single pulse, single carrier type). Strain in the medium surrounding the fiber or the structure to which it is attached causes sympathetic displacement of scatter sites within the fiber core affecting the optical phase of counter-propagating pulses. See main body text for description of operation.

At some time after launch the forward propagating interrogator pulse (solid red intensity profile) reaches the scattering inhomogeneity at *fiber distance* z_0 from the IU (dashed red profile) from which originates a weak counter-propagating pulse (solid blue profile).

Some time after the scatter event, the forward- and counter-propagating pulses will have travelled equal but opposite distances from the scatter site (e.g. to the positions shown) with the counter-propagating pulse ultimately being detected back at the IU at time $t = 2nz_0/c$ relative to time of launch. With knowledge of the mean effective index of refraction in the fiber, n, and the speed of light in vacuum, c, fiber distance z_0 to the scatterer can be determined from round-trip time t.

Crucially, it is also possible for the *phase* of the counter-propagating pulse to be measured. Whilst nominal fiber distance z_0 to the scatterer can be determined with spatial resolution approximately equal to pulse width (normally of order one metre) by the round-trip timing method described above, phase is sensitive to displacement of scatterers on the sub-optical wavelength scale.

A single scatter event is shown for clarity at Figure 2 but, in practice, the forward-propagating pulse gives rise to a continuous, overlapping succession of counter-propagating pulses from the myriad scattering inhomogeneities encountered along the full length of fiber allowing phase to be measured as a function of fiber distance. The optical phase *difference* between any two such counter-propagating pulses originating from a spatially separate pair of scatter sites provides an extremely sensitive measure of their separation and, as such, is a proxy for strain-induced elongation of the fibre on that spatial interval, defined as the *gauge length* of the IU.

Launching pulses at regular intervals allows the range-dependent change of elongation between successive gauge-length-separated pairs of scatter sites to be sampled in time thereby building up a time history of strain at all fiber distances. The fiber has become a *fiber sensor*.

NOTE: The technique effectively measures the change in the spatial integral of elongation in the gauge-length interval and therefore cannot directly spatially resolve sub-gauge-length-scale structure in the strain field. Since gauge length is typically at least as great as pulse width – and is normally greater – it sets the *spatial resolution* of the system; the minimum length scale on which separate sources of strain activity can be resolved. (Note, however, that if two or more sources of strain activity occupy substantially different frequency bands, they might still be resolved *spectrally* even if they are spatially indistinguishable.)

To avoid range ambiguity, the upper limit on launch pulse repetition frequency or *interrogation rate* is set by the reciprocal of the round-trip optical time of flight to the end of the fiber sensor or the time interval over which the backscatter signal descends into instrumental noise, whichever is the shorter. In turn, the interrogation rate dictates the *Nyquist* bandwidth limit within which measurements of strain activity are free from frequency ambiguity or *alias*. (The Nyquist bandwidth limit is one half the interrogation rate.)

Interrogation rates are typically in the range 1 kHz to 100 kHz (respectively for a 100 km and 1 km fiber sensor) making the technique suitable for detection of many types of acoustically induced strain phenomena and leading to the widely adopted name *Distributed Acoustic Sensing (DAS)*. *Distributed Vibration Sensing (DVS)* is also in common use.

NOTE: We have described DAS in the context of short pulses since this is the most intuitive scheme for newcomers. Other sensing schemes exist. For example, the IU might employ long pulses in the form of coded sequences; e.g. linear frequency sweeps. In each case the time- and, hence, range-resolution with which variations in backscatter amplitude and phase can be resolved is limited by the *modulation bandwidth* of the launched pulse. All schemes offer their own engineering and performance advantages and disadvantages, but the fundamental principles of operation are as described above.

1.2.2 Strain conversion

Strain, symbol ε, is a measure of the elongation of a material caused by the application of an external force. There are two types of mechanical strain: *normal* and *shear*. Normal strain results in a change of material dimensions both in the direction of the applied force and transverse to it and, in general, gives rise to a change in material volume. Shear strain causes a change in shape but no change in volume.

For the purposes of this document, we are concerned only with normal strain – which we will refer to simply as "strain" – causing changes predominantly in the length of the sensing fiber.

Strain is a dimensionless quantity given, in the context of this document, by the ratio of the algebraic change in length, Δl, of a section of fibre under axial tension or compression, to the magnitude of its natural length, $|l|$:

$$\varepsilon = \frac{\Delta l}{|l|}$$

We adopt the convention that a force that *increases* the mechanical length of a section of fibre (i.e. stretching) causes *positive* strain within it; i.e. $\Delta l > 0$ for axial stretching, $\Delta l < 0$ for axial compression. Since optical path length increases linearly or, at least, monotonically with mechanical length, it follows that positive strain within a section of fibre is associated with an increase in optical phase delay – the property measured by quantitative DAS systems – in the gauge length spatial interval within the same region.

The change in the optical phase difference, $\Delta\phi$, in backscatter from launch-consecutive pairs of counter-propagating pulses resulting from elongation of the fiber between a pair of scatter sites is proportional to the change of mean mechanical strain, ε, exerted between them:

$$\Delta\phi = \frac{4\pi n G \xi \varepsilon}{\lambda}$$

in which n is the mean effective index of refraction in the fiber (~1.46 for Silica at λ = 1550 nm), G is the gauge length over which the phase difference is measured, ξ is the *photo-elastic scaling factor* (~0.78 for Silica at λ = 1550 nm), and λ is the IU operating wavelength specified in vacuum.

Since optical phase measurement allows sub-optical wavelength changes in fiber length to be determined, microscopic fluctuations in strain can be measured allowing vibration in the medium in which the fiber is buried or the structure to which it is attached to be inferred. Since this measurement can be made for many such successive pairs of scatter sites along the fibre sensor, the time-fluctuating strain field can be measured as a function of range.

1.2.3 DAS trade-offs and considerations

The longer the gauge length the greater the sensitivity to comparatively large-scale strain features since a smaller change in mean strain is required in a longer gauge length to produce the IU's minimum measurable change in optical phase, but the less precisely the IU is able to spatially resolve comparatively small-scale sources of strain. There is a compromise, therefore, in the choice of gauge length between strain sensitivity and range resolution.

NOTE: When employing the test procedures described in this document to objectively compare the sensitivity of two or more different IUs, it is important to recognise the influence of different gauge length settings on the units under test. The tests in Section 4 advise measurements should be made at a particular strain level (or range of strain levels) divided by the IU gauge length value *in metres*; e.g. "0.17 $\mu\varepsilon$ to 14 $\mu\varepsilon$ / (gauge length)" thereby ensuring all IUs under test are exposed to the same degree of optical phase change – the measured quantity – in their respective gauge length spatial intervals.

Improved strain sensitivity can also be achieved by aggregating measurements or *decimation* across multiple launch pulses – reducing output *sample rate* compared to input interrogation rate – but this reduces the maximum frequency of vibration that can unambiguously be measured according to the Nyquist constraint (now one half the sample rate). Thus, for a given fiber sensor length, there is a trade between strain sensitivity and useful acoustic bandwidth.

Whatever the effective measurement rate (either at launch pulse interrogation rate or at reduced sample rate after decimation), frequency resolution – the ability to resolve a source of vibration at one frequency from a co-located source at another – improves with collection time. The trade here is between frequency resolution and the ability to time-resolve a change in vibration amplitude.

If the change of strain between launch events in a gauge length spatial interval is such that the associated change in optical phase exceeds more than ±180 degrees (±π radians), the direction and magnitude of phase change is ambiguous and may lead to incorrect reconstruction of the strain waveform. This manifests as distortion or *overscale* in the recovered waveform. Lower measurement output rates, due either to operation on long fiber or through decimation, or applications in which strain signals are large and/or rapidly changing, increase the potential for overscale.

1.2.4 Strain power and amplitude spectral density plots

It is common practice in engineering to express the frequency content of a signal and/or noise waveform in the form of a *Power Spectral Density (PSD)* plot. It is important to stress that whilst the output of a Fourier transform provides a *spectrum* of the input waveform, it does not in general provide a measure of spectral density unless carefully scaled as such, just as the mass of an arbitrary quantity of water only informs its density when correctly scaled for (divided by) its volume. Just as mass density is a *specific* measure of mass *per unit volume*, so power spectral density is a specific measure of power *per unit of frequency bandwidth*.

The "power" we refer to here is shorthand for any quantity that has an energy transfer associated with it. In the DAS context, where external forces are doing work on the fibre giving rise to a fluctuating strain and corresponding optical path length field, it is common to express PSD in "strain-squared per Hertz" or optical phase "radians-squared per Hertz", for example.

Noise PSD is not normally a uniform function of frequency. Often, noise PSD rises significantly with decreasing frequency; so called *one-over-f* (1/f) noise. In that case, signal content at low frequencies will be more challenging to detect than at high frequencies. PSD plots are therefore a useful tool for describing the spectral shape or *distribution* of signal and noise power content. Their relative strengths as a function of frequency inform the suitability of DAS for different strain sensing applications targeting signal content in specific frequency bands.

To improve visibility of low-power spectral features in PSD plots they are often expressed in *decibels*; that is $10 \times \log_{10}(PSD)$ is plotted on the y-axis rather than the PSD values themselves. It is therefore common to see y-axes labelled "dB strain^2 / Hz", "dB radians^2 / Hz" or similar. To return PSD in linear units, raise 10 to the power of one-tenth the decibel PSD value; $PSD = 10^{PSD_{\mathrm{dB}}/10}$.

Amplitude Spectral Density (ASD) is simply the square root of PSD having units "strain per root-Hertz" or "radians per root-Hertz", for example.

CAUTION: Confusion sometimes arises when decibel ASD values are quoted or plotted. Decibel ASD values should be expressed as $20 \times \log_{10}(ASD)$ with ASD in linear units being found by raising 10 to the power of one-twentieth the decibel value; $ASD = 10^{ASD_{\mathrm{dB}}/20}$. The reader should exercise caution when encountering decibel ASD values. Seek clarity from the provider if in any doubt. All good vendors will be happy to clarify their performance data units.

To illustrate their use, Figure 3 shows simulated instrumental noise ASD curves for a typical DAS system for front, middle and end positions in each of a 5 and 50 km fibre at a gauge length setting of 6.38 m. 1/f noise is clearly visible in each case as an increase in amplitude density with decreasing frequency. At around mid-position in the 50 km fiber case, ASD at 100 Hz is approximately 42 dB pico-strain per root-Hertz or $10^{42/20}$x10^{-12} = 126x10^{-12} strain per root-Hertz. The RMS level of strain noise in a 10 Hz band centred on 100 Hz in that fibre location – and therefore the sensitivity limit of detection at that position and in the same band – would be around 126x10^{-12} x √10 = 400 pico-strain (i.e. the IU should be expected to exhibit approximately 400 pico-strain RMS noise level in the time-domain DAS signal derived from mid-position of the 50 km fiber in the 10 Hz band centred on 100 Hz at a gauge length setting of 6.38 m).

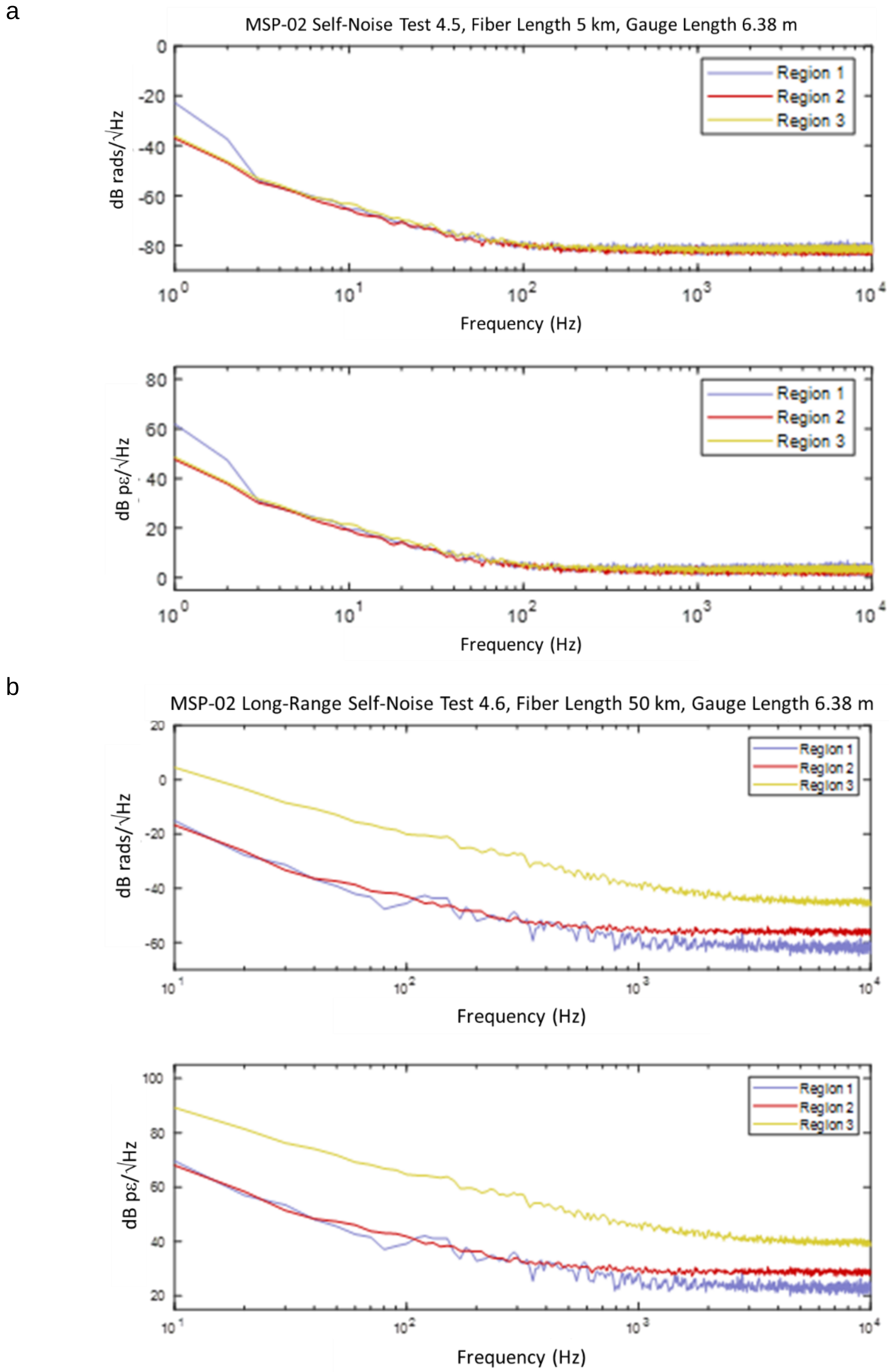

Figure 3: Typical DAS amplitude spectral density curves (simulated SEAFOM Self-Noise tests 4.5 and 4.6) expressed in both decibel radians and decibel pico-strain (pε) per root-Hertz. a: 5 km fiber; regions 1-3 = 0-1, 2-3, 4-5 km. b: 50 km fiber; regions 1-3 = 0-5, 22.5-27.5, 45-50 km. Gauge length 6.38 m in each case

1.3 Definition of DAS / DVS and its associated elements

A DAS / DVS system comprises an interrogator and optical fiber sensor that measures dynamic strain signals at acoustic frequencies at any point along the fiber, as well as the means to process and archive those measurements in order to derive useful information. Common abbreviations used include:

- DAS = Distributed Acoustic Sensing
- DVS = Distributed Vibration Sensing

A typical DAS / DVS system is simply represented at Figure 4 below and comprises three key elements:

1. **DAS Interrogator Unit (IU)** – The opto-electronic instrument that is connected to the sensing fiber and measures and records the dynamic strain along the fiber.
2. **Distributed Sensor** – The fiber optic assembly, cabled or packaged appropriately for the sensing application. This may or may not be provided by the same business or organisational entity that provides the DAS IU. Its length is generally considered to be the linear value if the sensor is straightened.
3. **Processor / Data Archiver / User Interface** – Portrayed as a separate system element within Figure 4, but could be integral to the DAS IU. It provides processing functions (standardized or customized), data archiving (usually standardized), and also provides an interface to configure and control the Interrogator, select processing options, and define and implement the data collection options (triggered, timed, or other).

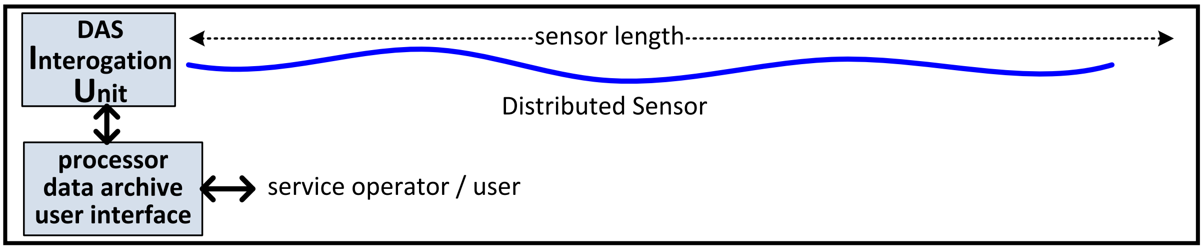

Figure 4: DAS system elements

1.4 Definition of terms / acronyms

ASD............... Amplitude Spectral Density (also known as magnitude spectral density).

AWG.............. Arbitrary Waveform Generator.

DAS............... Distributed Acoustic Sensor.

DAQ .... Digital Acquisition (system).

dB.................. Decibels – 10 x $\log_{10}$(power ratio) or 20 x $\log_{10}$(amplitude ratio).

DVS............... Distributed Vibration Sensor.

DR .... Dynamic Range.

FBG............... Fiber Bragg Grating.

FFT................ Fast Fourier Transform – time domain to frequency domain conversion.

FR.................. Frequency Response.

IU................... Interrogator Unit.

Length .... Mechanical length of fiber (not optical path length).

MSP............... Measurement Sensor Performance.

NA .... Numerical Aperture.

PSD .... Power Spectral Density.

RMS .... Root Mean Square.

rt-Hz .... root Hertz = square-root Hertz (spectral density term).

SEAFOM .... Subsea Fiber Optic Monitoring Group.

SFS .... Simulated Fiber Sensor.

SME............... Subject Matter Expert.

SNR............... Signal to Noise Ratio.

SSL .... Spatial Sample Location.

Strain .... Sensed parameter. Fiber strain (not optical path change), unit ε.

TFL................ Total Fiber Length (mechanical length, not optical path length).

THD_{FT} .... Total Harmonic Distortion.

2 Key DAS performance parameters

The parameters that may be used by the operator to assess the performance of a DAS system are enumerated below. The test procedures and requirements to measure these parameters are explained in detail in subsequent sections.

A. **Dynamic Range** – the maximum level of uniform strain stimulation that can be applied at a given frequency such that the measured DAS response is not corrupted as compared to the input stimulus.

B. **Frequency Response** – the response of the DAS system over the full required or specified frequency range. Measurements are made to determine the magnitude "transfer function" of the system.

C. **Fidelity** – refers to the accuracy and 'purity' of the DAS response compared to the original stimulus, which is determined by checking the level of distortion of the signal caused by the presence of harmonics.

D. **Self-Noise** – the DAS response in a quiet environment (i.e., free from external acoustic or vibrational stimulus). The self-noise test considers noise measurements in various ways, such as broad band "spot" noise and noise densities in pre-determined frequency bands.

E. **Spatial Resolution** – the shortest fiber range distance within which the DAS system can spatially resolve localized acoustic or vibrational stimuli in the same frequency band. (If two or more sources of strain activity occupy different frequency bands, they might still be resolved spectrally even if they are spatially indistinguishable). This is different from - but in properly working systems, approximately equal in value to - the gauge length (see Section 3.1).

F. **Crosstalk** – the presence of unintended residual signals that appear in locations other than the location of the original stimulus.

G. **Loss Budget** – an estimation of the performance impact of loss in a fiber due to components over the fiber distance. DAS performance is evaluated as calibrated point losses are inserted to the standard sensor.

H. **Reflection Sensitivity** – refers to the impact on DAS performance of unplanned partial reflections ('dead zones') in the sensor fiber, which may cause signal saturation.

I. **Fading** – probability distribution of the occurrence of spatial sample locations where the measured optical phase noise floor is significantly higher than the median level for the full range of the fiber under test. Fading leads to localised instances of elevated acoustic noise compared to the wider self-noise level.

3 Definitions

This section provides a definition of terms, units and supporting parameters associated with the recommended procedures defined in the later sections.

3.1 Supporting spatial parameters

A list of supporting spatial parameters is presented. These, combined with other definitions provided in this section, set the nomenclature to be used when defining the measurement processes to assess DAS performance parameters.

A graphical representation of supporting parameters is provided in Figure 5 to assist understanding of the definitions with further clarifications in Figure 6.

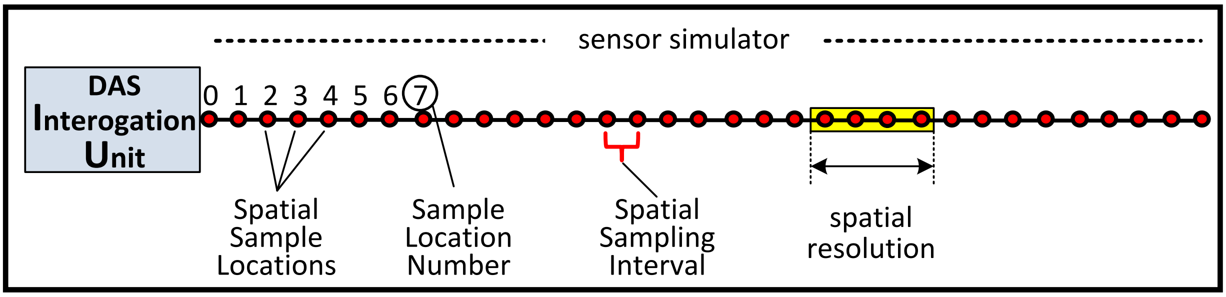

Figure 5: DAS Interrogator Unit test arrangement

3.1.1 Spatial Sample Location / Sample Location Number

The DAS IU samples the backscattered light from the sensor at different locations along the fiber sensor. These locations are defined through the interrogator configuration or setup and are represented spatially along the fiber as uniformly spaced dots: ● in Figure 5. A numbering system is defined such that the first Spatial Sampling Location starts at zero. Successive locations are numbered as positive integers which increase along the length of the sensor. The term Spatial Sample Location is abbreviated as SSL.

3.1.2 Spatial Sampling Interval

The mechanical separation in meters between consecutive Spatial Sample Locations defines the Spatial Sampling Interval. It should not be confused with 'Spatial Resolution'.

3.1.3 Fiber Distance

The mechanical distance in meters of fiber length from the connector of the IU to the desired Spatial Sample Location.

3.1.4 Interrogation Range

The Total Fiber Length (TFL) in meters (mechanical fiber length, not optical length) from the connector of the DAS IU to the final end of the fiber sensor. This end is either a purposefully cut or properly terminated end of the fiber. See Figure 6.

3.1.5 Gauge Length and spatial resolution

Gauge length is the distance (mechanical length along the fiber in meters, not optical length) over which the IU measures the change in optical path length and, hence, the change in spatial integral of strain. Gauge length might be defined in hardware or software configuration. It is not necessarily equal to the spatial resolution of the IU, which is a measured performance parameter. It should, for a properly operating IU, however, be a close approximation. See Figure 6.

.

3.1.6 Fiber Stretcher

A Fiber Stretcher, in the context of the Simulated Fiber Sensor, is a fiber wound on a piezoelectric cylinder. A voltage stimulus applied to the piezoelectric cylinder causes its diameter to increase or decrease so developing a voltage-proportional, uniform strain throughout the wound fiber length. The effective length of the fiber stretcher (its circumference multiplied by the number of fiber turns but excluding the fiber lead in/out) is recommended to be greater than twice the gauge length of the interrogator being evaluated. Fiber stretcher usage is described at Section 5.

3.2 Supporting DAS signal parameters

DAS interrogation generally involves periodically pulsed sampling of acoustically or vibrationally induced strain perturbations of the fiber sensor at each of the Spatial Sample Locations (Section 1.2). Thus, each Spatial Sample Location yields a sequence or *time series* of strain-change measurements (plus noise) which can be processed according to the intended application information desired.

This sub-section defines the signal parameters associated with both DAS interrogation and the measurement processes that assess DAS performance.

Figure 6 depicts these Supporting Signal Parameters showing how they make up the Time Series data and how they relate to spatial locations on the sensor fiber. Definitions of these Signal Parameters follow.

3.2.1 Output Data Rate

The rate at which the IU samples optical backscatter from Spatial Sample Locations. This is usually the sample rate of the DAQ, equivalent to the reciprocal of the optical round-trip time of flight over the Spatial Sampling Interval. See Figure 6.

3.2.2 Interrogation Rate

The rate at which the IU interrogates the fiber sensor. It is equivalent to the launch pulse rate for interrogators that perform optical pulse interrogation. It is equal to the inverse of the Sample Interval (not to be confused with the Spatial Sampling Interval). See Figure 6.

3.2.3 Amplitude Spectral Density

Also known as magnitude spectral density, ASD shows the spectral distribution of signal and noise content. It is the square root of the Power Spectral Density and is calculated by converting the time series data to frequency domain data with appropriate scaling to ensure conservation of power.

3.2.4 Sample Rate

Sample Rate is the rate at which raw acoustic data is output from the IU for every Spatial Sample Location.

NOTE: The maximum Sample Rate is equal to the Interrogation Rate. Sample Rate should be specified when decimation or some other means of rate reduction is applied.

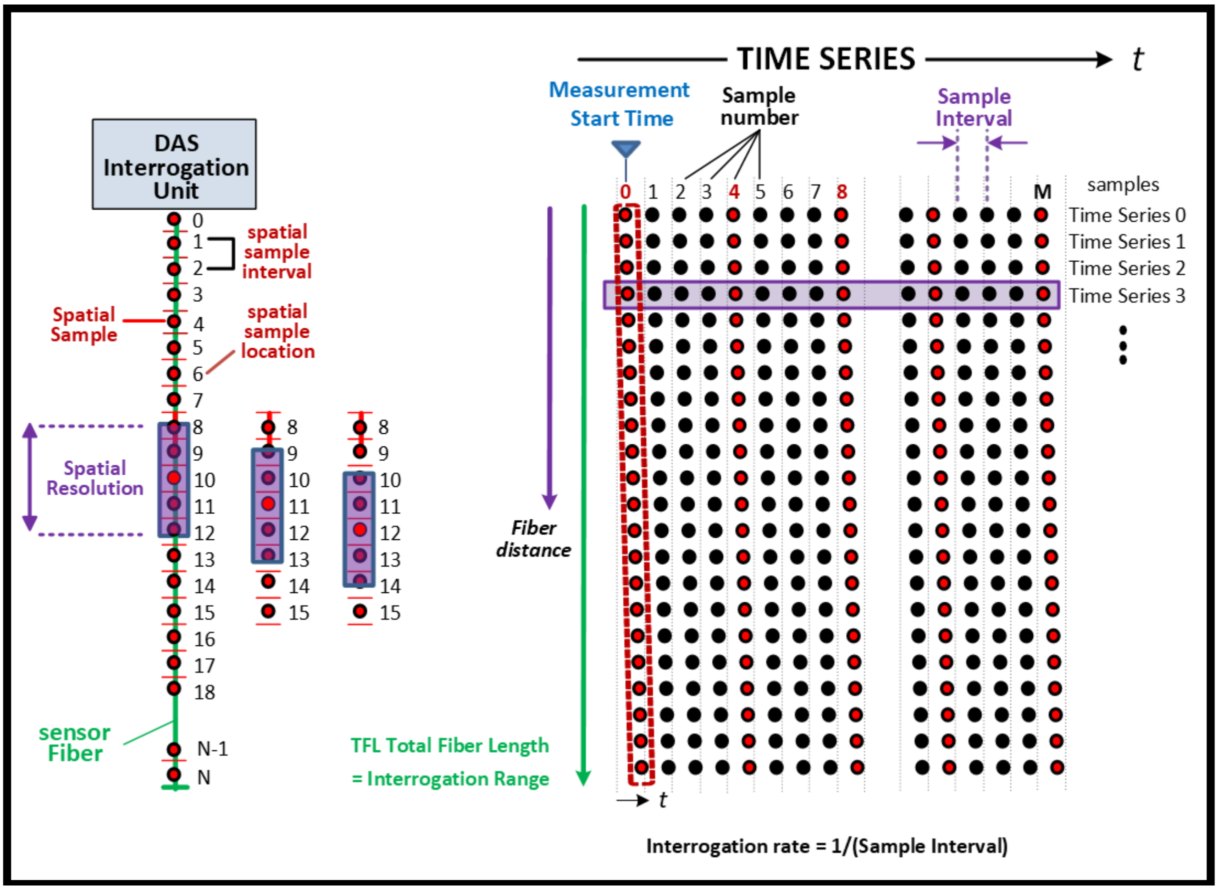

Figure 6: Signal parameters relating to Time Series and their Spatial Location Identification

3.2.5 Sample Number

The identifying sequence number of a Sample in a Time Series. See Figure 6.

3.2.6 Time Series

A measurement set for a particular Spatial Sample Location, whose samples are usually given at the Interrogation Rate, but can also be given at a lower Sample Rate if decimation or some other means of rate reduction is employed.

NOTE: Whatever rate is used, it must be used for all tests in Section 4.

3.2.7 Response Bandwidth

The minimum to maximum frequency range over which vibration of the fiber sensor is detectable (-3 dB decay points on the frequency response curve).

3.2.8 Nyquist Frequency

For the purposes of this document, Nyquist Frequency is the threshold below which the frequency content of acoustic or vibrational activity can unambiguously be determined; i.e. free from frequency alias. It is given by one half of the Interrogation or Sample Rate, whichever is smaller. Example: If the Interrogation rate is 20,000 samples per second (20 kS s^{-1}, as might be the case for a 5 km TFL), the Nyquist frequency will be 10 kHz.

<u>Conformance to common parameter definitions</u>:

SEAFOM parameter definitions described in sections 3.1 and 3.2 above have been developed to maximise commonality with other standards being developed for DAS. Section 6.3 maps between SEAFOM MSP-02 and ENERGISTICS PRODML v2.0 DAS parameter definitions.

3.3 Standardization of DAS performance parameter measurement units

In consideration of standardization of the DAS performance parameters, the measurements made that characterize performance parameters should be represented in (or converted to) units of **<u>strain (ε).</u>**

Normalization Considerations: Certain strain measurements are to be modified to accommodate normalization as needed. For example:

<u>Measurements which are influenced by system noise may be modified by normalizing to a particular noise bandwidth.</u> Metrics here are “strain per square root Hz” or “strain/rt-Hz” for example.

<u>Measurements using stimulus which are influenced by the gauge length</u> are made with the stimulus being normalized by the gauge length. This includes all required tests except for Self-Noise, Loss Budget and Fading tests.

4 Procedures for measurement of performance parameters

The performance parameters considered meaningful for characterizing DAS Interrogator performance are identified below:

1. Dynamic Range
2. Frequency Response
3. Fidelity
4. Self-Noise
5. Long-range self-noise (optional test)
6. Spatial Resolution
7. Crosstalk
8. Loss Budget
9. Sensor Reflection Effects (optional test)
10. Fading (optional test)

This section describes outline procedures for measurement of these performance parameters. Greater detail is provided in Section 7, Appendix: Test procedures.

<u>Baseline considerations for test procedures</u>

The SEAFOM DAS working group endeavoured to develop the test procedures and recommendations for the anticipated test apparatus (Section 5) and data processing (Section 7) to be “within reach” of practicing organizations’ resident skill sets and metrology budgets.

Additionally, attempts have been made to ensure the recommended procedures are not overly complex in scope whilst not compromising the efficacy of the reportable results.

The key objectives were:

A. **DAS SME not required:** One should not need to be a DAS subject matter expert to run the tests and prepare the test results. General engineering and data processing skills should be sufficient.

B. **Single test bed for all procedures:** All Procedures have been developed such that a single test bed is required. This is defined as the Simulated Fiber Sensor (SFS) and is detailed in Section 5.

4.1 Long-range and offset performance testing

This document was originally intended primarily to address the needs of DAS deployments to oil and gas well sensing applications. These scenarios typically involve the IU being connected either directly or via a relatively short interconnecting fiber to a sensing fiber of around 5 km in length, strain activity being recorded along the entire connected length. Fiber lengths in the Simulated Fiber Sensor configuration given at Section 5.1 and the set of performance tests prescribed in this section reflect this initial Use Case.

However, with increasingly diverse utilization of DAS there are other fiber configurations that may need to be simulated due to the addition of longer sensor fibers, longer interconnects and other components that have the potential to significantly affect performance.

Prior to describing the performance tests, long-range sensing and long interconnect fiber configurations are discussed to ensure test results are representative of the use cases they seek to represent. After these test configuration modifications are applied, the same test procedures described in sections 4.2 onwards can meaningfully be applied.

4.1.1 Long-range fiber sensing

Long-range sensing refers to interrogation along the entire fiber length, but for much longer fibers. The transition from 'standard' to 'long-range' is not clear-cut, but this configuration is relevant in cases where there is significant variation in performance along the fiber. This occurs due to lower backscatter intensity returning to the interrogator from longer distances compared to that from close in. This has implications for photon shot noise and photoreceiver saturation, for example.

The standard SFS is designed to be a static component which is not reconfigured between measurements. As detailed in Section 5, the standard layout allows the operator to choose a length appropriate for their specific requirements – i.e. an operator specializing in longer fiber applications can build the SFS with a longer length – however, this may be too inflexible if different lengths are to be tested.

To accommodate some flexibility in SFS length, an adjustable-length SFS is presented in Section 5.2. This allows additional fiber lengths to be added in two locations such that the existing tests can be carried out as normal but localized to the start, middle and end of a simulated long fiber with length configured on a per-application basis. To determine self-noise performance as a continuous spatial distribution on long fibers, an additional test, 4.6, is added. As with other standard tests, Test 4.6 is compatible with both the SFS and the adjustable-length SFS.

4.1.2 Offset fiber sensing

In some deployment scenarios, interrogation may be performed along a standard-length fiber section (e.g. 5 km), but with the region of interest starting after some considerable span of interconnecting fiber. This interconnect, also known as offset fiber, step-out fiber, or lead-in fiber, is often not interrogated (the acoustic/vibrational activity in this fiber span being of no operational interest), but it could affect performance due to distributed losses, point losses, and the change to the interrogation rate (and Nyquist bandwidth limit) required to satisfy the range ambiguity constraint. The offset may be many kilometers in length, but even short fiber lengths placed between the interrogator and the sensing fiber may impart a significant insertion loss.

Offset fibers may consist of a range of elements including continuous fiber lengths, point losses, as well as passive or active components used to compensate for losses. Such a range of possibilities means that DAS performance in the region beyond the offset can vary greatly depending on the exact offset configuration.

To accommodate offset deployments, sections 5.3 and 5.4 give details of a modified fiber layout for carrying out offset fiber tests. This includes an avenue for using any custom offset emulator, as well as a standardized procedure for constructing a long-offset fiber emulator. It allows all tests (including the optional long-range self-noise test) to be carried out on the modified setup.

4.2 Dynamic Range Test

Finds the maximum amplitude of sinusoidal strain stimulation to the SFS (Section 5) for each of a set of fixed frequencies below which the resulting DAS signal is not corrupted compared to the input stimulus. Stimulus is applied at three different locations TP1, TP2, and TP3 along the sensor as shown in Figure 7.

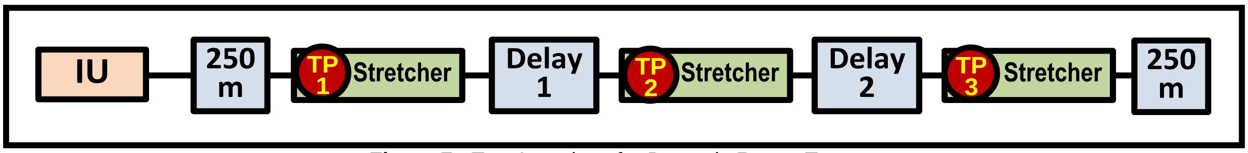

Figure 7: Test Locations for Dynamic Range Test

4.2.1 Stimulus (Dynamic Range Test)

Signal Type:	Sinusoidal
Frequencies:	1%, 5%, 20% and 80% Nyquist
Signal Level (peak):	(0.17 $\mu\varepsilon$ to 14 $\mu\varepsilon$) / (gauge length) Thus, if gauge length is 10 m, then signal level range is 0.017 $\mu\varepsilon$ to 1.4 $\mu\varepsilon$.

The upper strain levels for each test are guide values only. Stimulus signal amplitude should start from zero and be increased slowly and linearly beyond the maximum limit of uncorrupted response. See Section 7.1 for details.

NOTE: This test is defined at frequencies regarded as achievable using readily available test apparatus in the SFS; e.g. commercially available fiber stretchers. It does not prevent vendors/suppliers from testing at frequencies outside the recommended range using, for example:

1. *Fiber stretchers to achieve higher frequency stimuli.*
2. *Mechanical or other substantial means to achieve typically larger amplitude, lower frequency stimuli.*

Stimulation should be applied at each test position location in turn (i.e. not simultaneously).

4.2.2 Data to be collected at each test location (Dynamic Range Test)

Samples per location:	As necessary to cover stimulated regions.
Measurement duration each location:	As needed to cover stimulus amplitude range at each frequency of interest.

Refer to Section 6.2 to ensure good quality data is collected.

4.2.3 How data should be processed (Dynamic Range Test)

Signal: Examination of time domain response to determine the maximum amplitude of stimulus at which linear response breaks down for each stimulus frequency.

Limit: Consider this limit to be when the DAS response signal becomes distorted or experiences its first discontinuity, no longer faithfully resembling the input stimulus. Test can be rerun 5 times to obtain the “best” result. This limit is determined to be the dynamic range.

Details: See Section 7.1, Measurement of dynamic range

4.2.4 Data Reporting (Dynamic Range Test)

Report the maximum peak strain attained immediately prior to signal corruption, multiplied by the gauge length. This is the strain-gauge length limit. This is for all four recommended frequencies at each of the 3 positions (12 values in total). A tabular format is recommended for reporting purposes.

4.3 Frequency Response Test

Stimulate the SFS (Section 5) at constant stimulus amplitude at a set of discrete frequencies spanning the IU functional frequency range. The magnitude of the frequency response is measured at the three locations TP1, TP2, and TP3 as shown in Figure 8.

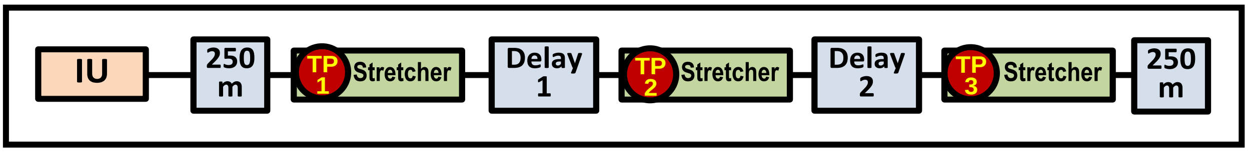

Figure 8: Test Locations for Frequency Response Test

4.3.1 Stimulus (Frequency Response Test)

Signal Type: Stepped frequency sinusoidal sweep (40 frequency steps). See Section 7.2.
Frequencies: 2% to 80% Nyquist, 40 steps, 2.5 s each. 100 s sweep.
Signal Level: 0.08 $\mu\varepsilon$ (peak) / (gauge length) or, if needed, at lower levels to ensure monotonic IU response over the frequency range. This is determined by the test manager.

The stimulus may be applied to all three locations simultaneously or independently. This will be the test operator's choice.

4.3.2 Data to be collected at each test point location (Frequency Response Test)

NOTE: Data collected for processing should meet the criteria of Good Quality Data (Section 6.2). Repeat test as necessary to ensure this condition is met.

Time Duration of Sweep: 100 s (2.5 s at each of 40 discrete stimulus frequencies).
Samples Recorded: Sufficient to cover the full 100 s sweep.

4.3.3 How data should be processed (Frequency Response Test)

Time records are first converted to frequency-domain ASD via FFT with no window function. Then the data are further processed to represent the interrogator response (transfer function) and used to determine a frequency response plot. See Section 7.2.

4.3.4 Data reporting (Frequency Response Test)

Plot 1: Interrogator Response to Stimulus. Three plots corresponding to responses from locations TP1, TP2 and TP3. Details described in Section 7.2.4. Units are dB re. strain level vs frequency.

Plot 2: Corrected and Normalized Frequency Response. Three plots corresponding to responses from locations TP1, TP2 and TP3. Details described in Section 7.2.4. Units are dB (response) vs frequency.

NOTE: This test does not accommodate very low frequencies (below 2% Nyquist). For those practitioners wishing to measure lower frequencies, it is recommended that a similar test be performed over the desired frequency range and additionally to report that information. Also note, lower frequency tests can be performed at a higher stimulus amplitude, e.g. if frequency range is restricted to 10% of the stimulus frequency range of Section 4.3.1, stimulus amplitude can be increased by 10x.

4.4 Fidelity Test

Stimulate the SFS (Section 5) with a sinusoidal tone of varying amplitude. Recommended measurements are to be taken at the three locations TP1, TP2, and TP3 as shown in Figure 9.

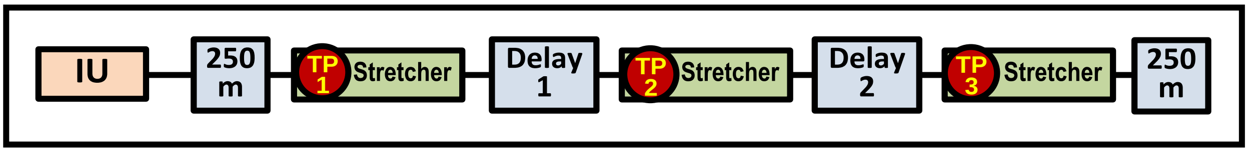

Figure 9: Test Locations for Fidelity Test

4.4.1 Stimulus (Fidelity Test)

Signal Type:	Sinusoidal
Frequency:	10% Nyquist. If frequency coincides with “line interference” it is acceptable to move it by +/-2% Nyquist.
Signal Levels (peak):	(0.08 $\mu\varepsilon$, 0.25 $\mu\varepsilon$ and 0.8 $\mu\varepsilon$) / (gauge length) Example: If gauge length is 5 m, then levels are 0.016 $\mu\varepsilon$, 0.05 $\mu\varepsilon$ and 0.16 $\mu\varepsilon$.

The stimulus may be applied to all three locations simultaneously, or independently. This will be the test operator’s choice.

4.4.2 Data to be collected at each test location (Fidelity Test)

1. Collect time series data at each of the stimulus locations.
2. Samples to record at each selected SSL: one minute duration.

4.4.3 How data should be processed (Fidelity Test)

1. Parse the one-minute time series data records to smaller length Time Series of length 16,384 samples.
2. Discard any Time Series that do not meet the criteria of “Good Quality Data” (Section 6.2.1). The objective is to yield at least 10 sets of good quality data at each test point location.
3. Multiply each remaining Time Series by the Flat Top apodization window (Section 8.1) and convert to the single-sided magnitude spectrum by FFT.
4. Calculate the Total Harmonic Distortion (THD) in percent using harmonics 2-5 in equation 1 below and averaging results from 10 spectra. Vx = signal magnitude (not power) where x is the harmonic. (Subscript “FT” denotes “Fidelity Test”.)

$$THD_{FT} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2}}{V_1} \qquad \text{(EQ 1)}$$

4.4.4 Data reporting (Fidelity Test)

Report Total Harmonic Distortion in percent at each of the three levels at each of the three locations (nine values to report in total). A tabular report format is recommended.

4.5 Self-Noise Test

The purpose of this test is to evaluate the intrinsic or self-noise of the DAS Interrogator. The recommended measurement is the Amplitude Spectral Density (ASD) of the noise response of the IU in the absence of external sources of noise. The spatial histogram of ASD can also be evaluated as an optional processing step to evaluate Fading (see Section 4.11). The SFS (Section 5) should be isolated from environmental vibration and temperature fluctuation. Tests are to be taken at three different locations along the sensor as shown in Figure 10 and labelled as sec 1, 2, 3 within the two delay coils.

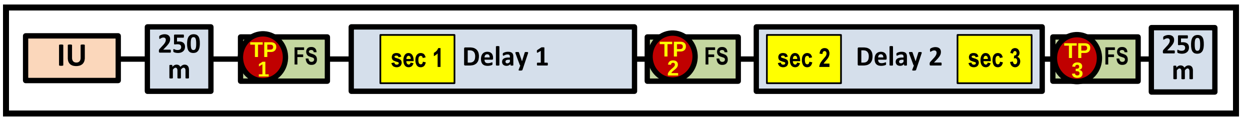

Figure 10: Test Locations for Self-Noise (FS denotes fiber stretcher)

4.5.1 Stimulus (Self Noise Test)

None. The SFS should be isolated from vibration and temperature fluctuation.

4.5.2 Data to be collected at each test location (Self-Noise Test)

Collect data as required per Section 7.4. All data may be collected simultaneously or independently at the section locations. This is the test operator's choice.

4.5.3 How data should be processed (Self-Noise Test)

Analyse data from three different sections:

Sec 1: 300 consecutive SSLs in delay 1 (starting 250 SSLs in)

Sec 2: 300 consecutive SSLs in delay 2 (starting 100 SSLs in)

Sec 3: 300 consecutive SSLs in delay 2 (ending 100 SSLs before the end of delay 2)

Analysis to be performed as prescribed at Section 7.4. In short:

1. FFT each of the sections' 300 time series resulting in "single sided" magnitude spectra, units of self-noise magnitude vs frequency.
2. Normalize each of the FFT records to a 1 Hz bandwidth (i.e. ASD) and convert to strain per rt-Hz.
3. Average all of the 300 noise traces in each of the three sections such that the result is one ASD plot for each of the three sections. (Averaging should be performed by taking the square root of the mean of the squares.)
4. Convert the averaged strain ASD spectra to dB units (20*Log_{10}(strain ASD))

4.5.4 Data reporting (Self-Noise Test)

Report one strain ASD spectrum per test section:

- Noise density in dB(strain/rt-Hz).
- Frequency in log scale, covering full bandwidth of test (1 Hz – Nyquist).
- The gauge length setting of the interrogator will be reported on the test result.

Details: See Section 7.4, Measurement of DAS self-noise

4.6 Long-Range Self-Noise Test (OPTIONAL)

This test extends the self-noise test of the preceding section (which evaluates noise at isolated regions near the front, middle and end of the SFS) by examining the spatial distribution of self-noise on a more continuous basis (Figure 11). It is appropriate to include this test when evaluating the performance of an IU for use on a long-range fiber deployment; i.e. where performance is expected to vary over the range of interest owing to a non-negligible increase in two-way optical attenuation. Measurements covering almost the entire length of the SFS are made (spanning sections sec 1, 2 in the long delays in Figure 11) yielding ASD at periodic intervals. It is an optional test which allows the operator to choose the frequencies of interest for which the ASD will be reported.

NOTE: Sections 5.2 to 5.4 recommend modifications to the standard test configuration at Section 5.1 to accommodate long-range and offset deployments. This includes an avenue for using any custom offset emulator, as well as a standardized procedure for constructing a long-offset fiber emulator. It allows all tests (including the optional long-range test) to be carried out on the modified setup.

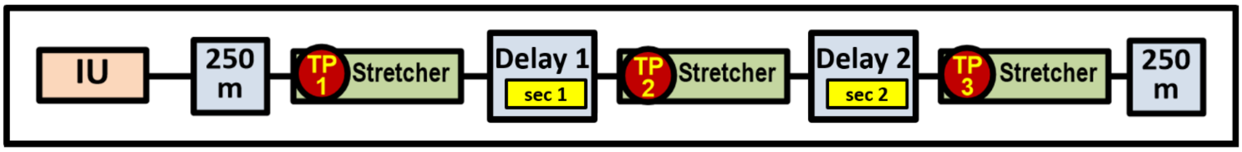

Figure 11: Test Locations for Long-Range Self-Noise Test – self-noise is measured within delays 1 and 2 spanning almost the entire test fiber length.

4.6.1 Stimulus (Long-Range Self-Noise Test)

None. The SFS should be isolated from vibration and temperature fluctuation.

4.6.2 Data to be collected at each test location (Long-Range Self-Noise Test)

Collect data from the entire SFS length for 30 s. This may be collected as part of the standard Self Noise Test (Section 4.5).

4.6.3 How data should be processed (Long-Range Self-Noise Test)

Analyze data from two different sections –

- Section 1: Starting 250 SSLs after the beginning of Delay 1 and ending 100 SSLs before the start of TP2 (length includes the first extra fiber length if the variable-length SFS is used).
- Section 2: Starting 250 SSLs after the beginning of Delay 2 and ending 100 SSLs before the start of TP3 (length includes the second extra fiber length if the variable-length SFS is used).

Analysis to be performed:

1. ASD is found for each SSL along both measurement sections, using the approach detailed in Section 7.4. The result is two 2-dimensional arrays (frequency, distance).
2. The operator may choose the frequencies of interest as well as the spatial sampling of the result. For example, the 10 Hz ASD may be reported every 5 km along the length. To find each point value of ASD, the following averaging should be carried out:
3. For a spatial reporting interval X, averaging of ASD values may be carried out up to ±X/2 from the reported interval. E.g., if reporting every 5 km, then the value at 15 km may be an average over 12.5 to 17.5 km.
4. For a frequency F, averaging of ASD values may be carried out up to ±5% of the value. E.g., for 10 Hz, the average from 9.5 Hz to 10.5 Hz may be used.
5. Averaging of ASD values must be carried out by taking the square root of the mean of their squares.
6. The result is two 1-dimensional arrays of averaged ASD versus distance, one array per section.
7. Convert the ASD to PSD in dB units (20*log10[ASD])

4.6.4 Data reporting (Long-Range Self-Noise Test)

Plot the two arrays of PSD versus distance as lines on a single graph, with distance on the X axis and PSD on the Y axis. The lines will be separated by the length of TP2 (plus the surrounding margins). If this length is negligible, then the plotted arrays may be connected as one. If sections of the fiber are situated outside the acoustically and vibrationally isolated chamber, then the plot may show indication of such sections.

4.7 Spatial Resolution Test

Stimulate the SFS with a continuous sinusoidal wave at moderate amplitude. Only one frequency is required. Recommended measurements are to be taken at the three locations TP1, TP2, and TP3 as shown in Figure 12.

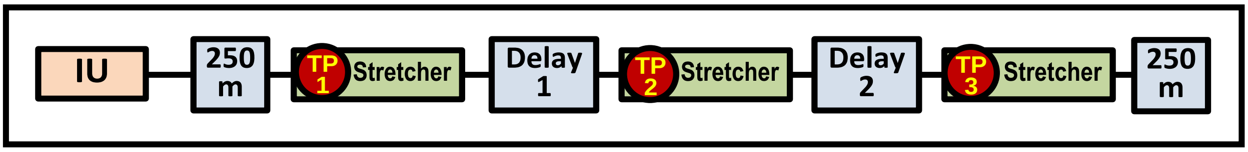

Figure 12: Test Locations for Spatial Resolution Test

4.7.1 Stimulus (Spatial Resolution Test)

Signal Type:	Sinusoidal
Frequency:	2% Nyquist. Note: if frequency coincides with line interference it is acceptable to move by +/-20%
Signal Level (peak):	0.5 $\mu\varepsilon$ / (gauge length)

4.7.2 Data to be collected at each test location (Spatial Resolution Test)

Collect time series data at consecutive Spatial Sample Locations (SSL) that cover the length of fiber on the fiber stretcher plus two-gauge lengths on each side, as shown in Figure 13. The stimulus may be applied to all three locations simultaneously, or independently. This will be the test operator's choice.

Samples to record at each selected SSL: one minute duration.

NOTE: Data acquisition for both Spatial Resolution and Crosstalk tests (Section 4.8) can be taken at the same time by increasing the range out to +/-50 gauge lengths from each stretcher.

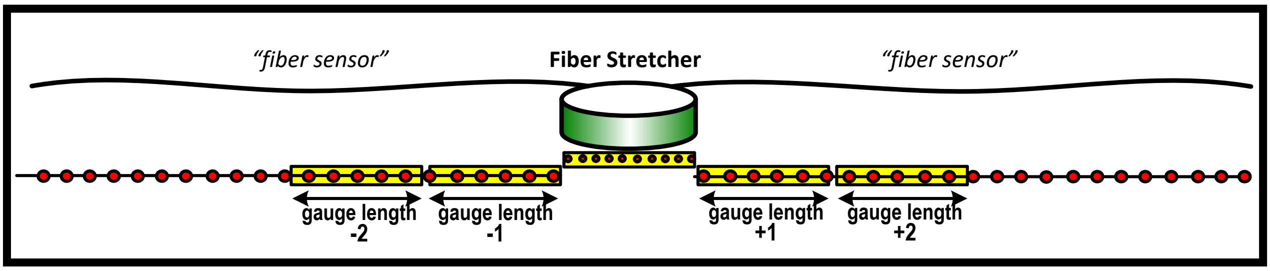

Figure 13: Locations to collect data for spatial resolution test (spanning at least 2 gauge lengths on either side of each fiber stretcher).

4.7.3 How data should be processed (Spatial Resolution Test)

The objective is to make accurate estimates of the amplitude of the measured signal at the stimulus frequency at each Spatial Sample Location both on and adjacent to each stretcher.

Amplitude estimates are made using Flat Top windowed FFTs of the time series (Section 8.1), using the magnitude of the spectral component at the stimulus frequency.

Use only Good Quality Data as defined in Section 6.2. It is recommended that each FFT block be shorter than the one-minute record to increase the probability that data blocks at each SSL have high signal to noise ratio (i.e. fade free).

Details of this process are outlined in Section 7.5, Measurement of spatial resolution.

4.7.4 Data reporting (Spatial Resolution Test)

Calculated Spatial Resolution values (in meters) for each of the three different test locations.

4.8 Crosstalk Test

This test measures the residual signals that occur in locations other than that of the applied stimulus to make a determination of 'crosstalk'. Stimulation of the SFS (Section 5) is a continuous sinusoidal wave at moderate amplitude. Only one stimulus frequency is required. It is applied at each of the three fiber stretcher locations as shown in Figure 14.

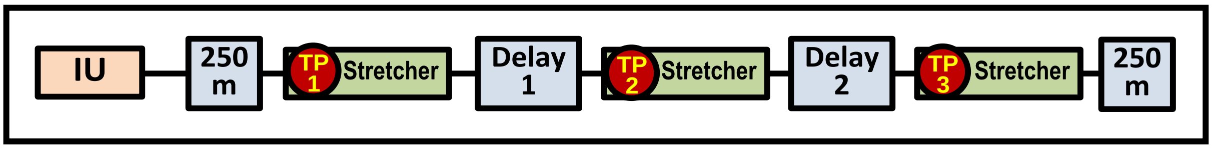

Figure 14: Test Locations for Crosstalk Test

4.8.1 Stimulus (Crosstalk Test)

Signal Type:	Sinusoidal.
Frequency:	2% Nyquist Note: if frequency coincides with “line interference” it is acceptable to move by +/- 20%
Signal Level (peak):	0.5 $\mu\varepsilon$ / (gauge length)

The stimulus may be applied to all three locations simultaneously, or independently. This will be the test operator’s choice.

4.8.2 Data to be collected (Crosstalk Test)

Collect time series data at the location of the fiber stretcher and Spatial Sample Locations between +3 to +50 gauge lengths and between -3 to -50 gauge lengths OR a minimum length of +/-250 meters, as in Figure 15.

Time series data to be collected for one minute.

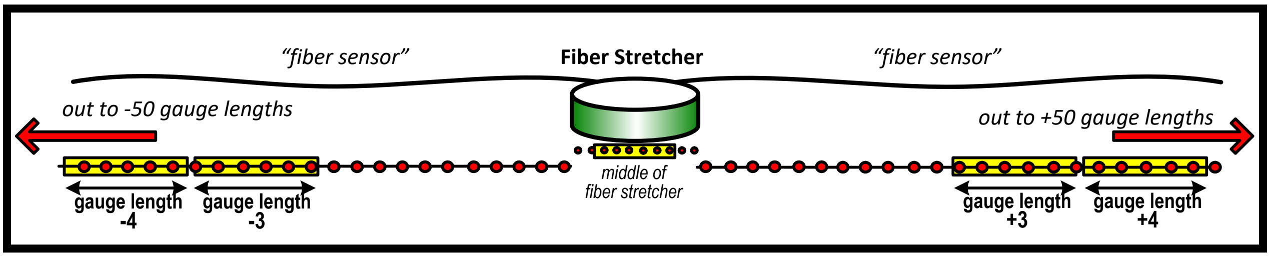

Figure 15: Locations to collect data for Crosstalk Test. The first two gauge lengths on either side of the fiber stretcher are not included in the analysis.

4.8.3 How data should be processed (Crosstalk Test)

Calculate reference amplitude and crosstalk data as instructed in Section 7.6. Crosstalk values represent data elements in the range of +3 to +50 and -3 to -50 gauge lengths. Determine crosstalk by calculating the ratio of crosstalk power to reference power (in dB).

Details of this process are outlined in Section 7.6, Measurement of crosstalk.

4.8.4 Data reporting (Crosstalk Test)

Single plot dB level of crosstalk versus SSL at each test point TP1, TP2, TP3. See example in Section 7.6 Measurement of Crosstalk.

4.9 Loss Budget Test

The Loss Budget Test evaluates the impact on IU performance for non-ideal sensor installation conditions. The dominant consideration is that optical loss is caused at the beginning of the sensor fiber, in the vicinity of the well head exit or other proximal interfaces between the IU and the deployed sensor.

4.9.1 Stimulus (Loss Budget Test)

The test protocol calls for placing an optical attenuator (as stimulus) between the IU and the input to the SFS as depicted in Figure 16. Here we show an input optical attenuator and three designated test points, TP1, TP2, and TP3, which represent the beginning, middle and end of the SFS.

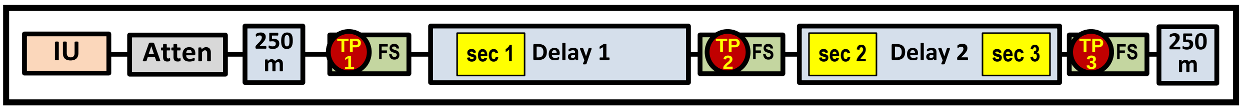

Figure 16: Test Locations for Loss Budget Test

Recommended attenuator stimulus: (one way attenuation values)

Test 0 0 dB *reference data from self-noise test (Section 4.5)*
Test 1: -2 dB
Test 2: -4 dB
Test 3: -6 dB

4.9.2 Data to be collected (Loss Budget Test)

A self-noise test is required at the three test points identified for each of the attenuation levels.

4.9.3 How data should be processed (Loss Budget Test)

Perform self-noise test as defined in Section 4.5.

4.9.4 Data reporting (Loss Budget Test)

Determine the spot frequency noise level at 50% Nyquist for test 0-3.

This would be a single value in dB strain per rt-Hz, normalized to 1 Hz noise band, and citing the gauge length used.

These values should be reported in two tables. The first table presents the noise levels for the four tests at each of the three locations. The second table presents the difference (in dB) of tests 1-3 relative to reference test 0 at each of the three locations.

4.10 Sensor Reflection Effects Test (OPTIONAL)

Optical point reflections in deployed sensors can cause two unwanted effects:

1. *A dead zone (distance) following the reflection location, where no useful measurement can be made.*
2. *A performance degradation along part of or the whole fiber length which causes signal degradation.*

This test recommends that three separate sensor reflection scenarios be considered.

NOTE: This is an optional test, partial testing is acceptable.

The test involves placing partial reflectors at the front, at the end, or at both the front and the end of the SFS. The three test arrangements are shown in Figure 17. The partial reflectors are mated to the start and/or end connectors of the SFS. The SFS is shown depicting the three sections where Self-Noise data will be collected (sec 1, 2, 3), and the three test positions where Fidelity testing will be performed (TP 1, 2, 3).

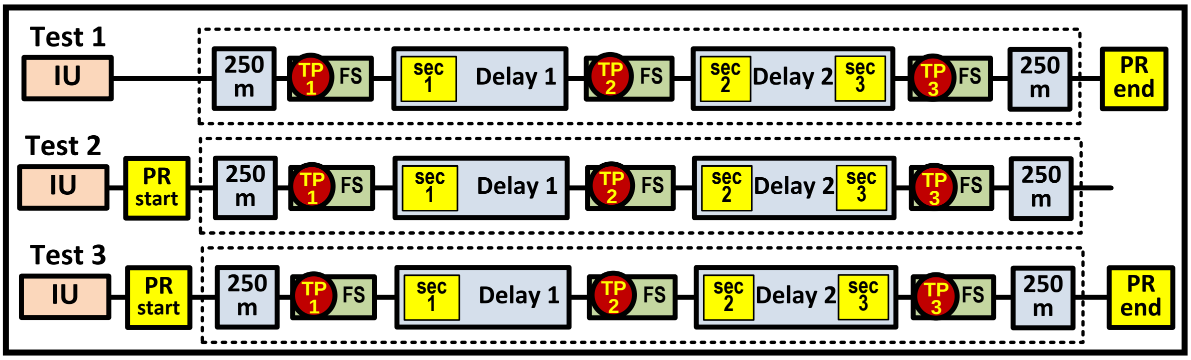

Figure 17: Three test configurations for reflection and dead zone evaluations. (PR: Partial reflector.)

4.10.1 Stimulus (Sensor Reflection Effects Test)

As per the two larger-amplitude stimuli used in the Fidelity Test (Section 4.4):

Signal Type:	Sinusoidal
Frequencies:	10% Nyquist
Signal Level	(0.25 $\mu\varepsilon$ and 0.8 $\mu\varepsilon$) / (gauge length). Example: If gauge length is 5 m, then levels are 0.05 $\mu\varepsilon$ and 0.16 $\mu\varepsilon$

4.10.2 Partial reflectors (Sensor Reflection Effects Test)

Partial reflectors must be in-line fiber elements. They must provide known partial reflection strengths at the wavelength(s) of operation of the IU. These can be custom Fiber Bragg Gratings FBG configured for the desired operating wavelength and reflectivity, or other fiber assemblies. Figure 18 shows examples of easily fabricated partial reflectors with predictable reflection coefficients.

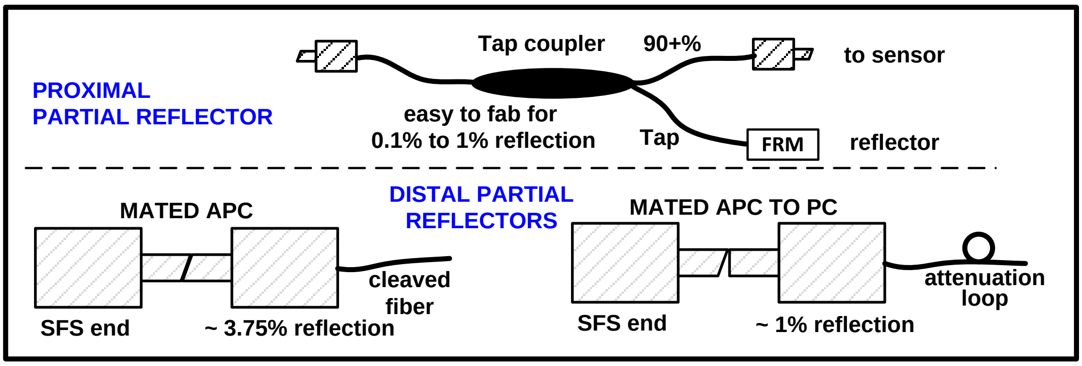

Figure 18: Recommended methods for creating partial reflections for the SFS.

Proximal reflections can be made using a “tap” coupler where most of the light passes to the sensor, and a small portion is directed to a “reflector”. Figure 18 shows a Faraday Rotator Mirror (FRM) as these types of mirrors come with pigtail fiber and are easy to implement, but the FRM type is not mandatory. Any other pigtailed fiber mirror should be acceptable.

Distal Reflections can be made by mating connectors as shown in Figure 18 to create the desired reflection.

The lower left diagram in Figure 18 “MATED APC” shows two angle connectors mated to a pigtail fiber which is cleaved at 90 degrees. This will provide for an approximate 4% reflection which would be the equivalent of the worst-case reflection a DAS sensor might reasonably be expected to encounter.

The lower right diagram in Figure 18 **“**MATED APC to PC” provides for approximately 1% reflection at 1550 nm (light which reflects from the PC connector surface). The pigtail fiber must include a series of tight loops (say 10 loops at 10 mm diameter) to attenuate the throughput light to a negligible value.

Recommended reflections for testing
This standard does not mandate the start and distal reflection values but does identify logical reflectivity ranges.

Start Reflection: Consider 0.5% to 1%
End Reflection: Up to 4%. This is the maximum light that can be reflected from a normal glass-air termination at the end of a fiber.

4.10.3 Data to be collected for all test configurations (Sensor Reflection Effects Test)

A. **Using Stimulus for Fidelity Test**: Per instructions in Section 4.4 but testing only at the two stimulus levels of (0.25 $\mu\varepsilon$ and 0.8 $\mu\varepsilon$) / (gauge length).
B. **Self-Noise Test:** Perform self-noise test as defined in Section 4.5

4.10.4 How data should be processed (Sensor Reflection Effects Test)

A. **Fidelity Test:** Same as in Section 4.4 (for the two stimulus levels)
B. **Self-Noise Test:** Perform self-noise test as defined in Section 4.5

4.10.5 Data reporting (Sensor Reflection Effects Test)

Fidelity at Fiber Stretcher: Compare with results from the standard fidelity test from Section 4.4. THD is presented in percentage values. Up to 18 are provided from reflection tests 1, 2 and 3 to compare with the 6 values from the standard fidelity test. A tabular report format is recommended.

Self-Noise: Compare self-noise levels in the presence of reflectors with self-noise results obtained under Section 4.5. The recommended report format is to use overlapping plots –two data sets on each plot – arranged to make differences between the two easily visible. The reference data set would be the self-noise measurement under identical conditions except with no reflections. The other data set would represent the noise data from Tests 1, 2, 3 sections 1, 2, 3 described in this section. Thus, if all tests were run, 9 overlapping plots would result.

4.11 Fading Test (OPTIONAL)

Most DAS IUs launch coherent laser light into the Fiber Sensor as described at Section 1.2 (or in a similar manner). At any instant, the myriad scatterers within the launch pulse footprint act as a large collection of secondary sources of backscattered light. Owing to the coherence of the backscattered light and the random spatial distribution of the scatterers from which it originates, optical interference arises in the resultant signal received by the IU from that region in the fiber. Interference may be constructive in some Spatial Sample Locations (leading to relatively bright returns) or destructive (leading to low brightness or 'fade') or at any level in between. Since accurate recovery of optical phase and, hence, acoustically or vibrationally induced strain in a region of fiber relies on sufficient light being backscattered from it, fade gives rise to elevated levels of acoustic noise at the Spatial Sample Locations in which it occurs. Strain "dead zones" are said to exist where fade-induced noise exceeds the threshold required for useful signal recovery.

This test re-uses the data from the Self-Noise Test of Section 4.5 but processes and displays the data differently in order to quantify fade statistics for the IU under test.

4.11.1 Stimulus (Fading Test)

None. The SFS should be isolated from vibration and temperature fluctuation.

4.11.2 Data to be collected (Fading Test)

Collect data as required per the Self-Noise Test Section 7.4.2 step 3 (30 seconds). All data may be collected simultaneously or independently at the section locations. This is the test operator's choice.

4.11.3 How data should be processed (Fading Test)

Analyse data from three different sections (identical to the processing of the Self-Noise Test):

Section 1: 300 consecutive SSLs in delay 1 (starting 250 SSLs in)

Section 2: 300 consecutive SSLs in delay 2 (starting 100 SSLs in)

Section 3: 300 consecutive SSLs in delay 2 (ending 100 SSLs before the end of delay 2)

Analysis to be performed as per Section 7.9 to calculate the variance (the square of the standard deviation) on the strain measured in every individual Spatial Sample Location. The units of the result are dB rel. 1 με; for example, a value of 30 dB rel. 1 με represents a standard deviation of 31.6 με.

Fading is assumed to be frequency independent. The self-noise spectra are therefore integrated over frequency to produce a single RMS noise value for each spatial location. As described in Section 7.9, the default frequency band for integration is from 2% to 80% of Nyquist frequency, similar to the Frequency Response test. In special circumstances, a different frequency range may be selected (such as a fixed range not dependent on sampling frequency), but this should be clearly stated in the test results.

4.11.4 Data reporting (Fading Test)

It is recommended that the resulting statistical distribution of RMS noise values are reported in both histogram and survival function graphical forms. (The survival function is also referred to as the reliability function.) See Figure 19 and Figure 20 for examples. The units of the horizontal axes should be RMS strain expressed in dB rel. 1 με (computed as 20 x $\log_{10}$(RMS strain)).

Figure 19 shows an example of the histogram graph, which should have a linear vertical axis. Note that the example simulated distribution has the median value replaced with “X”, but in practice this should be the observed median RMS value. Similarly, other values in the example plot show numbers relative to X; these should also be replaced with observed values.

This graph clearly demonstrates if the distribution is symmetrical and if there are outliers especially at large RMS strain values. The RMS strain values should be noted in the graph for the following percentiles: 25th, 50th (median), 75th, and 95th. The graph indicates, for example, that 95% of spatial samples have a noise level lower than X+32.9 dB rel. 1 με.

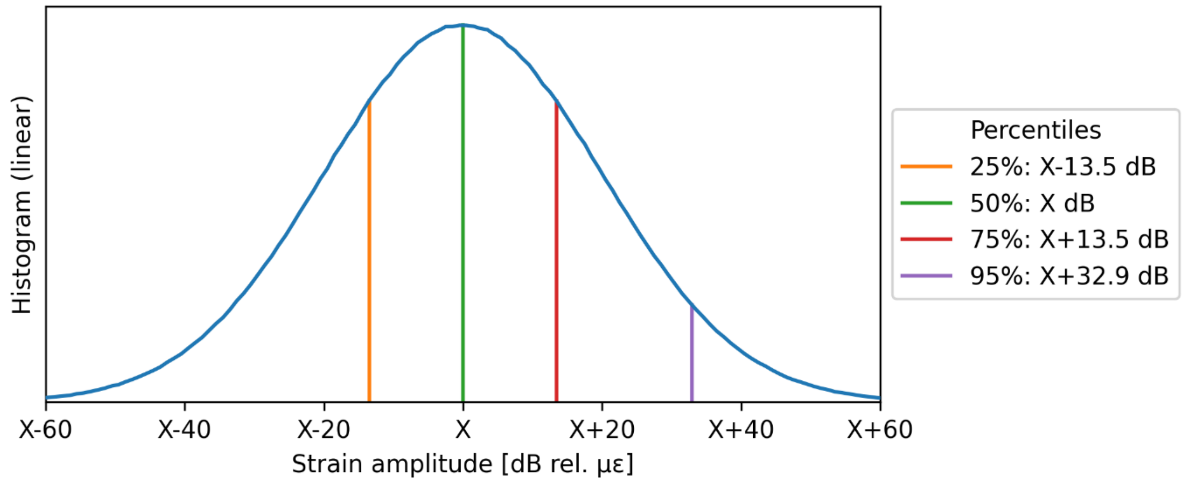

Figure 19: Noise distribution plotted as a histogram. The median value is marked as X in order to generalize the example values.

As shown in Figure 20, the survival function graph has a logarithmic vertical axis since this gives the clearest view of noise outliers that indicate signal fading. The same strain percentiles should be indicated on the graph: 25th, 50th, 75th, and 95th. For example, the graph shows that the worst 10% of fiber locations ($y=10^{-1}$ and below) have a noise level in excess of approximately X+26 dB rel. 1 με.

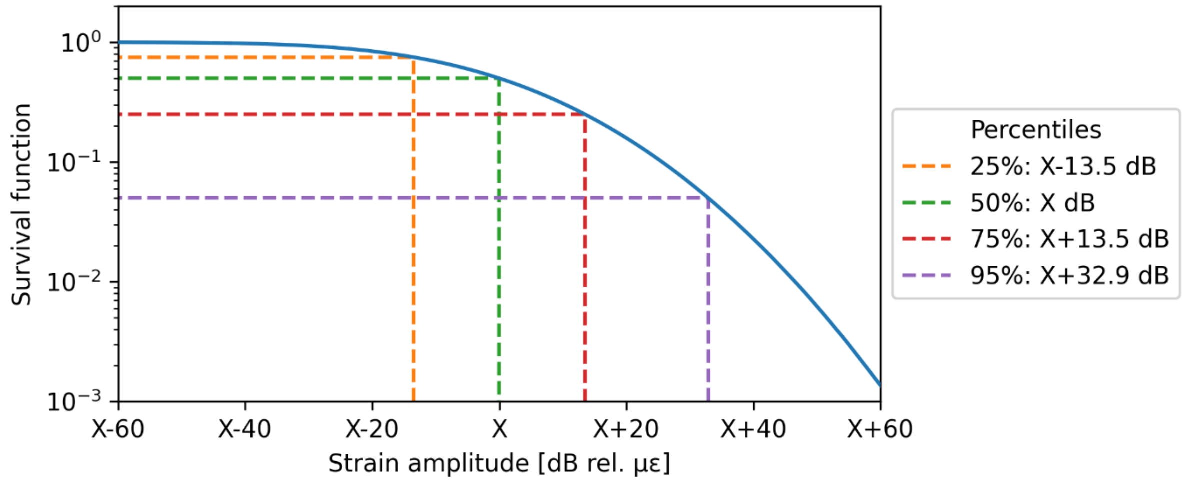

Figure 20: Noise distribution plotted as a survival function. The coloured lines connect a cumulative fraction of the spatial sample locations along the vertical axis to a noise value at the horizontal axis. The purple line, for example, shows that for 95% of the spatial sample locations the noise is lower than X+32.9 dB re 1 με.

5 Recommended test apparatus

5.1 Simulated fiber sensor to be used for characterization

Each of the performance parameter tests detailed in this document are to be evaluated using a **Simulated Fiber Sensor** (SFS) of length defined by the IU's stated range, or alternatively a range specific to an application. The length selected becomes the 'Total Fiber Length' or TFL.

The Simulated Fiber Sensor will be arranged as shown in Figure 21. It comprises four delay coils and three fiber stretchers which are spliced together to form a contiguous fiber sensor of mechanical length TFL. In Figure 21 the assembly is shown with pigtail fibers angle terminated with the connector of choice at the start and end of the TFL.

All elements of the SFS are housed in an isolated container that provides immunity from environmental acoustics and vibration.

The three fiber stretchers which are each of length Ls are located between the four delay coils and represent test point locations for many of the performance parameter tests described in this document. These are TP1, TP2, and TP3.

Determinations for the lengths of Delay 1 and Delay 2 are made using the following relationships.

1. Ls is equal to the mechanical length in meters of fiber wound on each stretcher.
2. TFL' is set to be equal to TFL- 500 - 3Ls meters (EQ2)
3. TFL' / 2 is the mechanical length in meters of the Delay 1 and Delay 2 coils (EQ3)

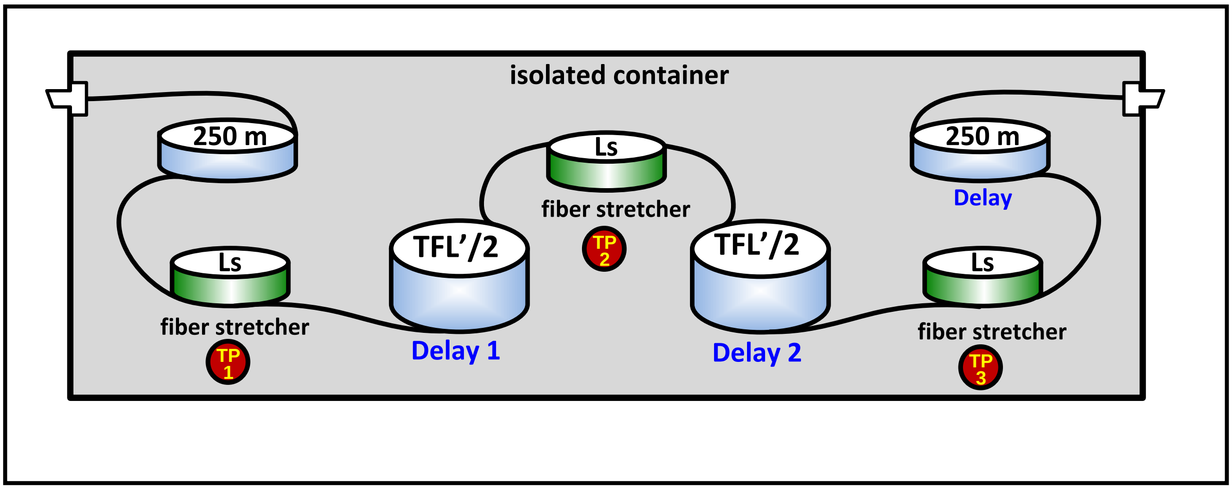

Figure 21: Simulated Fiber Sensor (SFS) incorporating three Fiber Stretcher sources of strain stimulation.

The three test positions in Figure 21 coincide with the locations of the fiber stretchers and are designated as follows:

TP1: "Start"	Located before Delay 1
TP2: "Midpoint"	Located between Delay 1 and Delay 2
TP3: "End"	Located after Delay 2

These three test positions are depicted in Figure 22 and identified as test positions or test points 1-3, specifically designated as TP1, TP2, TP3. IU refers to the DAS Interrogator Unit.

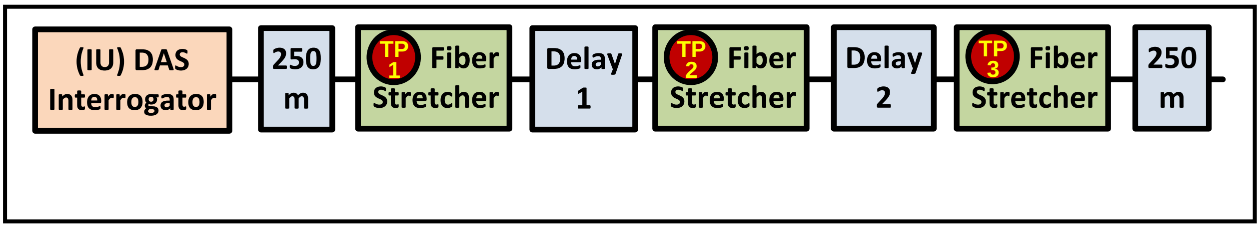

Figure 22: Test Configurations for SFS showing three test positions.

5.1.1 Recommended standard lengths for the Simulated Fiber Sensor

The Total Fiber Length (TFL) of the Simulated Fiber Sensor (SFS) may be any mechanical length applicable for the DAS interrogator being evaluated.

The DAS working group did determine that it may be useful to recommend a standard TFL for the SFS. A standard TFL establishes a common baseline on which to make objective comparisons of different IU offerings.

The DAS working group determined the following:

The standard TFL for the SFS = 5 km

In either event, use equations 2 and 3 above to determine the lengths for Delay 1 and Delay 2.

Sections 5.2, 5.3 and 5.4 describe modifications to this design that accommodate long range and/or offset SFS schemes.

5.2 Adjustable length SFS for long-range performance testing

To allow for performance testing on a range of fiber lengths, an adjustable-length SFS can be constructed, which is a modification to the standard fiber layout. The principle of this layout is presented in Figure 23 (to be compared with Figure 22), which shows two pairs of connectors inserted at two locations of the standard SFS. The first location is between Delay 1 and TP2, and the second is between Delay 2 and TP3. Fifty percent (50%) of the extra fiber length should be added in each location, using either APC connectors or “make and break” splices.

It should be noted that this configuration can be returned to normal by ‘shorting’ the APC connector pairs together. The connections could be spliced to minimize point losses; however, this would require the splices to be cut and re-spliced every time the length is changed (a.k.a. make-and-break). This would consume fiber length over time, so it would be a decision for the test operator.

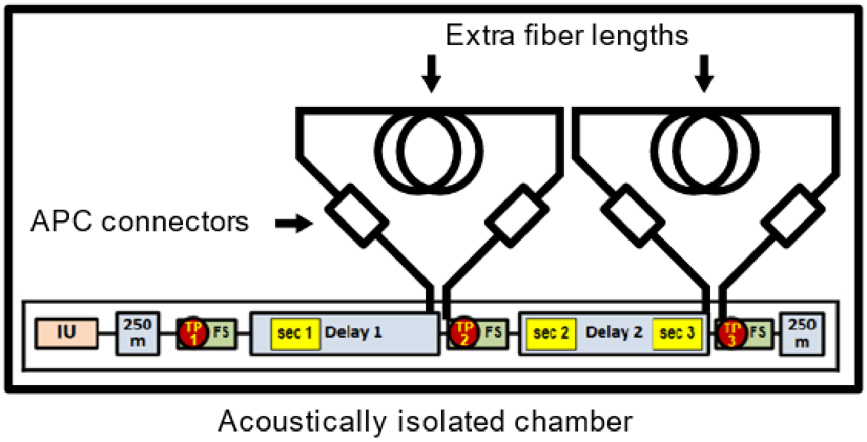

Figure 23: Adjustable length SFS layout

The effect of adding lengths in between the three TPs is to show evidence of acoustic noise and signal fidelity at the start, middle, and end of the extended fiber length when standard tests are carried out. Furthermore, the optional test 4.6 will show the spatial profile of the self-noise along the entire length. Together, this should give a meaningful impression of how acoustic performance varies over a long-range fiber.

It is recommended to house the new lengths inside an acoustically and vibrationally isolated chamber because the Self-Noise, Spatial Resolution and Crosstalk tests record data in the lead ins to TP2 and TP3, coinciding with the extra fiber lengths. If this is not possible due to spatial constraints, then a compromise could be achieved by adding short fiber lengths before TP2 and TP3 inside the chamber, with connectors added before these lengths. Where this is the case, the non-isolated sections should be marked on the final ASD plot of optional test 4.6. The fiber layout is illustrated in Figure 24.

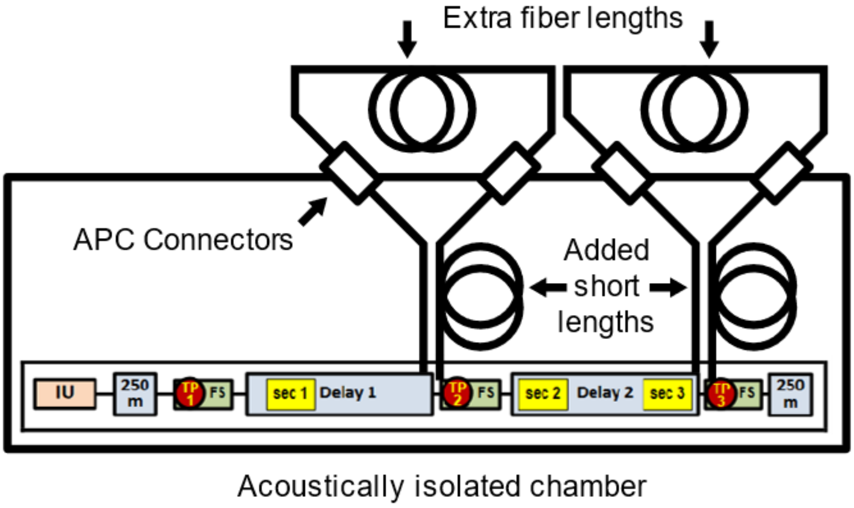

Figure 24: Alternative adjustable length SFS layout, with extra lengths external from acoustically and vibrationally isolated chamber

If the layout shown in Figure 24 is used then, when shorting the APC connectors together, the total length will still include the additional short fibers. Therefore, the Delay sections should be shortened by the same amount to maintain the operator's preferred minimum SFS fiber length.

5.3 Long-offset fiber tests

In applications where tests are to be performed on sensing fiber located after an offset fiber, a modified test procedure may be followed. Test operators can prepare 'emulator' fibers to represent a specific offset fiber and should carry out all tests with the SFS section connected after the offset. Such emulators may include passive or active optical components to overcome performance degradation; these components may be included in the emulator section during tests. As illustrated in Figure 25, in tests that call for attenuators and proximal reflectors (Sections 4.9, 4.10), these should be connected between the offset fiber end and the SFS start.

In presenting the results of such tests, it is the responsibility of the operator to describe and give evidence of the emulator fiber accuracy, such as the use of OTDR traces and details of additional optical components. The real-life conditions of fiber connectors may also be emulated, such as return losses at connectors, as this may affect performance on the sensing fiber. The operator should convey relevant details of their emulator when presenting test results.

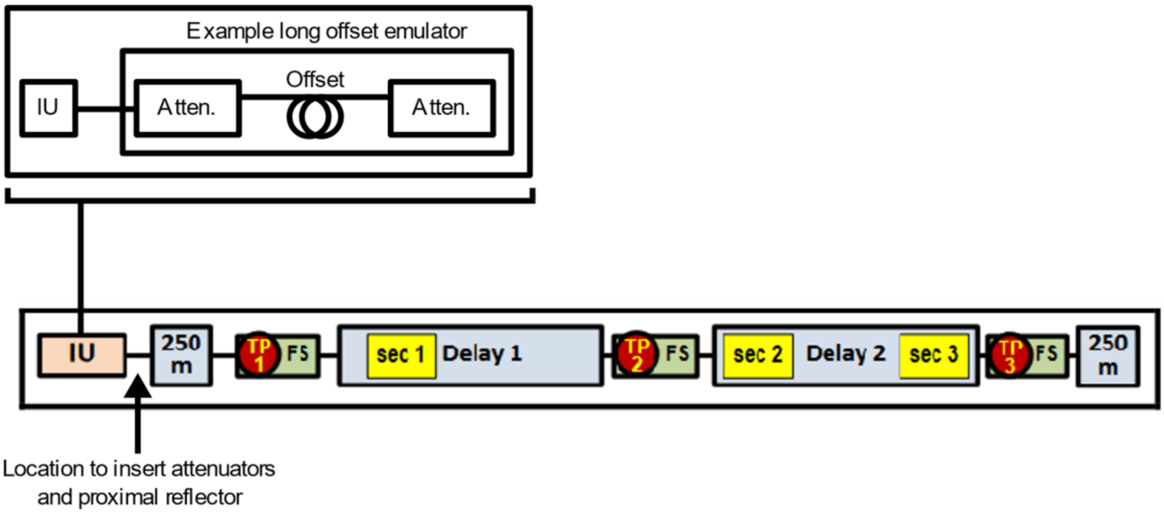

Figure 25: Approach to performing long-offset fiber tests. Figure shows an example offset emulator that may have been mandated for a specific application.

5.4 Standardized long-offset fiber emulator

There may be scenarios where there is a call for tests with an offset fiber of a given length and a given total insertion loss. To avoid inconsistent representations of performance, a standard approach to constructing an offset emulator is illustrated in Figure 26. The emulator should be constructed as follows:

- The required offset length should be represented with a real optical length of single mode fiber – not an equivalent point insertion loss. This is essential, because it may be possible to achieve unrealistic performance if a shorter, yet equally lossy fiber length is used.
- Small point losses associated with APC connectors (< 0.2 dB) are acceptable along the offset fiber, if the emulator is constructed with multiple fiber reels.
- If necessary to achieve a required total insertion loss, additional loss should be added as a point insertion loss (e.g., via an attenuator) at the end of the offset fiber. Additional loss should not be added elsewhere.
- The offset fiber need not be enclosed in an acoustically or vibrationally isolated chamber during tests.

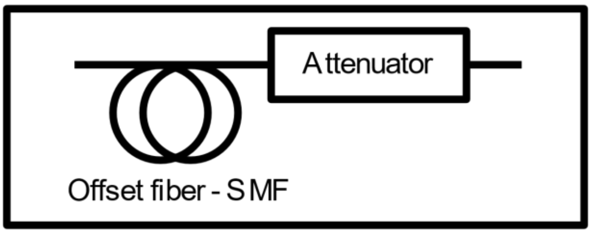

Figure 26: Standardized long-offset emulator construction approach.

5.5 Fiber Stretcher to be used for characterizations

The three, identical fiber stretchers are used for most of the performance parameter tests that require “stimulus”.

They comprise of “sensor fiber” representative of the intended deployment(s) wrapped around a piezoelectric cylinder which is radially poled. The fiber stretcher, in order to be effective for conducting performance parameter testing, should satisfy the following conditions:

Cylinder Diameter **Fiber Type**	>50 mm (for low macro-bend loss). Same as SFS fiber.
Fiber Stretcher Length	At least two gauge lengths. However, if this length does not cover at least 10 Spatial Sample Locations, add length for such coverage. Longer lengths acceptable.
Sensitivity	Uniform over entire wound section of fiber.
Frequency Range	At least 2% to 80% of Nyquist frequency - *see note 1 below.*
Strain Levels (dynamic)	Up to **(**14 $\mu\varepsilon$ peak) / (Gauge Length) - *see note 2 below.*

NOTE 1: *Ideally, the "sensitivity" response (strain / volt) of the fiber stretcher should be constant over the entire frequency range. In practice this is unlikely to be the case and the circumferential resonance of the piezo cylinder will cause some increased sensitivity at higher frequencies. In order to ensure the accuracies of Dynamic Range (4.2) and Frequency Response (4.3) tests, one will need to know the frequency response of the fiber stretcher for amplitude compensation purposes. Ensure the supplier provides this information, or that the fiber stretcher can be calibrated to obtain it. In the event that additional fiber stretcher drive signal amplification is employed (see NOTE 2), remember to include the amplification factor – and possible frequency dependence thereof – in the strain / volt calibration.*

NOTE 2: *The high strain level indicated is required to satisfy the lowest frequency for the Dynamic Range test. It may be (for this one test) that a voltage amplifier will be required between the signal generator and the fiber stretcher. All other tests in this standard involve much lower dynamic strain levels and should not need amplification.*

Commercial fiber stretchers

Known fiber stretcher manufacturers with commercial offerings at the date of publishing this document are:

- Evanescent Optics, Inc.
- General Photonics
- Optiphase - A Halliburton Service

Alternative: Various organizations fabricate their own fiber stretcher solutions.

5.6 Signal generation / amplification instrumentation

The fiber stretcher requires a signal generator to produce the drive signals. It must be capable of operating over the 'Frequency Range' specified in Section 5.5. Most fiber stretcher designs are capable of being driven directly using COTS signal generators.

In regard to the low frequency (<2% Nyquist) Dynamic Range test identified in Section 4.3, there will likely be a need to amplify the signal generator output to higher voltages to achieve the prescribed **(**14$\mu\varepsilon$ peak) / (gauge length) level.

5.6.1 Recommended signal generators and amplifiers

Signal Generator: Many COTS generators are available. One should ensure that the generator produces low distortion sine waves (THD < -54 dB) and has low spurious outputs (< -60 dB) within the 'Frequency Response' range.

Waveform generation for the frequency response test will require up to 10 M sample memory. Examples of commercial products which satisfy this are as follows:

- Keysight Models 33511B, 33521B with "Add 16 M memory" option.
- B&K Model 4077B, 4080B (16 M memory)
- Rigol DG5071, DG5072 (128 M memory)

Voltage Amplifier (if needed): The amplifier should apply sufficient, linear gain to the signal generator output to attain fiber strain levels commensurate with the low frequency Dynamic Range testing requirements.

It will need to be able to drive a capacitive load (the PZT element) covering the stimulus frequencies called out in Section 5.5. Examples of products that meet the requirements for most SFS designs are as follows:

- TREK, INC. http://www.trekinc.com/
- Piezo Systems Inc. http://www.piezo.com/
- PiezoDrive http://www.piezodrive.com
- Noliac http://www.noliac.com/
- AA Lab Systems http://www.lab-systems.com/

5.7 Optical attenuator

A set of calibrated, fixed-value optical attenuators or a single variable optical attenuator that can be self-calibrated will be required for optical loss budget performance parameter testing.

5.7.1 Attenuator requirements

Recommended:

Calibrated for operating wavelength....... Yes or self-calibrate with power meter.
Attenuation Range................................. -2 dB to -6 dB (one way).
Step size (resolution).............................. As needed, assume accurate to 0.1 dB.
AM modulation...................................... < -50 dBc (relevant only for electronically controlled
.... attenuators).

5.7.2 Commercial suppliers

Many manufacturers and suppliers for fiber optic tuneable attenuators can be found when conducting a web search for "variable fiber optic attenuator".

5.8 Isolation chambers / vibration isolators

The Simulated Fiber Sensor (SFS) uses fiber coils which are sensitive to environmental disturbances, namely room acoustics and room / benchtop vibrations.

One must take measures to ensure such environmental disturbances do not degrade test data for the measurement of performance parameters.

Such decisions / implementations will be left to the test operator.

Two isolation approaches are outlined below spanning the budget/performance range. **Neither is mandatory**. It does make sense, however, to provide some degree of isolation when conducting noise tests (Sections 4.5, 4.6, 4.9, 4.11) so as to not to over-estimate IU self-noise due to environmental noise.

5.8.1 Simple isolation approach

A. Place the elements of the SFS in a thick-walled metal container. This will serve to provide mass and to block airborne room acoustics.

B. Support the container on a partially inflated inner tube to "float" the SFS container off the table surface. The lower the resonant frequency, the better. This will serve to reduce table-borne vibrations.

5.8.2 High performance isolation approach

A. Use a vibration isolation table. Products from Minus K Technology *www.minusk.com* and others.

B. Place the vibration isolation table (with SFS) inside an acoustic isolation chamber. Reference supplier Herzan LLC (southern California) www.herzan.com and others.

Example of a high-performance vibration and acoustic isolation apparatus: Employ an acoustic enclosure, "Herzan" Silencer model with performance upgrade DE, to provide a thermally stable and acoustically shielded experimental environment. Within this enclosure the experiment is further decoupled from the environment with a Minus-K negative stiffness vibration isolation platform, 50BM-4. This provides isolation from low frequency vibrations down to of the order of 1 Hz. This offers an experimental working volume approximately 40x40x50 cm^3.

6 Appendix: Reference material (excluding test procedures)

This section provides for reference: processes, conversion relationships and derivations which support standardization of data conversions and methods to ensure data quality prior to processing.

6.1 Conversion of optical phase measurement to strain

Most DAS interrogators considered for use in oil and gas applications implement some methodology that relies on the determination of changes in optical phase on some spatial interval (the gauge length) as the native quantity measured, relating to the fiber sensitivity.

The conversion of this optical phase measure to standard strain units requires the following:

A. Account for the strain-induced elongation of the fiber.
B. Account for the "double path" nature of DAS backscatter measurements. The sensed light is based on the folded optical path nature of the measurement which produces an optical path length change twice that implied by the linear strain across the optical gauge length itself, i.e. L in equation 4 below is twice the gauge length.

The following derivation provides for the appropriate conversions:

When light travels through a section of fiber of mechanical length L and effective refractive index n, the optical path length in terms of phase is:

$$\phi = nkL \qquad \text{(EQ 4)}$$

where k is wavenumber (k = 2π/λ) and λ = vacuum wavelength. Changes in optical path length and, hence, phase owing to strain-induced elongation can in general be categorized as originating from changes in three different sources; namely mechanical length, effective refractive index, and wavelength, expressed as:

$$\frac{d\phi}{\phi} = \frac{dL}{L} + \frac{dn}{n} + \frac{dk}{k} \qquad \text{(EQ 5)}$$

We assume for the purposes of this document that wavelength – and, hence, k – is effectively constant and dk/k = 0

When the fiber experiences strain-induced elongation ε (= dL/L) one might therefore be inclined to assume that the amount of strain is directly translated to the amount of change in phase delay, as dϕ/ϕ = ε, <u>but this isn't true as strain also causes changes in the effective index of refraction</u> n through the photo-elastic effect[1], and it is necessary to introduce a scale factor ξ as:-

$$\xi = 1 - \frac{1}{2} n^2 [P_{12} - \nu(P_{11} + P_{12})] \qquad \text{(EQ 6)}$$

in which P_{ij} is the strain optic coefficient allowing us to rewrite equation 5 as:

$$\frac{d\phi}{\phi} = \xi\varepsilon \qquad \text{(EQ 7)}$$

[1] Giallorenzi T G *et al* "Optical fiber sensor technology" IEEE J. Quantum Electronics, v**18** 626-65, 1982

For silica: $P_{12} = 0.27$, $P_{11} = 0.12$, $\nu = 0.17$, $n = 1.4682$ resulting in $\xi \approx 0.78$.

Combining equations 4 and 7 establishes the linear relationship between strain and the resulting change in optical phase as:

$$d\phi = \frac{2\pi n L \xi \varepsilon}{\lambda} \qquad \text{(EQ 8)}$$

Accounting for the particular measurement of the IU where the length L, in equation 8 is represented below by the **double transit** of a mechanical gauge length, G, the optical phase is represented as:

$$d\phi = \frac{4\pi n G \xi \varepsilon}{\lambda} \qquad \text{(EQ 9)}$$

Equation 9 is rearranged to show the strain sensitivity:

$$\varepsilon = \frac{\lambda d\phi}{4\pi n G \xi} \qquad \text{(EQ 10)}$$

Where the parameters of equation 10 are defined as:

λ	the operating optical wavelength of the DAS system (in vacuum).
n	the effective index of refraction of the sensing fiber (group index).
G	the gauge length employed by the DAS system.
ξ	the photo-elastic scaling factor for longitudinal strain in isotropic material (0.78 for silica, *see EQ 6*).
$d\phi$	the noise floor of the system in radians in a given frequency band.
ε	the noise floor of the system defined as a strain in the same frequency band.

Calculated Strain / Optical Phase values for given Gauge or Fiber Stretcher Lengths

The optical phase-strain relationship from equation 9 is shown in Table 1.

It provides the optical phase level required to attain stimulus strain levels in relation to the amount of optical fiber wound on the fiber stretcher. Alternatively, it provides the optical phase "accumulated" across a gauge length for a given uniform strain level.

Thus, it may be used as a convenient look-up table to determine the drive level required for fiber stretchers for the various tests within this document.

Strain	0.025με	0.05με	0.1με	0.25με	0.5με	1με	2.5με	5με
Gauge or fiber stretcher length (m)	optical phase radians	optical phase radians	optical phase radians	optical phase radians	optical phase radians	optical phase radians	optical phase radians	optical phase radians
1	0.23	0.46	0.93	2.32	4.64	9.28	23.21	46.42
2	0.46	0.93	1.86	4.64	9.28	18.57	46.42	92.84
3	0.70	1.39	2.79	6.96	13.93	27.85	69.63	139.27
4	0.93	1.86	3.71	9.28	18.57	37.14	92.84	185.69
5	1.16	2.32	4.64	11.61	23.21	46.42	116.06	232.11
6	1.39	2.79	5.57	13.93	27.85	55.71	139.27	278.53
8	1.86	3.71	7.43	18.57	37.14	74.28	185.69	371.38
10	2.32	4.64	9.28	23.21	46.42	92.84	232.11	464.22
12	2.79	5.57	11.14	27.85	55.71	111.41	278.53	557.07
15	3.48	6.96	13.93	34.82	69.63	139.27	348.17	696.34
20	4.64	9.28	18.57	46.42	92.84	185.69	464.22	928.45
25	5.80	11.61	23.21	58.03	116.06	232.11	580.28	1160.56
30	6.96	13.93	27.85	69.63	139.27	278.53	696.34	1392.67
35	8.12	16.25	32.50	81.24	162.48	324.96	812.39	1624.79
40	9.28	18.57	37.14	92.84	185.69	371.38	928.45	1856.90
45	10.45	20.89	41.78	104.45	208.90	417.80	1044.50	2089.01
50	11.61	23.21	46.42	116.06	232.11	464.22	1160.56	2321.12

Table 1: Optical phase and strain relationship for fused silica with effective index of refraction, n=1.468, photo-elastic scaling factor, ξ=0.78, and vacuum wavelength, λ=1550nm.

6.2 Good quality data

This element covers tests 4.2: Dynamic Range; 4.3: Frequency Response; 4.4: Fidelity; 4.7: Spatial Resolution; 4.8: Crosstalk; and 4.10: Sensor Reflection Effects.

The procedures for these tests require a sufficiently high signal to noise ratio to make a precise measurement. Because DAS systems are influenced by Rayleigh fading statistics, where backscatter from some Spatial Sample Locations exhibits poor signal to noise ratio, one needs to ensure that "bad" data sets aren't used.

The process steps to conduct this Good Quality Data examination are detailed below:

6.2.1 Ensuring good quality data in single-tone stimulus tests

The following is recommended:

A. Take multiple simultaneous time series over the required set of Spatial Sample Locations with the single tone stimulus on. The time duration to be recorded should be whatever the specific test calls for.

B. Process each of these time series data by (FFT) converting to the frequency domain to examine the signal to noise ratio of the stimulus as follows:
   a. Select one second of time series data from approximate mid-point of the time series. Only use 1 second *(this normalizes noise bandwidth)*
   b. Perform FFT on the one second record. Optional but not necessary to use data window such as Blackman-Harris

c. Plot the signal magnitude in units of dB of the frequency domain data sets (single sided) and examine. Evident should be the single tone signal superimposed over the noise level in the surrounding frequencies.

C. Time series that exhibit an amplitude SNR of ~32x (power SNR ~30 dB) or higher qualify as Good Quality Data.

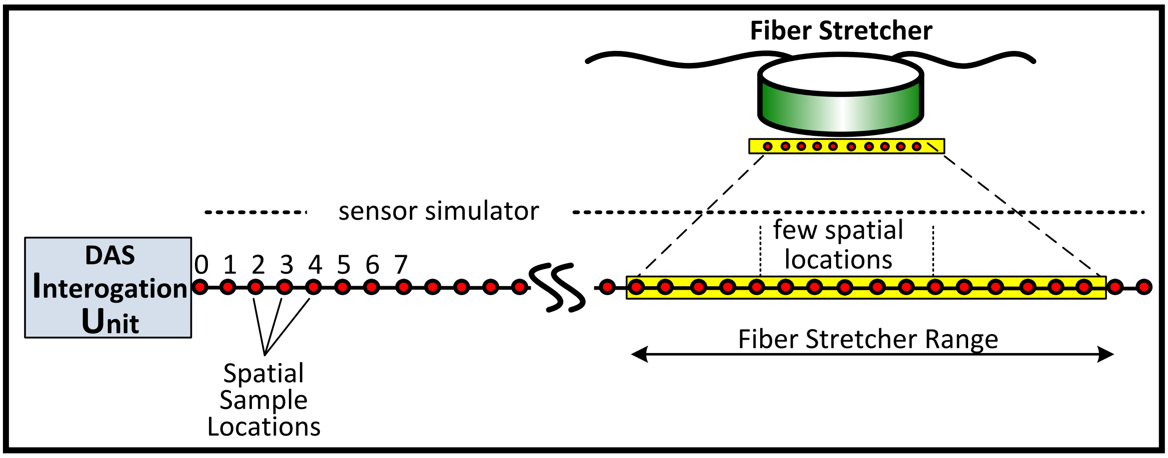

Figure 27: Fiber Stretcher Spatial Sample Locations

An example plot for examination of data quality is shown in Figure 28. Shown here is a large SNR (~60 dB).

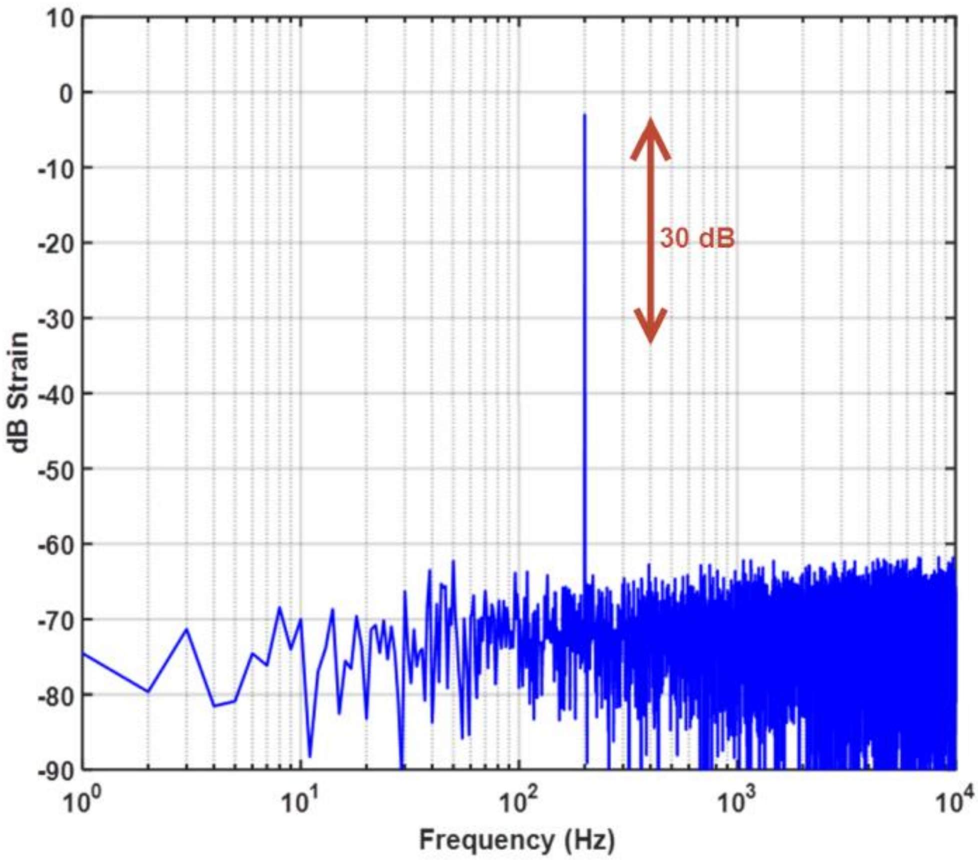

Figure 28: Frequency domain plot of single tone stimulus

6.2.2 Ensuring good quality data in multi-tone stimulus tests

The following is recommended:

A. Section 4.3 identifies the stimulus as a stepped frequency sinusoidal sweep lasting 100 seconds. Take multiple simultaneous time series data at each Spatial Sample Location covered by the fiber stretcher. Ensure the time series captures the full 100 second, 40 tone stimulus (go a little longer if needed)

B. Process each of these time series data (100 second stepped frequency sweep) by converting to the frequency domain via FFT process to examine the signal to noise ratio of the stimulus signal for all 40 tones. The specific steps to perform this calculation are identified in Section 7.2.

C. Time series that exhibit an amplitude SNR of ~32x (power SNR ~30 dB) or higher across all stimulus tones qualifies as Good Quality Data.

An example plot for examination of data quality is shown in Figure 29. Shown here is a large SNR (~46 dB).

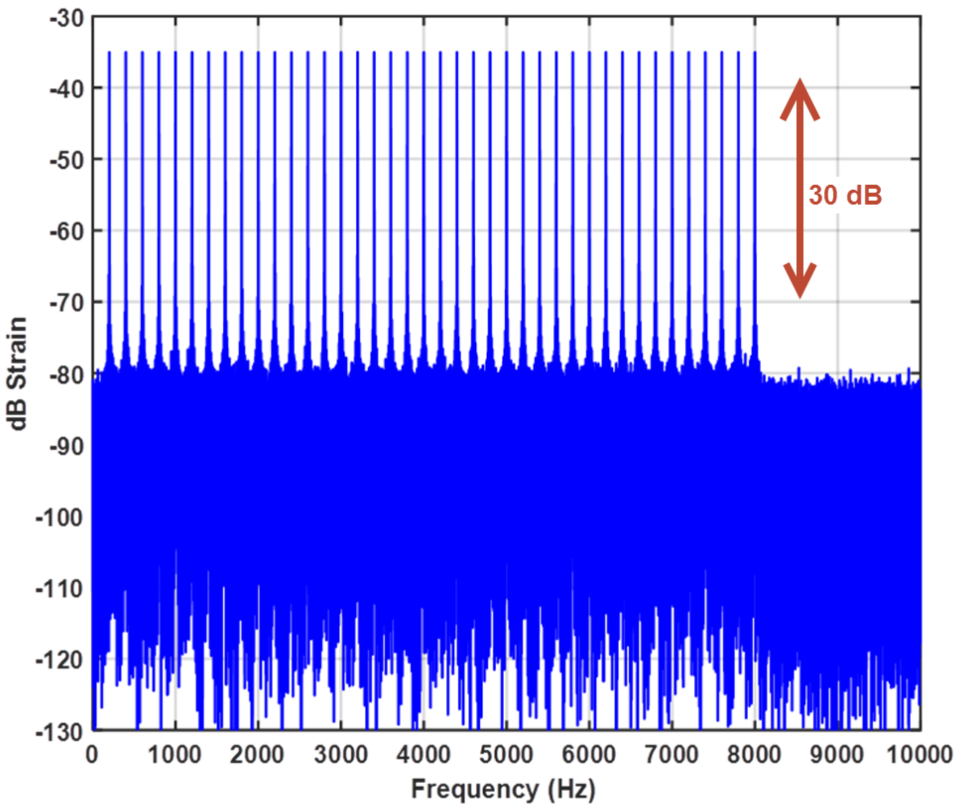

Figure 29: Frequency Response plot of multi-tone stimulus

6.3 Conformance to common parameter definitions

SEAFOM parameter definitions described in Section 3 of this document have been developed in an effort to be common to other standards being developed for DAS. During the evolution of this MSP-02 standard, the SEAFOM DAS working group coordinated with the ENERGISTICS PRODML v2.0 working group on the naming and definitions of the supporting parameters. Table 2 below outlines the comparisons.

SEAFOM	ENERGISTICS	Comment
Spatial Sample Location	Loci	Represents the position on a fiber where a time-series of strain measurements is made.
Sample Location number	Locus Index	Integer value representing a whole number of Spatial Sampling Intervals along the fiber sensor. Starts at zero.
Spatial Sampling Interval	Spatial Sampling Interval	The mechanical separation between two consecutive Spatial Sample locations on the fiber. Units: meters of mechanical fiber length.
Sample Location Zero	Locus Index Zero	Location of output connector of DAS Interrogator.
Gauge Length	Gauge Length	Represents the design-intended spatial resolution of the Interrogator. Units: meters of mechanical fiber length.
Total Fiber Length (TFL) = Interrogation Range	Fiber End	Represents the end of the fiber being interrogated. Units: meters of mechanical fiber length.
Fiber Distance	Fiber Distance	The distance in meters from the connector of the IU to the desired Sample Location. Units: meters of mechanical fiber length.
Output Data Rate	Output Data Rate	The rate at which the IU provides output data for all Spatial Sample Locations or Loci. Equal to the Sample Rate multiplied by the number of Spatial Sample Locations for which data are output. Units: Samples per second (or Hertz).
Interrogation Rate	Interrogation Rate	The rate at which the Interrogator Unit interrogates the fiber sensor (can be considered pulse or frame rate). Units: Pulses per second (or Hertz).
Sample Rate	Sampling Rate	The Interrogation Rate or an integer fraction thereof. Units: Samples per second (or Hertz).
Sample Number	Sample Number	The sequence number of a Sample within its parent Time Series.
Time Series	Time Series	Time history of optical phase or strain measurements associated with a Spatial Sample Location/Locus.

Table 2: SEAFOM / ENERGISTICS parameter definition comparisons.
Source: https://docs.energistics.org/PRODML/PRODML_TOPICS/PRO-DAS-000-070-0-C-sv2000.html

6.4 What to do if your test tone lines up with a "line" frequency or harmonic

If deemed necessary, modify the frequency of stimulus to avoid the overlap.

7 Appendix: Test procedures

7.1 Measurement of dynamic range

This appendix outlines a suitable method to determine the Dynamic Range of a DAS system.

Background

The aim of a DAS system is to yield a signal that is directly proportional to the amplitude of a time-varying acoustically or vibrationally induced strain acting on the fiber sensor. The dynamic range of the system is a measure of the range of amplitudes over which the system can accurately represent the acoustic or vibrational stimulus applied for a given frequency.

As the magnitude of a sinusoidal stimulus increases, IU-induced distortion will begin to occur. Some practitioners have coined this phenomenon as the "**slew rate limit**" which is applicable only to phase sensitive DAS interrogators which implement large angle phase demodulation based on quadrature measurement ("I" and "Q") of the interferometric return signals.

These measurement approaches usually use inverse trigonometric calculations of the I and Q terms to determine the optical phase (on the "unit circle") for each time series sample. The large angle phase determination involves (as the time series progresses) tracking the optical phase beyond the 0-2π limits of the unit circle. This is accomplished by using "unwrapping" techniques.

If the rate of change of the signal being demodulated is too fast, the unwrapping techniques can fail causing an instantaneous jump in phase, which can be some multiple of π radians, (often 2x). Onset of these errors define the slew rate limit of the IU. They also represent the frequency-dependent signal amplitude limit for making linear measurements, and thus are considered in this document to be the Dynamic Range.

Note, that this dynamic range limit definition does not consider the range from the noise floor to the maximum linear operating level. It only considers the maximum linear level.

Example of slew rate limit causing dynamic range limit

Figure 30 shows a simulation of an IU measurement of a 100 Hz sinusoidal stimulus signal starting at zero amplitude gradually increasing over a 30 second time frame. It shows both the stimulus signal in red, and the IU measured optical phase signal (or dynamic strain signal) in blue. At approximately 17 seconds, the IU experiences a discontinuous transition of the type described. This is shown in zoom view in Figure 31.

The amplitude of the strain stimulus signal (optical phase units converted to strain units per equation 10) is defined as the Dynamic Range for that frequency.

Regarding the Dynamic range test (Section 4.2), this test may be taken up to 5 times at each test frequency / each stimulation point to obtain the reported value.

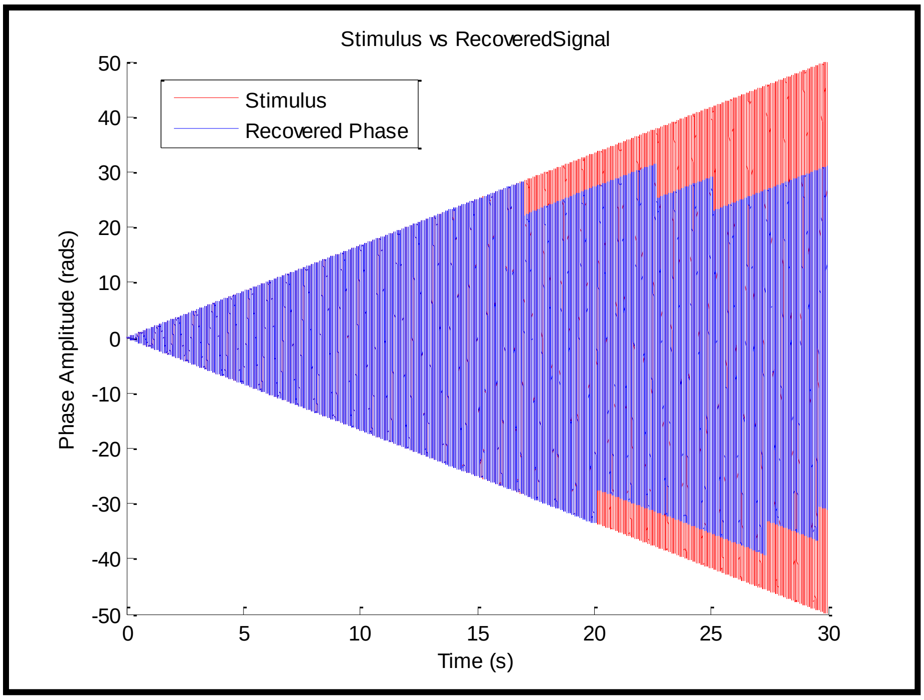

Figure 30: Stimulus signal (red) and IU response (blue) showing linear response limit at approx. 17 seconds.

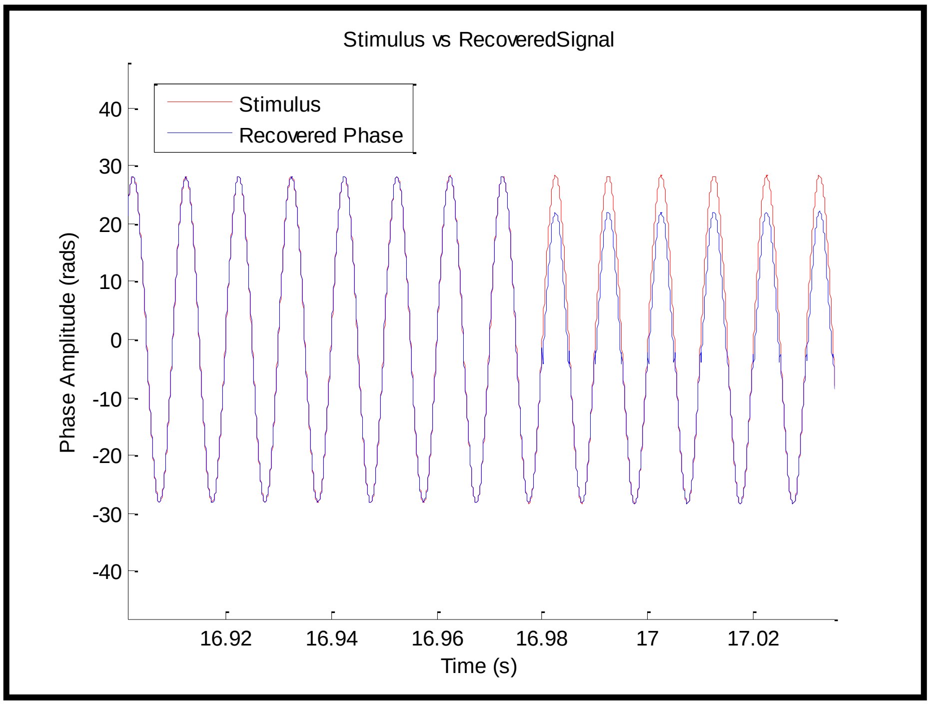

Figure 31: Zoom view of stimulus signal and IU response showing 2π phase jump at 16.98 seconds.

7.2 Measurement of frequency response

The frequency response test for the IU represents the accuracy of the IU to measure the sensed signal amplitude over the operational frequency range.

This document (MSP-02) only covers the magnitude and "gain flatness" of the frequency response. It excludes phase response measurement as no simple process for this could be determined. SEAFOM realizes that the phase response is an important parameter and will strive to include it in a subsequent revision.

7.2.1 Test approach

This test procedure stimulates the SFS with a test signal that covers the Nyquist bandwidth of the IU to evaluate its frequency-dependent transfer characteristic. (Near-DC and near-Nyquist frequencies – which can be problematic – are omitted.)

Ideally such a test would be made with a frequency sweep input that covers all frequencies of interest, but it was determined that a continuous sweep would not provide for sufficient signal to noise ratio to produce accurate measurements. It has been replaced with a stepped frequency sweep utilising a finite number of frequencies to be tested where time spent at each discrete frequency produces enough energy to provide a sufficient signal to noise ratio level to permit accurate evaluation.

The stimulus signal is defined as follows:

Frequency Range (Interrogation Rate ≤ 20kHz): ....2% to 80% Nyquist Frequency **See note FR1.**

Frequency Range (Interrogation Rate > 20 kHz) ....200 Hz to 8.00 kHz

Number of Frequencies: 40

Stimulus time for each Frequency ....2.5 seconds

Sweep time for Frequency Range ....100 seconds

Strain Amplitude .... 0.08 $\mu\varepsilon$ peak / (gauge length in meters)

With the stimulus signal defined, the test approach involves the following:

1. Generate the stimulus file for implementation in the fiber stretcher drive waveform generator.
2. Apply the stimulus to the three test points TP 1, 2, 3 defined in Section 4.3. *Note: this can be done simultaneously (all three test points) or one at a time*
3. Collect data per Section 4.3.2

***NOTE FR1**: Piezoelectric fiber stretchers exhibit a resonant response to transient input signals ('ringing'). In order to minimize transients, **<u>the drive waveform should be continuous at the frequency step boundaries.</u>** The stimulus frequencies can be slightly altered to accommodate this condition, as illustrated by the drive waveform generation code sample in the next section.*

7.2.2 Stimulus waveform generation

An algorithm using MATLAB commands is provided as an example for generation of a stepped frequency fiber stretcher drive waveform that avoids transients between frequencies. The method can be adapted for use in other programming languages.

Sweep signal generation

```
if interrogation_rate > 20000            % Determine Sample Rate for the waveform generator.
        Fs = 100000;
else
        Fs = interrogation_rate * 5;
end
Fn = interrogation_rate / 2;             % IU Nyquist frequency (Hz).
D = 100;                                 % Test duration (s).
N = 5;                                   % No. frequency steps (-).
d = D / N;                               % Duration of each frequency step (s).
F = linspace(0.02, 0.8, N) * Fn;         % Nominal test frequencies (Hz).
m = F .* d;                              % Number of cycles at each test frequency, non-integer in
                                         general (-).
F = round(m) ./ d;                       % Adjust test frequencies to ensure integer no. of cycles per
                                         test frequency.
i = 0:(D .* Fs);                         % Waveform sample index (-)…
t = i ./ Fs;                             % … and corresponding sample time (s)…
j = min(fix(t ./ d) + 1,N);              % ... and corresponding frequency look-up index (-).
S = A * sin(2 .* pi .* F(j) .* t);       % Stepped frequency drive waveform with amplitude A (V).
```

NOTE: The stepped frequency sweep assumes the Fiber Stretcher has a constant sensitivity over all frequencies. In practice, this is not usually true. Fiber Stretcher response typically increases slightly with increasing frequency. To ensure the frequency response test is accurate, it will be necessary to modify the stepped sweep to compensate for the frequency response of the fiber stretcher; i.e. constant stimulus amplitude A in the code sample above becomes a frequency-dependent variable. (By arranging for the frequency transitions to occur at zero crossings in the drive waveform, the above code sample additionally ensures drive continuity if stimulus amplitude A changes at frequency step boundaries.) Alternatively, modify step C in 7.2.3 to compensate for Fiber Stretcher frequency response.

The resulting array S is loaded into the waveform generator. The waveform should be clocked out at sample rate Fs to develop the required stepped frequency sweep Fiber Stretcher drive signal.

The waveform generator output signal should be scaled to the level necessary to produce the recommended strain amplitude (Section 4.3.1, 7.2.1).

7.2.3 Processing the data collected

The test in Section 4.3 requires "Good Quality Data" be collected (see Section 6.2). Once this data is selected, the processing to be performed is exemplified using the workflow described below.

The data to be processed for a single SSL are in array SR in units of strain. It will be first converted to magnitude frequency domain data.

Magnitude of determination

NOTE: The measurement described below involves performing a Fourier transform to determine the measurement in the frequency domain. **This particular data set will not transform correctly if an apodizing window function is applied. Do not apply a window function.**

A. Perform fft,

Y = fft(SR);

B. Determine Normalization Factor[1]

P = normalization factor = sqrt(2)/N

[1] Normalisation factor P = sqrt(2)/N, in which N is the length of IU measurement array Y, is in error but is retained for consistency with previous editions of this document. To estimate stimulus amplitude from the positive frequency Fourier coefficients returned by fft(…) use P = (2/N) * (D/d) in which D is acquisition duration and d is frequency step duration (defined in the code sample at Section 7.2.2).

Note: this normalization factor is used to revert data to the same input referenced signal level when determining M below.

C. Get abs and multiply P to get magnitude M

M = P*abs(Y);

An example of a plot of M is provided below in Figure 32. Here the interrogation rate was 20 kHz and the test result shows the 40 stepped tones occupying 2-80% Nyquist.

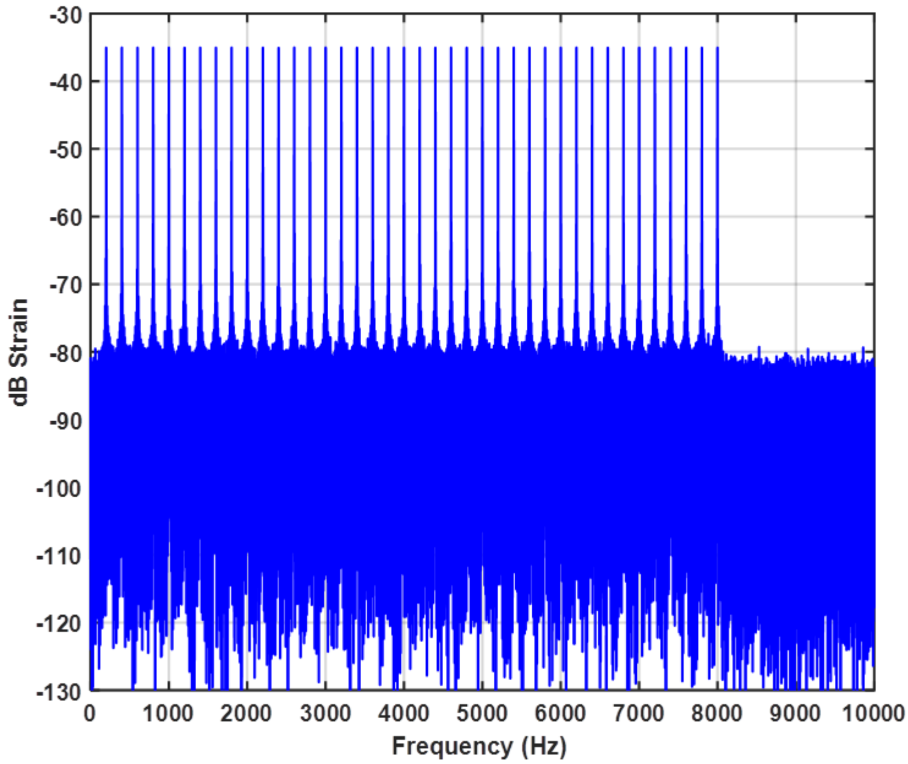

Figure 32: Magnitude response M showing the forty stimulus signals.

7.2.4 Data reporting

Data reporting for the frequency response test shall be a single plot which represents the magnitude response of the 40 test frequencies. It should be derived from the magnitude (M) data taken and processed as follows.

1. Plot 1: Shows the interrogator response M to the test stimulus. Example plot is shown in Figure 33:
   a. Frequency Range: linear from 0 to Nyquist Frequency
   b. Amplitude Scale: dB Peak relative to strain units.
   c. Amplitude Range: 30 dB. Include Indicator of the intended stimulus input

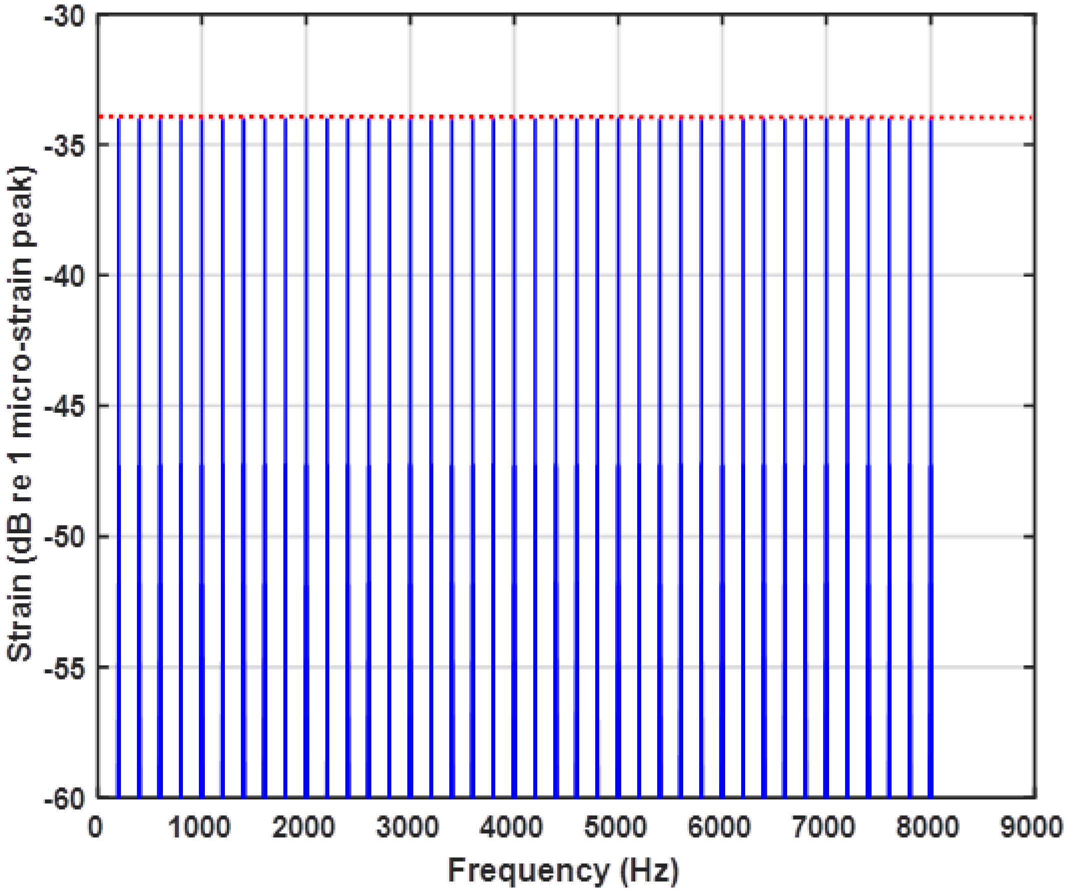

Figure 33: Example test result plot for Frequency Response test, scaled in dB strain units, shown in frequency domain.

2. Plot 2: Corrected and normalized frequency response. Example plot is shown in Figure 34:
   a. Correct the response file M to compensate for the (magnitude) frequency response of the fiber stretcher (see note FR2 below). Result array is MC in units of strain and retain only the 40 peak values.
   b. Calculate the mean value of the 40 MC peak values corrected and normalized to that level. Result File is MCN
   c. Create Plot 2 of MCN.
      i. Frequency Range is linear from 0 to highest frequency tested.
      ii. Amplitude Scale: dB(20*Log_{10} (MCN value))
      iii. Amplitude Range: 9 dB (+3 to -6). *Note, if actual data falls outside of the range specified, then open up the plot range on either end to accommodate.*

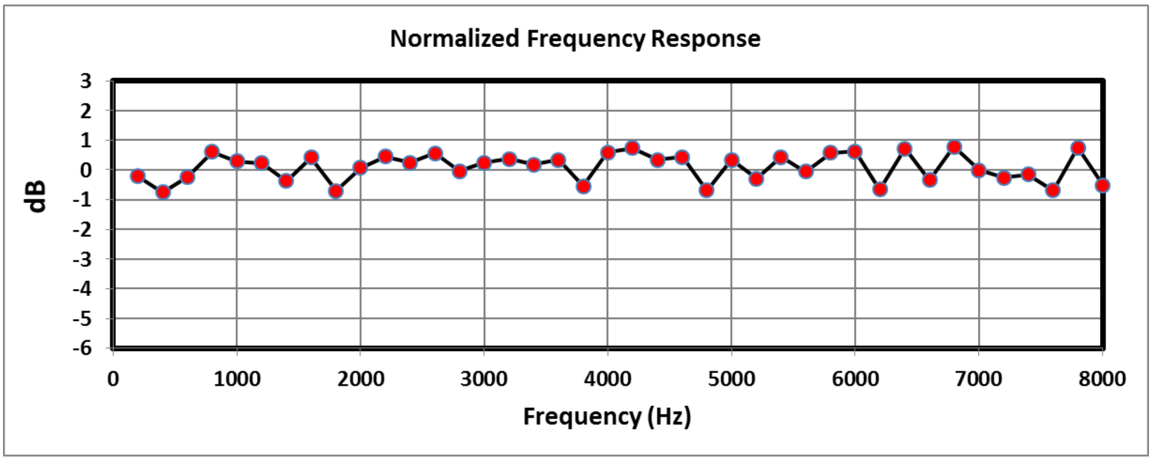

Figure 34: Example test result plot for normalized Frequency Response plot example

***NOTE FR2**: Fiber Stretcher frequency response may not be perfectly flat over the stimulus frequency range. Typically, the sensitivity increases with increasing frequency as the drive signal approaches stretcher resonance. If this is the case then Plot 2 (Figure 34) compensates for this, correcting the data from M so that variation with frequency relates only to the IU response.*

7.3 Measurement of fidelity

Additional detail for this test is not required.

7.4 Measurement of DAS self-noise

This section outlines a suitable method to determine the noise floor of a DAS system.

7.4.1 Background

The noise floor of a system is a critical specification of its performance. It determines the smallest signal the system is capable of measuring.

The measurement approach assumes that the DAS system being evaluated employs an interferometric approach. Thus, the IU fundamentally measures the change in optical path length expressed in terms of phase delay dΦ over the defined gauge length, G. This fundamental output is measured in radians.

In order to present the noise floor in a common form independent of the exact nature of the DAS sensor methodology and operational wavelength, it is necessary to convert the DAS output to the physical strain in the gauge length employed by the DAS system. The conversion from optical phase to strain is described in equation 10 in Section 6.1 This however now makes the noise floor a function of the employed gauge length and so for direct comparison between specifications the gauge length must be quoted with the noise floor, when presented as a strain.

$$\varepsilon = \frac{\lambda d\phi}{4\pi n G \xi}$$

7.4.2 Acquire and process the noise data

In order to measure the noise levels observed by DAS systems installed in real world applications it is important to ensure that the noise floor of the interrogation process of the IU be measured and not the environmental noise of the location in which the Fiber Sensor is placed.

As with a real-world application, the IU should be installed in the laboratory as it would be in the actual application, not within a shielded enclosure unless such is typical for deployment. The Simulated Fiber Sensor (SFS) should, however, be placed within the shielded environment see Section 5.8).

Step 1: Connect the IU to the Simulated Fiber Sensor (SFS) as required, i.e. of the correct length and fiber type.

Step 2: Setup the DAS system as per the manufacturer's instructions, again as appropriate for the fiber configuration with the intended interrogation parameters best suited to the SFS.

Step 3: Acquire Data: Take a data set **30 seconds in duration** for the three test sections (300 contiguous SSLs per section as described in 4.5.3 and Figure 10 This yields the raw (optical) phase response of the Simulated Fiber Sensor (SFS). ***NOTE****: data can be taken over the entire SFS and later processed for the three sections.*

Step 4: Process SSL "ping" Data: The acquired data set is a 2D array of values in each of the three test sections representing the time varying acoustic field as a function of distance. For simplicity of explanation we define two domains, the spatial domain, representing the distance along the fiber (a series of consecutive Spatial Sample Locations or SSLs) and the ping domain, i.e. a 1D data set (Time Series) for each SSL with a sampling rate equal to the Interrogation Rate. See Figure 36 (Ping Domain Process).

The acquired data is to be processed as described in Section 7.4.3 "Process approach for ping domain data".

The result here will be Amplitude Spectral Density (**ASD**) data traces (300 per test section, 900 in total) representing the IU noise response, which has been normalized to a 1 Hz resolution bandwidth and converted to units of strain per root Hertz. *This data should not yet be converted to dB levels.*

Step 5: Average the SSL ASD Data: Spectrally average the data from Step 4 in three sets representing the three test sections. Averaging of ASD values must be carried out by taking the square root of the mean of their squares. Thus, the 300 traces from each section are averaged into one trace per section. The units remain as strain per root Hertz.

Next, express the resulting three average traces as **dB re 1 micro-strain / root Hz**. *This conversion is performed as 20*Log_{10} (strain / rt-Hz).*

Step 6: Plot the noise data

This will be three plots (one per section) which can be shown independently or all on the same plot. The plots will also indicate the gauge length used when the data was collected. Figure 35 shows example output for a single section (1550 nm wavelength, 10 m Gauge length).

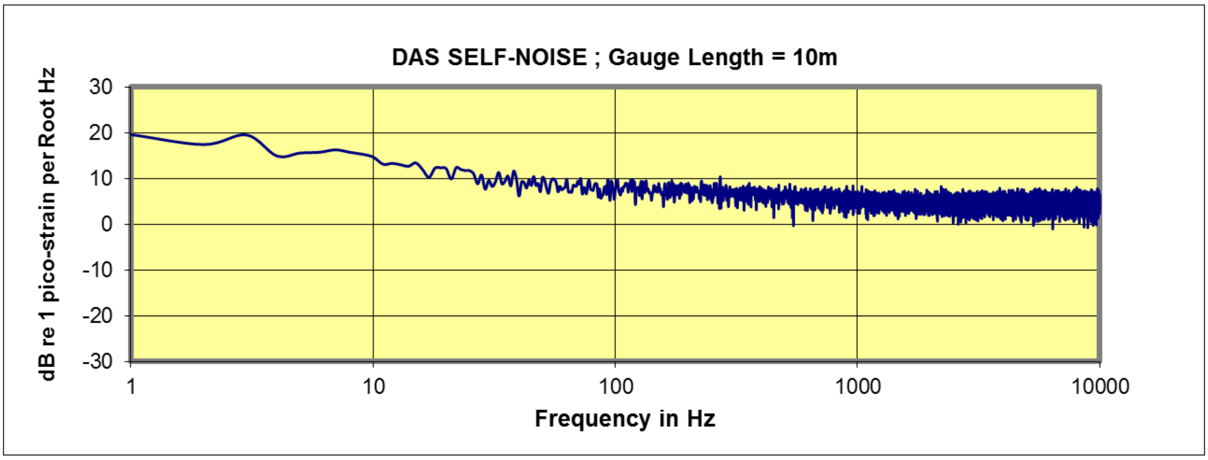

Figure 35: Example plot of DAS Self-Noise data

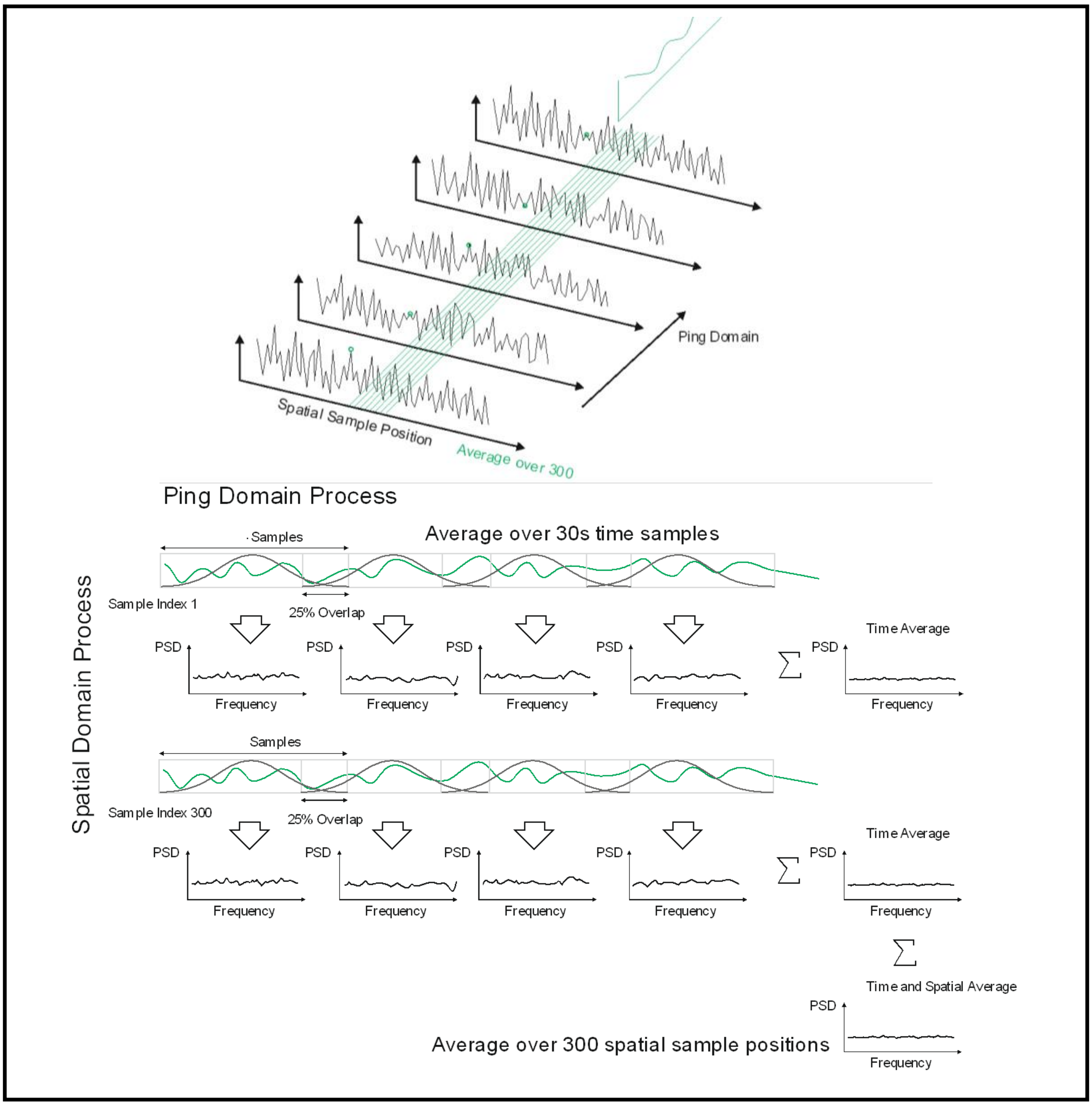

Figure 36: System noise floor data processing schematic

7.4.3 Process approach for Ping domain data

Take each of the three Ping Domain data sets (per-SSL Time Series) and process them to the frequency domain to determine the RMS noise spectral density in rads / √Hz, which will then be converted to units of strain /√Hz.

There are two options to process the Ping domain data. The first has more computational steps (but is preferred by some). The second less so. Either is acceptable

OPTION 1: Process each SSL 30 second Ping Time Series **in many segments.**

For each Spatial Sample Location (300 per section, 900 in total), take the ping domain time series and split the 30s recording into several overlapping "**blocks**" each of a chosen FFT length.

If the FFT lengths are chosen to be 1 s in duration, the noise bandwidth will be automatically normalized to a 1 Hz noise band. There can be overlap between the data blocks if desired. Some experts favour a 25% overlap.

The FFTs should be windowed using a Blackman-Harris window (see Section 8.2). The detailed process steps for the FFT conversion are provided in Section 7.4.4 as a MATLAB process. Further, the resulting frequency domain data should be converted to magnitude and retain only the positive frequency Fourier coefficients (out to the Nyquist frequency).

All of the “Ping” blocks within each SSL (data units of radians per root Hz) should be averaged by finding the RMS for each 1 Hz frequency bin to determine a single noise spectrum measurement. (FFT magnitudes should be averaged by taking the square root of the mean of their squares.) After averaging, convert the resultant data (in units of radians per root Hz) to strain units using equation 10 (Section 6.1).

The result should be three sets of 300 noise spectra, one for each of the three segments identified in Section 4.5.3.

OPTION 2: Process each SSL 30 second Ping time series **in a single segment**.

For each Spatial Sample Location (SSL, 300 per section, 900 in total), the chosen FFT length would be that of the entire 30 second Time Series.

The FFT should be windowed using a Blackman-Harris window (see Section 8.2). The detailed process steps for the FFT conversion are provided in Section 7.4.4 as a MATLAB process. Further, the resulting frequency domain data should be converted to magnitude, normalized to a 1 Hz noise bandwidth and retain only the positive frequency Fourier coefficients (out to the Nyquist frequency).

Next, convert the resultant data (in units of radians per root Hz) to strain units using equation 10 (Section 6.1).

The result should be three sets of 300 noise spectra, one for each of the three segments identified in Section 4.5.3.

7.4.4 Details of the FFT process that calculates DAS self-noise

This process is shown as a MATLAB approach.

1) Detrend the data to remove DC offset and linear slope. (This step is optional and performed in MATLAB by:

Data = detrend(Data)

Define the apodizing window function to multiply the time domain data by (same length as data to Fourier transform, powers of 2 much faster when using FFT). In MATLAB, a Blackman-Harris window may be created by calling the ‘blackmanharris’ function and specifying the data length:

Window Coefficients **W = blackmanharris(L_{FFT}, ‘periodic’)**

2) Calculate the window gain, GW:
   G_W = L_{FFT}/sum(W)

3) Apply window to data
   Windowed Data = G_W.*W.*Data

4) FFT the windowed data
   FFT output = fft(G_W.*W.*Data)

5) Normalise fft output by number of samples (FFT length, L_{FFT})
   Normalised FFT = fft(G_W.*W.*Data)/L_{FFT}

6) Convert from double-sided to single-sided equivalent amplitude, accounting for power split between +ve & -ve frequencies, i.e. single-sideband output SSB = 2*output of +ve frequency power spectrum, or sqrt(2)*amplitude spectrum, as

produced by the fft function. Also, we are interested in the magnitude of the amplitude spectrum, so take the absolute values:

SSB = abs(sqrt(2).*fft(G_W.*W.*Data)/L_{FFT})

7) Calculate noise equivalent bandwidth; accounting for FFT resolution and window noise equivalent bandwidth:

FFT resolution $f_{Res} = f_{Sample} / L_{FFT}$, where f_{Sample} is the sample rate of the data.

Window noise equivalent bandwidth W_{NBW}, must be looked-up for the specific window function. MATLAB has a function 'enbw' for computing the equivalent noise bandwidth from the window coefficients.

W_{NBW} = enbw(blackmanharris(L_{FFT}))

$Noise_{BW}$ = sqrt(W_{NBW} * f_{Res}) % *determine the noise bandwidth*

Note: sqrt as linear in power, fft data is amplitude based.

8) Corrected output normalised to FFT bandwidth (SSBNorm):

SSB_{Norm} = (abs(sqrt(2).*fft(G_W.*W.*Data)/L_{FFT}))/ $Noise_{BW}$

units of radians per square root Hertz OR rads/rt-Hz OR rads $Hz^{-1/2}$

9) SSB_{Norm} needs to be converted to units of "strain noise" This is performed using equation 10 in Section 6.1 where SSB_{Norm} represents the term $d\phi$

$$\varepsilon = \frac{\lambda SSB_{\mathrm{Norm}}}{4\pi n G\xi}$$

λ:	the operating optical wavelength of the DAS system (in vacuum).
n:	the effective index of refraction of the sensing fiber (group index).
G:	the gauge length employed by the DAS system.
ξ:	the photo-elastic scaling factor for longitudinal strain in an isotropic material (= 0.78 for Silica, *see equation 6*).
SSB_{Norm}:	the noise floor of the system in radians / rt-Hz.
ε:	the noise floor of the system defined as a strain / rt-Hz.

Conversion example for silica fiber:

λ:	1550 nm
SSB_{Norm}:	1 radian / rt-Hz
n:	1.4862
G:	10 m
ξ	0.78

$\varepsilon =$ 0.0106 micro-strain / rt-Hz.

7.5 Measurement of spatial resolution

The Spatial Resolution Test verifies the manufacturer's specification of the IU gauge length. This measurement should, for a properly operating IU, return a close approximation to the gauge length.

Step 1:

Setup an IU as shown in Figure 37 below. Delays 1, 2, and 3 are known lengths and test points TP1, 2, and 3 span known Spatial Sample Locations. The length of the fiber winding on the piezo element of the fiber stretcher should be longer than the IU design gauge length (recommend at least 2x).

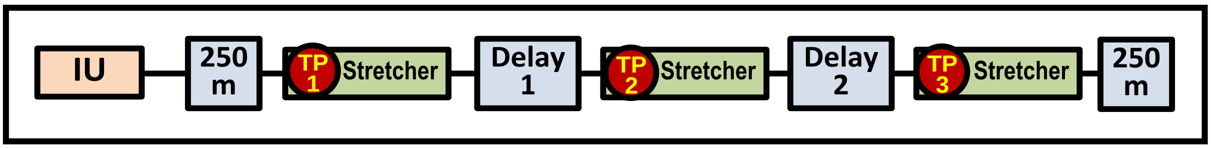

Figure 37: Test arrangement for Spatial Resolution Test

Step 2:

Apply a sinusoidal stimulus to the piezo stretchers. Set the frequency of the stimulation to be 100 Hz and amplitude to be 0.5 $\mu\varepsilon$ peak / gauge length. (The precise stimulus amplitude is not critical. It is selected only to provide good signal to noise in the response. However, it is critical that the stimulus amplitude is consistent for the entire test.)

Step 3:

Begin a Time Series acquisition. The duration should be long enough to ensure that "**good quality data**" (see Section 6.2.1) are collected at all spatial sample locations.

Step 4:

Convert the IU Time Series data (assume optical phase or other "linear" measure of the IU) into frequency domain.

The Time Series data to be converted for the spatial resolution determination should minimally cover the Spatial Sample Locations depicted in Figure 38. Here each red dot represents a Spatial Sample Location, but if the operator wishes simultaneously to cover the full range for the Crosstalk Test (4.8), acquisition should include +/- 50 gauge lengths either side of each Fiber Stretcher section.

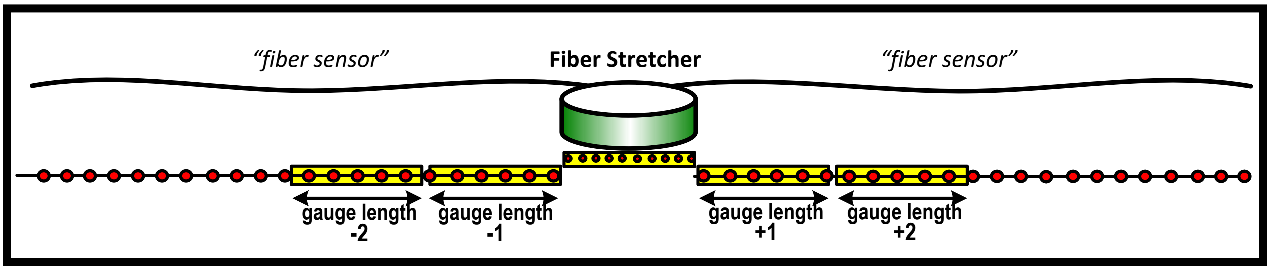

Figure 38: Spatial Sample Locations (highlighted red dots**)** to be used for Spatial Resolution Test

The recommended approach is as follows:

Time series data samples:	16384
Window function for the data:	Flat Top (see Section 8.1)
Frequency Conversion Method:	Fast Fourier Transform (FFT)

It is recommended that each FFT be small blocks (16384) so that numerous blocks can be processed at each SSL to eliminate the possibility that faded signals corrupt the result. Use only amplitude data that exhibits a high SNR at each SSL as identified in Section 6.2.1.

Step 5:

Record the obtained magnitude data at the stimulus frequency (100 Hz peaks) for each Spatial Sample Location (SSL). Create a plot like that shown in Figure 39 where the X axis represents SSL locations and the Y axis shows the magnitude of the signal recovered at the stimulus frequency at each of those positions.

Apply a piecewise straight line fit as shown (red line) in Figure 39. This shows numerically simulated data for a gauge length of 5 spatial sample units in two different scenarios.

The first “Asymmetric Data Set” uses a fiber stretcher spanning 10.5 spatial sample intervals and is asymmetrically situated with respect to Spatial Sample Locations.

The second “Symmetric Data Set” uses a fiber stretcher spanning 11 spatial sample intervals and is symmetrically placed with respect to Spatial Sample Locations.

Both data sets are simulated using a gauge length corresponding to 5 spatial sample intervals and assume perfect performance of the IU where gauge length would then be equal to Spatial Resolution.

<u>The Spatial Resolution is estimated as follows.</u>

Measure the widths (i.e. spatial extent) of the left and right downward sloping lines and designate them as LL and LR.

Spatial resolution is estimated as (LL + LR) / 2

NOTE: *These measurements are in units of Spatial Sample Intervals. Prior to “reporting” they should be converted to mechanical fiber distance in meters.*

The data presented should be a single value representing spatial resolution in meters at each of the three test point locations, TP1, TP2, and TP3.

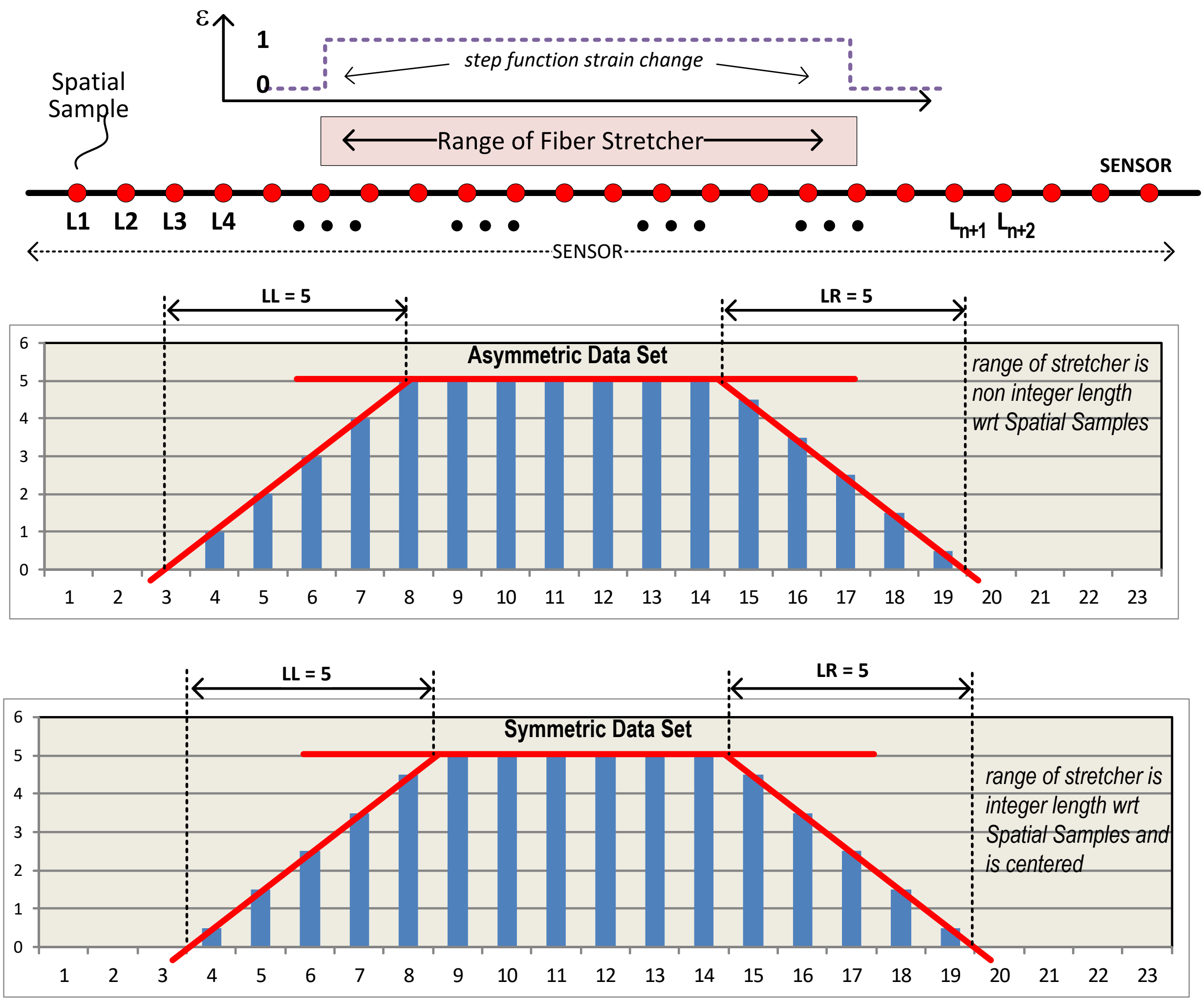

Figure 39: Graphical plotting approach used to determine Spatial Resolution

7.6 Measurement of crosstalk

NOTE: Data collection and processing is very similar to the Spatial Resolution Test (Section 4.7, 7.5) with the exception that the data collected span +/- 50 gauge lengths (or a minimum of +/- 250 meters) either side of each Fiber Stretcher as shown in Figure 40.

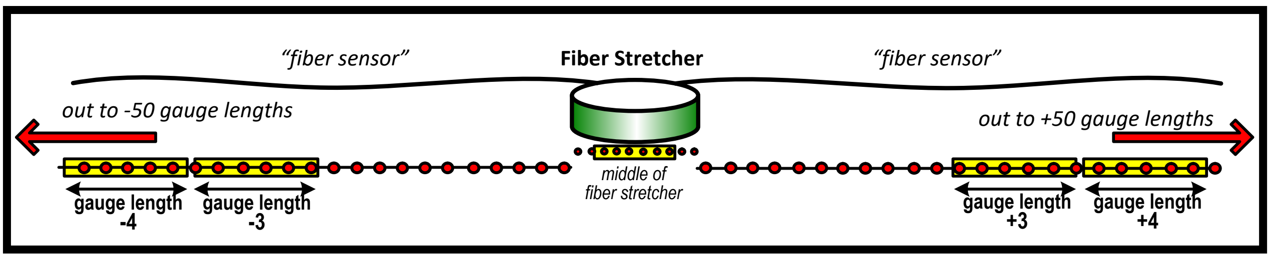

Figure 40. Highlighted Spatial Sample Locations (red dots) to be sampled for the Crosstalk Test (note includes gauge lengths +/- 3 to +/- 50 as indicated by the red arrows)

The test arrangement showing placement of the fiber stretchers is shown in Figure 41.

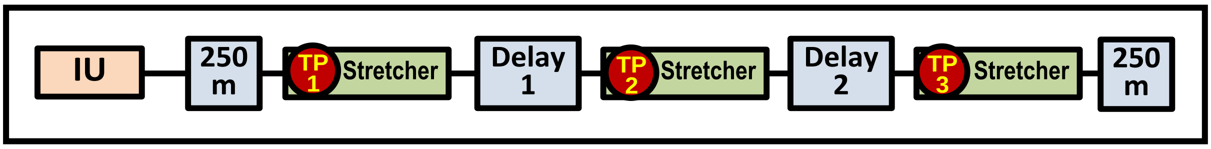

Figure 41: Test arrangement for crosstalk measurement

The data collection steps are identical to those defined in Section 7.5 (Spatial Resolution Test). As before, a stimulus of 100 Hz is recommended. If all Fiber Stretchers are driven simultaneously then different frequencies close to 100 Hz should be used at each test point to ensure crosstalk from stimulus at any one Fiber Stretcher is spectrally distinguishable from stimulus at any other.

Step 1:

A: Determine Reference Level (RL): Use the phase data from steps 1-4 defined in Section 7.5 Spatial Resolution Test. Determine the reference magnitude value averaging the phase data over the flat top portion of the Fiber Stretcher; i.e. from Spatial Sample Locations close to the center of the range covered by the Fiber Stretcher.

B: Determine Crosstalk Levels (CL): Use the phase data from steps 1-4 defined in Section 7.5 Spatial Resolution Test. Determine the magnitudes of the signals (at the stimulation frequency) for Spatial Sample Locations covering the span +3 to +50 Gauge Length and -3 to -50 gauge lengths from the Fiber Stretchers (TP1,TP2, and TP3) as indicated in Figure 40 above.

C: Determine Crosstalk Ratios: Take the ratio of the crosstalk magnitudes to the reference magnitude for all Crosstalk data and express it in dB i.e. $20*\log_{10}$ (CL/RL).

Step 2:

Plot the data over the range of +/- 50 Gauge lengths from each fiber stretcher (TP1, TP2 and TP3) as shown in the example provided in Figure 42, which assumes a 6 m gauge length.

The units for each plot should be dB crosstalk versus length (meters) along the Simulated Fiber Sensor. A conversion of Spatial Sample Location to fiber length is required.

This results in three plots, one for each test point location, TP1, TP2 and TP3.

No data is shown within +/- 2 gauge lengths of the stimulus location.

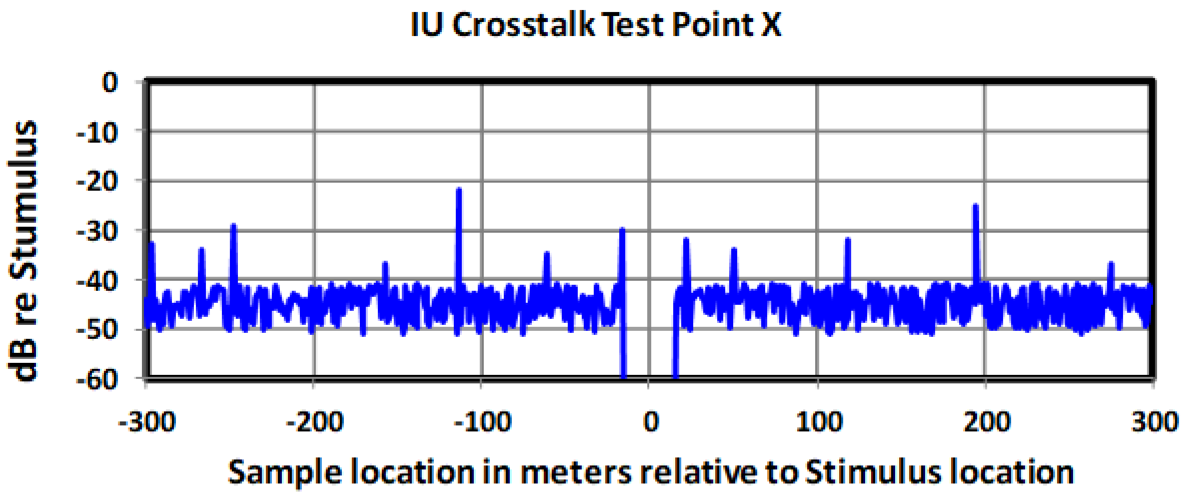

Figure 42. Example plot for Crosstalk Test results. Data is shown to cover +/- 50 Gauge Lengths relative to stimulus. This example uses a 6 m Gauge Length.

7.7 Measurement of loss budget

See Section 4.9.

7.8 Measurement of sensor reflection effects

See Section 4.10.

7.9 Measurement of fading

This process is carried out as part of the process in Section 4.11 Fading Test (OPTIONAL).

7.9.1 Acquire and process the noise data

Use the self-noise data collected for Test 4.5: Self-Noise , and follow the steps 1 through 4 as given in Section 7.4.2. Do not perform step 5 (averaging over the 300 Spatial Sample Locations in each section).

7.9.2 Process approach for Ping domain data

Self-Noise test data were collected as 30 s of time-varying strain measured at each of 300 Spatial Sample Locations corresponding to each of the three test sections (900 time series in total). After step 4 (Section 7.4.2), each of the three sets of 300 time series have been converted to ASD spectra.

The degree to which the strain signal obtained from a Spatial Sample Location is faded is determined by calculating its broad-band variance. Recalling that the Simulated Fiber Sensor is maintained quiet for this test, faded Spatial Sample Locations will give rise to relatively high variance whilst non-faded locations will give rise to low variance. The statistics of strain variance therefore provide a meaningful assessment of the degree to which IU measurements are affected by fade on that Fiber Sensor.

Time-domain variance in a given frequency band at a particular Spatial Sample Location can be calculated by integrating with respect to frequency the square of the ASD in that band. This test employs the frequency band 2 to 80% of Nyquist. If $\alpha(f, x)$ is the ASD at Spatial Sample Location x and having frequency resolution bin size Δf, and f_0 and f_1 are the frequency limits of integration, then strain signal variance at x is calculated as:

$$\mathrm{Var}(x) = \sum_{f \geq f_0}^{f<f_1} \alpha^2(f, x)\Delta f$$

Variance $\mathrm{Var}(x)$ is a function of distance x and can be expressed in units of $\mu\varepsilon^2$, which can be converted to dB values according to

$$\mathrm{Var}_{\mathrm{dB}}(x) = 10 \log_{10}(\mathrm{Var}(x)),$$

with units dB rel. $\mu\varepsilon^2$. These values are used to generate the statistical distributions described at Section 4.11.

8 Appendix: FFT window functions

This section provides information in support of processes recommended in Section 4, Procedures for measurement of performance parameters, and Section 7, Appendix: Test procedures.

In order to make precise measures of IU response signals, the time series data from certain tests will be converted to frequency domain via the discrete Fourier transform which can lead to amplitude/power estimation errors.

To mitigate these estimation errors, window function multiplication of Time Series data are required prior to some of the Fourier transforms used for the measurement of Performance Parameters.

8.1 Flat-top window used for frequency domain measurements of spectral peaks

The Flat-Top Window function will be used for the following Performance Parameter tests:

- Fidelity
- Spatial Resolution
- Crosstalk
- Sensor Reflection Effects

The **Flat Top window** has the best amplitude estimation accuracy of all the smoothing windows at ±0.02 dB for signals exactly between integral cycles. It is principally used for calibration purposes. The height of the broad peak produced by the Flat Top window is insensitive to precisely where the stimulus signal centre frequency lies relative to the Fourier Transform frequency resolution bin boundaries. The Flat Top window is therefore a good choice when it is necessary to make an accurate estimate of a signal's amplitude or power from its spectrum.

An open reference for the Flat Top window is found on Wikipedia pages with the link below, which shows the window function and its corresponding normalized transform.

https://en.wikipedia.org/wiki/Window_function#Flat_top_window

Figure 43 depicts the time-domain characteristics of the Flat Top window (left) for a time series of N samples. In the frequency domain, the corresponding Fourier transform exhibits a broad, central peak and low sidelobes.

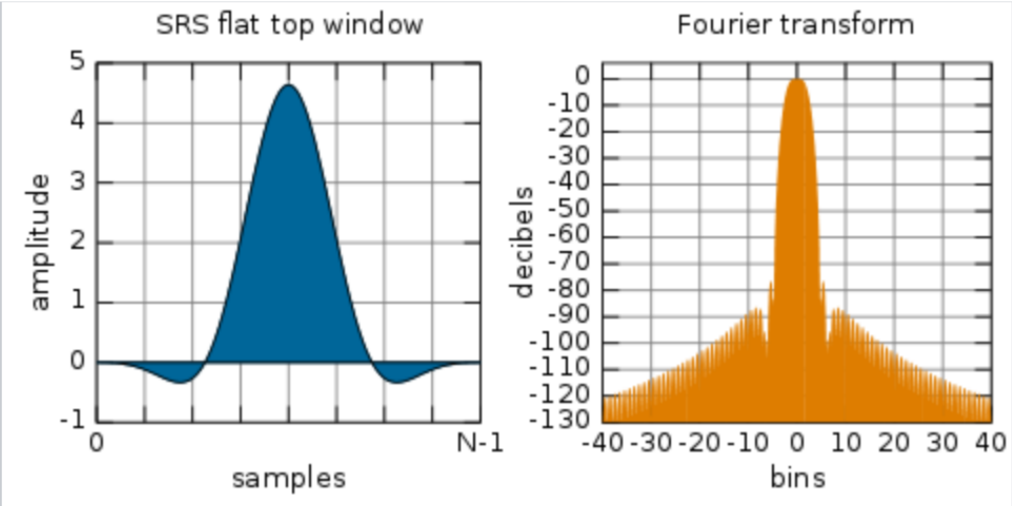

Figure 43: Flat-Top Window function and Fourier transform characteristics.

The generating function and associated amplitude coefficients for the flat-top window are provided below:

$$w(n) = a_0 - a_1 \cos\left(\frac{2\pi(n-1)}{N}\right) + a_2 \cos\left(\frac{4\pi(n-1)}{N}\right) - a_3 \cos\left(\frac{6\pi(n-1)}{N}\right) + a_4 \cos\left(\frac{8\pi(n-1)}{N}\right)$$

Where n is the sample index, $n = 1,2 \ldots N$
N is the number of samples

And the coefficients are[1]:

$a_0 = 1$
$a_1 = 1.93$
$a_2 = 1.29$
$a_3 = 0.388$
$a_4 = 0.28$

8.2 Blackman-Harris Window used for frequency domain noise measurements

The DAS self-noise tests in Sections 4.5 and 4.6 (and 7.4) prescribe the use of frequency domain data for the determination of the IU noise floor. It is recommended to use the Blackman-Harris window function when using the discrete Fourier Transform to convert to the frequency domain.

An open reference for the Blackman-Harris window is found on Wikipedia pages with the link below, which shows the window function and corresponding normalized transform.

https://en.wikipedia.org/wiki/Window_function#Blackman–Harris_window

Figure 44 depicts the time-domain characteristics of the Blackman-Harris window (left) for a time series of N samples. In the frequency domain, the corresponding Fourier transform exhibits a narrow, central peak and low sidelobes.

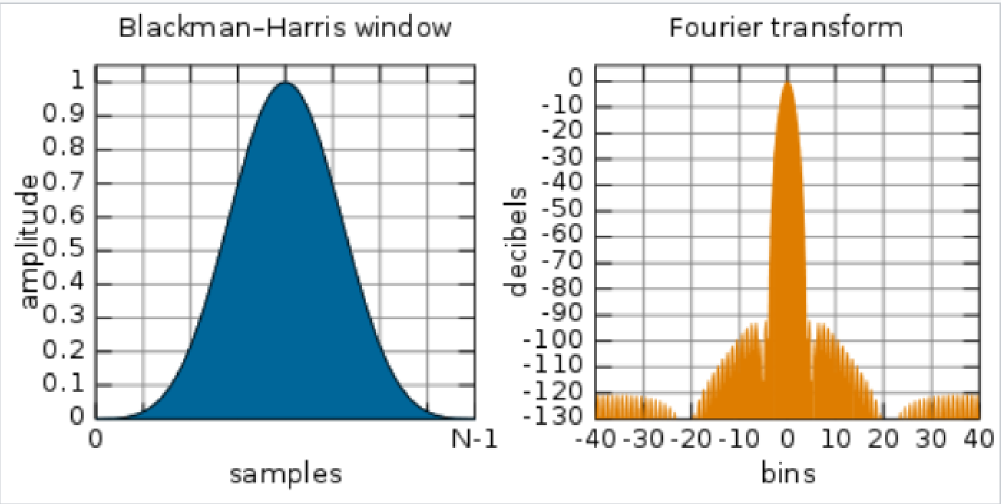

Figure 44: Blackman Harris Window and Fourier transform characteristics.

[1] Flat Top coefficient $a_4 = 0.28$ is in error but is retained for consistency with previous editions of this document. The correct value is $a_4 = 0.028$.

The generating function and associated amplitude coefficients for the Blackman-Harris window are provided below.

$$w(n) = a_0 - a_1 \cos\left(\frac{2\pi(n-1)}{N}\right) + a_2 \cos\left(\frac{4\pi(n-1)}{N}\right) - a_3 \cos\left(\frac{6\pi(n-1)}{N}\right)$$

Where n is the sample index, $n = 1,2 \ldots N$
N is the number of samples

And the coefficients are:

a_0 = 0.35875
a_1 = 0.48829
a_2 = 0.14128
a_3 = 0.01168