



Infrasonic performance of a passively stabilized, all-fiber, optical frequency reference

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Abstract: We report the infrasonic performance of a fiber optic laser frequency reference with potential application to space-based gravitational wave detectors, such as the Laser Interferometer Space Antenna. We determine the optimum cross-over frequency between an optical frequency comb stabilized to a Rubidium atomic reference and two passive, all-fiber interferometers interrogated using digitally enhanced homodyne interferometry. By measuring the relative stability between the three independent optical frequency references, we find the optimum cross-over frequency to occur at 1.5 mHz, indicating that our passive fiber frequency reference is superior to the optical frequency comb at all higher frequencies. In addition, we find our fiber interferometers achieve a stability of 20 kHz/ $\sqrt{\text{Hz}}$ at 1.5 mHz, improving to a stability of 4 Hz/ $\sqrt{\text{Hz}}$ above 3 Hz. These results represent an independent characterization of digitally enhanced fiber references over long time scales and provide an estimate of thermal effects on these passively isolated systems, informing future reference architectures.

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1. Introduction

The Laser Interferometer Space Antenna mission (LISA) [1,2] is scheduled to launch in 2034. It will consist of three spacecraft in earth-like heliocentric orbit forming a giant equilateral triangle with spacecraft separated by 2.5×10^9 m. The aim of LISA is to detect gravitational waves across a signal band from 20 μHz to 1 Hz with a strain sensitivity of better than 1 part in 10^{20} . To achieve this goal, each spacecraft will direct a collimated laser beam at the two other spacecraft in the constellation forming an active, three arm laser interferometer. Whilst Time Delay Interferometry [3] is expected to eliminate much of the laser frequency noise in these measurements, free running metrology grade lasers are still far too noisy. Active laser frequency stabilisation is therefore required to bridge this gap and reduce closed-loop laser frequency noise down to the 30 Hz/ $\sqrt{\text{Hz}}$ level across the desired signal band [4]. Whilst the standard means of achieving this is to use Pound-Drever-Hall locking (PDH) to servo the laser frequency to a chosen resonance of a Fabry-Perot interferometer, here we demonstrate an alternative method; a passively stabilized, all-fiber, optical frequency reference. Potential advantages of our all-fiber implementation include light weight and robust construction; ideal for space missions. In addition, our fiber frequency reference provides a high fidelity readout at arbitrary frequencies allowing a locked laser to be continuously frequency tuned if required. This feature will allow greater flexibility in complex space interferometer missions as laser beams from distant spacecraft often exhibit Doppler frequency shifts due to orbital dynamics.

To date, there have been several implementations using fiber optic delay lines which achieve similar performance to ULE spacer Fabry-Perot interferometers [5–8] over timescales up to 100 milliseconds, highlighting the potential of this architecture. A key challenge for optical fiber

based references however remains the maximum achievable integration time before the onset of thermally induced drift. Thermal drift causes changes to the physical length of the fiber, as well as shifts of the fiber mode refractive index. These changes amount to fluctuations in the optical path length of the interferometer, introducing phase noise in the sub hertz signal band.

Meanwhile, optical frequency combs provide a means for optical sources to be referenced to RF frequency standards which are stable over significantly longer time scales. In this paper, we compare frequency readouts from an optical frequency comb and fiber frequency reference. From this comparison we verify the readout calibration of the digitally enhanced fiber frequency references and further characterize thermal effects on these references down to frequencies approaching 10 μ Hz.

Initially developed for the Gravity Recovery And Climate Experiment follow-on mission [9], our ‘digitally enhanced’ fiber frequency references studied here employ the technique, digitally enhanced homodyne interferometry (DEHoI) [10]. This relies on the correlation properties of pseudo-random noise (PRN) codes in conjunction with a 4-level phase mapping to pseudo-randomly sample the interferometer outputs. In practice, this yields a Quadrature Phase Shift Key (QPSK) code sampling in all four quadrants of the IQ plane. It therefore enables the reconstruction of the interference fringe, and as a result, the optical phase from a homodyne interferometer.

Prior development of digitally enhanced fiber frequency references has shown the use of DEHoI demonstrating a high frequency noise floor of 10 Hz/ $\sqrt{\text{Hz}}$ [9]. DEHoI has also demonstrated the ability to remove residual modulation errors known as code noise from the measurement band [11]. In addition, DEHoI has also been employed to mitigate the effects of polarization drift and polarization noise in fiber interferometers [12]. The key aspect explored in this work is the role of fiber thermal dynamics on laser frequency measurements over extended timescales. By conducting synchronous measurements of a test laser with a fiber reference and an optical frequency comb, we observe thermally induced drift over multi-day intervals, and estimate a thermally limited operational bandwidth for the system.

2. Experimental implementation

The frequency noise of a free-running Orbits Lightwave 1550 nm fiber laser, with a nominal linewidth of 300 Hz, is measured using two digitally enhanced fiber frequency references (IF1 and IF2) and an optical frequency comb (OFC), shown in Fig. 1. After initially splitting the laser output between the fiber references and the comb, on the fiber reference side, we apply digital interferometry modulation in the form of a QPSK code. This is applied using an IntraAction FCM-401E5A acousto-optic modulator (AOM), with a centre RF frequency of 40 MHz and a DEHoI modulation frequency of 2 MHz. The DEHoI QPSK code is applied as a phase modulation on the RF carrier which enables highly repeatable $\pi/4$ phase shifts to be produced, necessary for optimal decoding [9]. Once encoded using the AOM, the optical beam is then split between IF1 and IF2, in-line Michelson interferometers, each acting as a fiber frequency reference. Figure 1(a) shows a simplified schematic of this experiment.

The in-line interferometers each consist of a single compact 4 km fiber spool. There are two reflection points per interferometer. The first, (reference) reflection at the start of the spool is caused by a flat surfaced fiber connector (FC/PC) providing approximately 4% reflectivity. The second long (signal) arm reflection is provided by a single-mode fiber retro-reflector (P5-SMF28ER-P01-1) from Thorlabs attached to the far end of the 4 km spool. The optical fields from each reflection are extracted using optical circulators and detected with Newfocus 1811 fiber coupled detectors.

In order to provide thermal and mechanical isolation to the fiber interferometers, both interferometers are placed in an isolation chamber consisting of nested polystyrene and aluminium boxes. Both of the aluminium boxes are constructed of 1 cm plate aluminium and the inside box

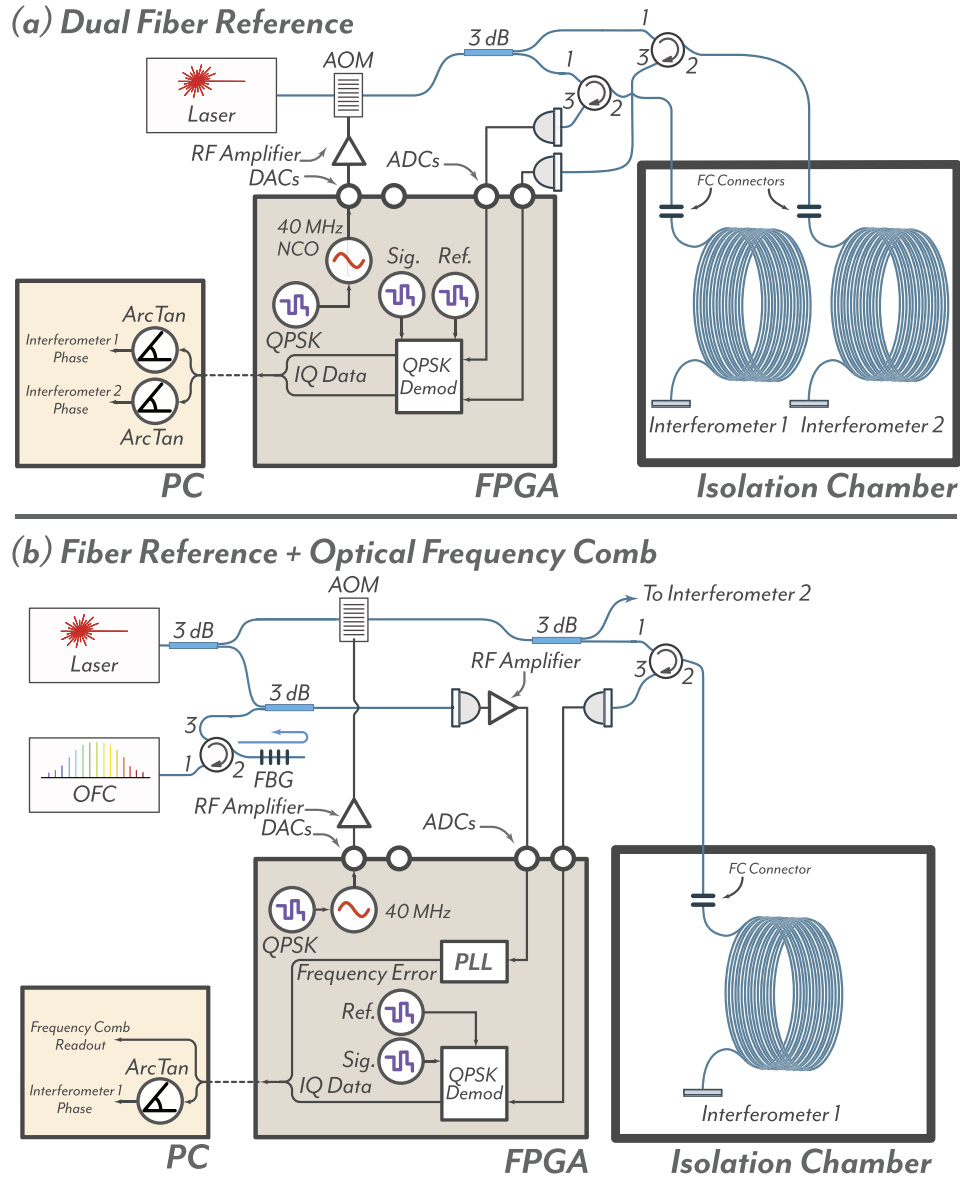


Fig. 1. The hybrid fiber-comb reference setup combines the fiber frequency reference and comb readouts with the Orbits Lightwave test laser split between the two references. Due to a limited number of ADCs, the reference must operate in either of two modes. (a) IF 1 and IF 2 both measure the Orbits laser frequency. IF1 - IF2 yields an estimate of the stability of each fiber interferometer independent of the Orbits Laser frequency noise. (b) IF 1 and the OFC both measure the Orbits laser frequency. IF1 - OFC characterizes the long term length stability of IF1 independent of the Orbits Laser frequency noise.

is hermetically sealed and pressure invariant. The polystyrene layers are each 5 cm thick. The use of this passive isolation system provides an effective second order thermal low pass filter with a time constant of ≈ 10.5 hours [7].

The generation of the QPSK modulation for the DEHoI readout and the AOM drive frequency is implemented on an NI 7966R Virtex 5 FPGA running at a clock frequency of 125 MHz. Analog interfaces with the digital system is provided by the NI 5782 transceiver card, with two 500 MS/s output DACs and two 250 MS/s ADCs.

Following photodetection, the outputs from both interferometers are digitized using the two input channels on the NI 5782 transceiver. Parallel double demodulation is then carried out producing an I/Q projection for each interferometer at a decimated rate that is an integer fraction of the code repetition rate.

Due to the two ADC channel limitation of the NI 5782 transceiver card used we performed two independent measurements; mode (a) with IF1 and IF2, and mode (b) with IF1 and the OFC.

The OFC used was a Menlo Systems FC-1500-250-WG with a 250 MHz tooth spacing. This OFC was stabilised to a Stanford Research Rubidium atomic clock. The laser frequency measurement using the OFC utilised standard heterodyne detection. The nearest neighbour comb tooth was isolated using a fiber Bragg grating, resulting in a heterodyne beat note within the 125 MHz bandwidth of the Newfocus 1811 photodetector. Following digitisation, the frequency of the beat note was tracked by a digital phase locked loop (PLL) operating on the same FPGA running both fiber reference modulation/demodulation systems. Due to the spectral width of the OFC teeth, the PLL bandwidth was optimized to a unity gain frequency of 300 kHz and an update rate of 12.5 MHz in order to maintain reliable tracking. The output of the PLL was then down-sampled in order to average and reduce the data rate.

Once recorded, the synchronous frequency noise measurements from the two references were subtracted yielding the relative stability between the two references under test. This was done for both configurations (a) and (b) shown in Fig. 1.

3. Measuring low frequency stability

We completed 48 hour measurements for both configurations (a) and (b) shown in Fig. 1. For these extended measurements the output sample rate was set to 30.29 Hz, achieved using a 2 MHz chip frequency, an 11 bit code with 2047 elements, and 32 code integrations. The PLL output decimation filters were matched to the fiber reference decimation filters ensuring that both readouts were synchronous. The time domain plot of the measurements over the entire 48 hour time span is shown in Fig. 2 and Fig. 3 for configurations (a) and (b) respectively.

Figure 2(a) plots the time domain traces from IF1 and IF2. We see the two traces overlap well indicating excellent agreement when measuring the Orbits laser frequency noise. The subtraction of these two traces, shown in Fig. 2(b), removes approximately 56 dB of common mode noise. Laser frequency noise is clearly common to both IF1 and IF2. However, placing both interferometers in a single chamber causes a common mode response to the chamber temperature dynamics, and therefore limits the independence of the interferometer readouts over thermal time scales. Whilst we have two identical isolation chambers operating in our laboratory, we have found that the thermal response of each chamber is so similar that even when IF1 and IF2 are in separate chambers, the common mode response over thermal time scales still causes a similar lack of independence.

The time domain measurement of IF1 and the OFC are shown in Fig. 3(a). Short term dynamics on the scale of 1-2 hours are common to both readouts, illustrating the dynamics of the Orbits laser over hour time scales. These are subtracted in Fig. 3(b) which shows the frequency difference between the two readouts. This frequency difference is primarily driven by thermal expansion-contraction, and consequential optical path length change of the optical fiber within IF1 and reaches a maximum deviation of 220 MHz over the 48 hour measurement. As both

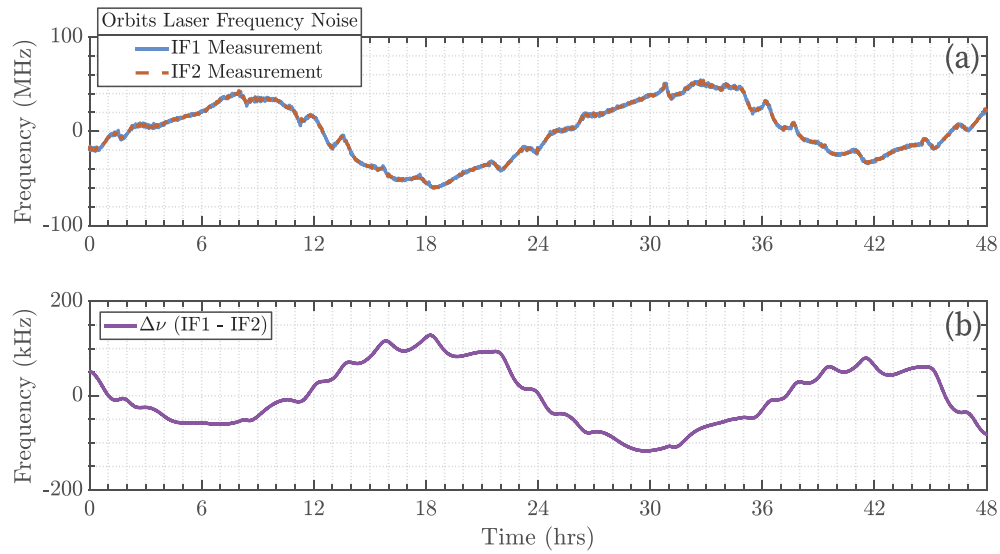


Fig. 2. (a) A time domain plot of the readouts from IF1 and IF2, each synchronously measuring the laser frequency noise of the Orbits laser. (b) The relative frequency stability of the two interferometers; IF1 - IF2. Note this difference is ≈ 1000 times smaller than IF1 and IF2 alone.

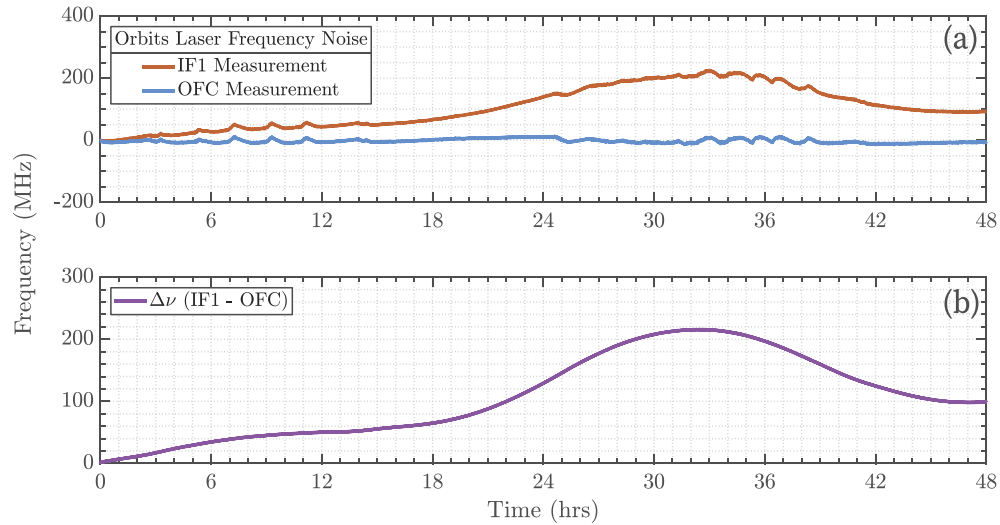


Fig. 3. (a) A time domain plot of the synchronised IF1 and the OFC readouts of the Orbits laser frequency. (b) The frequency difference between IF1 and OFC. Both plots are arbitrarily initialised to zero.

the thermal expansion-contraction and laser frequency discriminant scale identically with fiber length, the coupling of thermal effects into the frequency readout is independent of the total physical length of the fiber spool.

The time domain plots of Fig. 2 and Fig. 3 can be readily converted into spectral densities to determine the relative stability of the references, plotted in Fig. 4. Here trace (a) is the spectral density of the Orbits laser with respect to IF1 while trace (b) plots the Orbits laser with respect

to the OFC. Note that only data from IF1 is plotted as the spectrum from IF2 is identical on this scale. At frequencies below 100 mHz traces (a) and (b) overlap, indicating that in this low frequency regime, both reference measurements are dominated by the frequency dynamics of the Orbits laser. At still lower frequencies, below 50 μ Hz, traces (a) and (b) diverge where thermal dynamics of IF1 dominate trace (a) while trace (b) still records the Orbits laser frequency noise. Above 100 mHz, the traces diverge where (b) becomes dominated by the white frequency noise of the OFC at a level of around 20 $\text{kHz}/\sqrt{\text{Hz}}$, while trace (a) still measures the Orbits laser frequency noise.

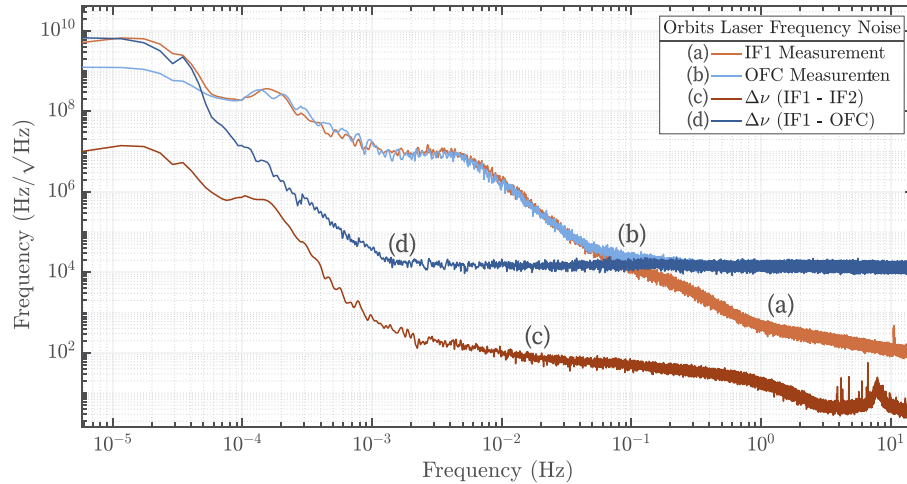


Fig. 4. A comparison between the measured spectral densities showing the relative frequency stability between the two fiber references and the optical frequency comb. All measurements were conducted over a 48 hour time period. a) IF1 measuring the Orbits laser, b) OFC measuring the Orbits laser, c) IF1 - IF2, d) IF1 - OFC.

Figure 4(c) plots the relative stability between IF1 and IF2 while trace (d) plots the relative stability between IF1 and the OFC. Trace (c) yields an estimate of the noise floor of each individual fiber reference. At 3 mHz this noise floor is ~ 5 orders of magnitude below the Orbits laser spectral density plots of traces (a) and (b) indicating that each fiber reference is recording the Orbits laser dynamics with ~ 100 dB dynamic range at this frequency. We also note that above 3 Hz the fiber reference noise floor asymptotes to $4 \text{ Hz}/\sqrt{\text{Hz}}$ with the exception of a mechanical mode of the isolation chamber at ~ 8 Hz.

Figure 4(d) subtracts out common Orbits laser frequency noise dynamics revealing a roll up for frequencies below 1.5 mHz due to thermally induced optical path length changes within IF1. While this low frequency noise feature is also present in IF2, trace (c) cancels out this common thermal noise and therefore underestimates the interferometer noise floor over thermal time scales. This common thermal response of the fiber interferometers causes a factor of approximately 40 suppression at 1 mHz and increases further at very lower frequencies. We therefore rely on the difference between IF1 and the OFC, recorded in trace (d), to give an accurate estimate of fiber reference performance below 1 mHz. Above 1 mHz trace (d) is limited by the high frequency noise of the OFC, and therefore, we determine the optimal IF1-OFC cross-over frequency to occur at 1.5 mHz.

To infer the onset of thermal drift in the fiber reference, we can use the IF1 and the OFC difference measurement to project the thermal drift corner frequency. To do this, we fit a f^{-3} curve to data below 1 mHz and extrapolate this curve to higher frequencies, as shown in Fig. 5 trace (c). A f^{-3} curve is selected as it fits the low frequency data well and is justified by the f^{-2} frequency

response of the isolation chamber while f^{-1} approximates the laboratory air-conditioner dynamics external to the isolation chamber. From this, we find the intersect between the interferometer stability curve of trace (a) and the extrapolated f^{-3} curve of trace (c), which from Fig. 5 we see occurs at 5.3 mHz. Above this frequency we assume that thermal dynamics are not significant within the isolation chamber. Using the f^{-3} , we can therefore infer the stability limits of IF1 and IF2 as highlighted by the shaded area in Fig. 5.

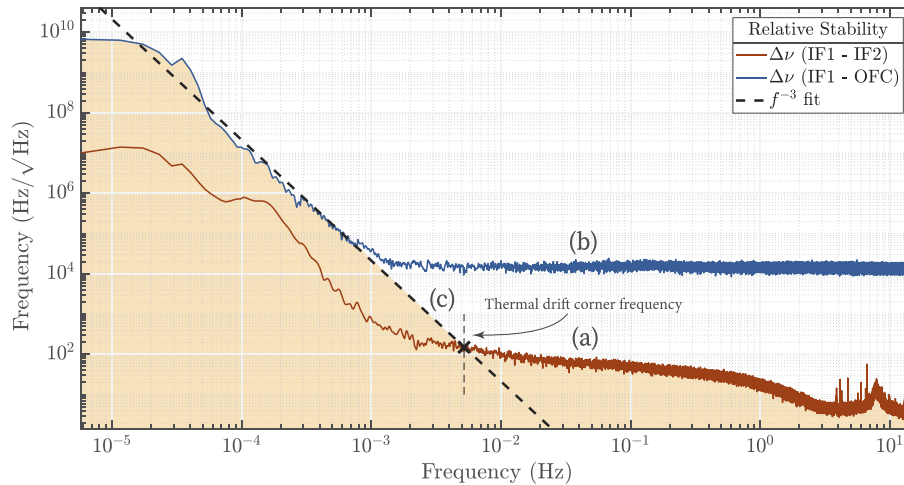


Fig. 5. The estimated infrasonic noise floor of our 4 km fiber frequency reference. Trace (a) is the subtraction of the two fiber frequency references, trace (b) is the difference between the optical frequency comb and the fiber frequency reference, and trace (c) is the fitted f^{-3} curve. The yellow shaded area then describes the inferred stability of the fiber references. The thermal corner frequency is given by the cross-over of (a) and (c) at 5.3 mHz.

4. Conclusion

We measure the low frequency noise performance and stability of a fiber frequency reference over a 48 hour measurement. We record a f^{-3} low frequency noise feature, corresponding to thermally induced expansion-contraction of the fiber reference, below Fourier frequencies of 1.5 mHz. To remove the common mode rejection of thermal drift between two fiber interferometers we use a Rubidium stabilised optical frequency comb as an independent frequency reference, showing 1 order of magnitude common mode rejection in the 100 μ Hz to 1 mHz band. From this comparison with the optical frequency comb, we identify an optimal cross-over frequency of 1.5 mHz. We further project the onset of thermal induced drift to occur at 5.3 mHz, above which, the stability of the fiber frequency reference can be assumed to be limited by non-thermal noise sources.

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Disclosures

The authors declare no conflicts of interest.

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