

Scale-factor measurement with a linear optical cavity for GRACE-like missions

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The Gravity Recovery and Climate Experiment (GRACE) missions monitor variations in the Earth's gravity field, primarily due to water transport, by measuring the change in the distance between two spacecraft. The next generation of GRACE-like missions is expected to rely on interspacecraft laser interferometry to recover these geodesy signals, necessitating the development of a technique to provide long-term laser frequency knowledge. A development electronics unit has been designed and manufactured to provide long-term absolute laser frequency knowledge for the GRACE-Continuity laser ranging system. This paper presents the first measurement of cavity ageing over 2.5 years using this technique and reports on the performance with sub-MHz errors in a GRACE-like optical cavity, sufficient for next-generation GRACE missions. Limitations caused by spurious etalons in the optical system are discussed.

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I. INTRODUCTION

The Gravity Recovery and Climate Experiment (GRACE) was first launched in 2002 to monitor changes in the Earth's local gravity field, primarily due to water transport. The GRACE Follow-On (GRACE-FO) mission, launched in 2018, included a laser ranging instrument (LRI) as a technology demonstration. The LRI was able to resolve range 2 orders of magnitude more precisely than the Microwave Instrument [1], and it is thus the leading choice for a primary instrument in future GRACE-like missions [2,3].

The GRACE gravity measurements are made monthly, and they include contributions from both a static gravity field and changes due to mass movement (e.g., water). The gravity field is recovered by the conversion of the phase measured by the LRI into a displacement measurement. This conversion is achieved using the wavelength $\lambda = c_0/\nu_R$, where c_0 is the speed of light in a vacuum and ν_R is the LRI laser frequency on the reference satellite, which is actively stabilized to an optical cavity. The GRACE mission architecture has a significant arm-length mismatch, which means it is particularly susceptible to laser frequency noise. The reference laser frequency may

drift over time as the cavity length changes (due to temperature and ageing), and the time-varying laser frequency (ν_t) can thus be related to the initial frequency (ν_0) using a scale-correction factor as [4,5]

$$\nu_t = \frac{1}{1 + \varepsilon_{\text{SCF}}} \nu_0. \quad (1)$$

The scale-correction factor, ε_{SCF} , provides an estimate of the change in the laser frequency since it was measured on the ground as ν_0 . The error in the estimated range is approximately $\varepsilon_{\text{SCF}}(t) \times L(t)$ [5], which represents the direct coupling of variations in the laser frequency into the range measurement and is known as the scale-factor error. The variation of the scale-factor correction on the GRACE-FO mission is of the order of 70×10^{-9} [5] and is inferred by direct ranging comparison with the microwave interferometer.

To enable a laser-only mission architecture, a long-term measurement of the absolute laser frequency is required to accurately null large static gravity signatures from month-to-month water maps. The leading option for next-generation missions is an additional cavity-readout technique that reads out the optical cavity free spectral range (FSR), from which absolute changes in frequency may be inferred ($\nu = n \times \text{FSR}$). A technique for measuring absolute changes in laser frequency using dual frequency modulation adapted from a proposal by Devoe and Brewer [6] was first developed at NASA/JPL [7], and it has since been further developed [8,9]. The final mission requirement for absolute knowledge of the laser frequency is expected to demand fractional accuracy on the order of 25

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parts per billion (ppb) [7,10], equivalent to an absolute frequency of 7 MHz. This constrains the coupling of the static gravity field to remain smaller than the LRI laser frequency noise.

The GRACE-Continuity (GRACE-C) mission is expected to launch in 2028 and will fly this FSR readout technique, along with associated hardware that augments the existing LRI to provide long-term laser frequency knowledge. For missions other than GRACE, this system could be used where stable optical cavities are already part of the payload. The Laser Interferometer Space Antenna (LISA) will use optical cavities similar to the GRACE missions' cavities, as the fractional frequency-stability requirements are near identical [11]. While LISA's absolute laser frequency requirements are less stringent than those of the GRACE mission (10^{-5} for LISA) [11], additional laser frequency knowledge could yield benefits in reducing acquisition time, for example, if the laser frequencies on different spacecraft are accurately known at all times. There may also be a science benefit to LISA in reducing the scale error to 25 ppb for signals with very high signal-to-noise ratios, and possibly in removing the confusion noise of white-dwarf binaries.

This paper presents the first long-term measurements using this FSR technique on a flight-like linear cavity. The measurements, made over 2.5 yr, are compared to an iodine-referenced laser, and the results indicate that the FSR readout technique is sufficiently accurate to fulfil the GRACE mission requirements over this time period and stable enough to measure cavity ageing. This is also the first result demonstrating the compatibility of the technique with a flight-representative linear cavity, with previous measurements using a traveling-wave cavity, a geometry naturally immune to spurious etalons [8,9]. This paper also presents an investigation of performance limits due to spurious etalons, in this case due to a mirror substrate antireflective coating. After identification of this limitation, it was resolved by the addition of a 0.5° wedge to the cavity mirrors.

Finally, all the results presented in this paper were achieved using an FSR readout development electronics unit, which is the first purpose-built hardware unit for this technique. The unit was designed in partnership with and manufactured by CEA Technologies, using components with space-qualified equivalents and compatible with GRACE-FO interfaces.

II. DUAL-FREQUENCY-MODULATION TECHNIQUE

A dual-frequency-modulation scheme was first proposed in the 1980s [6] as a way to stabilize and measure a laser frequency against an rf standard. The original paper used two optical modulators in series, creating a summed

modulation signal. This technique has been used in a number of applications since, including in gravitational-wave detectors to transmit sidebands through mode-cleaning cavities [12], and for measurement of cavity length and width by measuring the amplitude modulation in transmission [13]. Dual frequency modulation has also been used in spectroscopy applications. Noise-immune cavity-enhanced optical-heterodyne molecular spectroscopy combines frequency-modulation spectroscopy with optical cavities to improve sensitivity [14–16].

These implementations typically retain the use of two optical modulators in series, with one being driven at a frequency matching the optical cavity free spectral range. With this approach, GHz detection and demodulation is required. Further, the sideband pattern generated includes products around the laser carrier.

The approach used in this paper instead uses a single optical modulator driven by a nested modulation signal. This generates a different sideband pattern in which there is an absence of products around the carrier, resulting in a readout technique that is sensitive to the differential effect of mode-spacing change (scale factor) and is insensitive to common optical carrier frequency changes.

The original paper [6] describes the use of this technique to stabilize a laser to an optical cavity using the Pound-Drever-Hall technique and then to stabilize the optical cavity in turn to an external rf source. Rather than controlling the length of the optical cavity, the dual-frequency-modulation approach for the GRACE missions will instead update the frequency of the GHz modulation tone and track the cavity mode spacing.

The cavity mode spacing readout technique is described in detail in Ref. [8], with a summary included here for convenience. The modulation consists of a standard Pound-Drever-Hall (PDH) modulation tone ($\Omega_{\text{PDH}} = 2\pi F_{\text{PDH}}$) and a second tone at a frequency selected to match the optical cavity FSR ($\Omega_{\text{FSR}} = 2\pi F_{\text{FSR}}$). For a linear optical cavity of approximately 77 mm in length, the FSR is 1.9 GHz. In addition, the GHz sidebands are also phase modulated with a MHz tone different in frequency to that chosen for the PDH modulation. This tone is referred to as the scale-factor (SF) tone ($\Omega_{\text{SF}} = 2\pi F_{\text{SF}}$), as it is demodulated and read out to determine changes to the length of the optical cavity.

The modulation scheme is illustrated in Fig. 1. The laser carrier is depicted at the center, with the PDH modulation sidebands shown in blue. The FSR sidebands appear at the laser carrier ± 1 FSR, with the SF modulation sidebands around each FSR tone, both depicted in red. PDH sidebands are also present around the upper and lower FSR sidebands.

The dual-frequency-modulation scheme allows comparison of the on-board optical cavity to the frequency stability of an external reference oscillator disciplined to an ultimate standard such as Global Positioning System time.

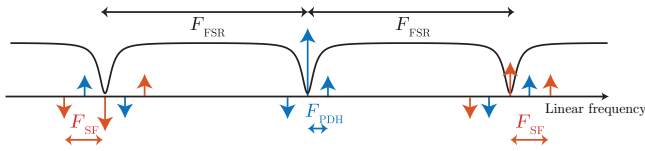


FIG. 1. Frequency phasor diagram illustrating the first-order terms of the optical modulator output. PDH modulation terms and the laser carrier are depicted in blue. The FSR and SF modulation tones are depicted in red. The FSR modulation frequency is chosen to match the cavity free spectral range, and the SF modulation frequency is chosen such that it is not equal to the PDH modulation frequency and can thus be read out independently.

This allows the tracking of long-timescale changes at the stability limit of the external clocking source.

III. EXPERIMENTAL SETUP

A. Development unit instrument design

In previous work [8,9], this technique was demonstrated with the phase-modulated GHz readout tone generated using a signal generator (Rohde & Schwarz SMA100B) and read out using a digitally implemented lock-in amplifier (Liquid Instruments Moku:Lab). The exact implementation of how the phase-modulated GHz tone is generated in this commercial unit is not publicly known. There are no options to calibrate the modulation signal, and the signal therefore cannot be optimized for the particular frequencies of interest. For future missions, a dedicated, space-qualified electronics unit would be required to incorporate all these functions and interface with the existing flight hardware.

A single-purpose signal generator paired with a read-back lock-in amplifier was designed as a development unit for the proposed flight hardware to implement this technique. The custom development electronics hardware unit was designed and manufactured using components with space-qualified equivalents and interfaces defined from the GRACE-FO mission. This is a critical step to increase the technology readiness level of this technique and demonstrate that the required performance should be achievable in a flight implementation. This unit is referred to as the scale-factor unit (SFU), and the final flight unit will generate a data product used to scale, or calibrate, laser ranging signals over the months-to-decade timescales of the mission.

A block diagram of the SFU and the interfaces with existing flight hardware is shown in Figure 2. The GRACE-FO architecture had the laser ranging processor (LRP) generating the PDH sidebands, with the modulation waveform directly passed to the electro-optic modulator (EOM). The proposed configuration for GRACE-C inserts the SFU between the LRP and EOM, with the SFU acting as a passive passthrough for the PDH modulation

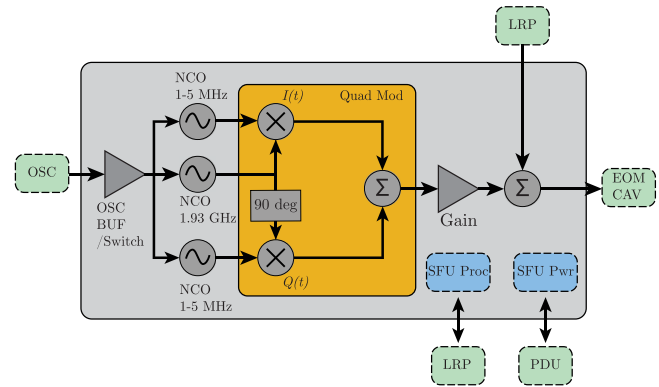


FIG. 2. Block diagram of the scale-factor unit (SFU), showing key components and signal paths. The oscillator (OSC) provides a 40-MHz clock source, which is used to generate an approximately 1.93-GHz carrier tone and a 1–5 MHz baseband tone for sampling cavity mode spacing using numerically controlled oscillators (NCOs). An in-phase-quadrature (IQ) modulator uses the baseband MHz tone to phase modulate sidebands onto the carrier tone. This signal is then passively combined with the PDH modulation signal provided by the laser ranging processor (LRP) before being sent to the electro-optic modulator (EOM) to modulate the laser light incident on the cavity. The power-distribution unit (PDU) provides mains bus power, and the LRP provides communication and control.

when unpowered. When powered, the SFU generates a phase-modulated carrier tone to probe the cavity spacing, combining this with the PDH modulation generated by the existing LRP.

The unit uses a 40-MHz clock signal (OSC) to synthesize the carrier GHz tone matched to the FSR of the optical cavity, and a baseband MHz tone to phase modulate the carrier tone. The phase modulation of the carrier tone is achieved using an IQ modulator to generate a very stable and low-distortion electronic phase-modulation waveform. Two other critical interfaces shown are the power-distribution unit (PDU), which provides mains bus power to the unit, and the second interface with the LRP, which provides communication with and control of the unit.

The architecture, while being designed specifically to meet the GRACE-C science requirements, is a general and flexible field-programmable gate array (FPGA) implementation producing an IQ modulation that can be calibrated. The flexibility in the modulation generation allows for in-orbit calibration that alternative architectures (such as a voltage-controlled-oscillator-based implementation) may not have been able to achieve.

B. Flight-like optical cavity

Previous performance results demonstrating the proposed dual-frequency-modulation technique for absolute frequency readout [8,9] were achieved using a triangular

traveling-wave optical cavity, with the FSR readout technique implemented using commercial off-the-shelf components. The GRACE-FO mission, however, uses a linear midplane cavity with a spacer length of 77.5 mm and a design finesse of 10 000 [17,18]. It is expected that future missions will continue to use a similar linear cavity to preserve flight heritage.

This change in cavity geometry (from triangular traveling wave to linear) posed a significant risk to the viability of the technique. Triangular traveling-wave cavities are geometrically immune to some types of parasitic or spurious etalons. Linear cavities, however, are susceptible to this noise source, which can completely mask the signal if the spurious etalon is sufficiently large.

As the technique had not previously been tested on a linear cavity, there was a risk that the differences in geometry of the linear cavity would prevent it from being able to accurately measure the cavity FSR. Demonstrating compatibility with the linear cavity geometry was therefore essential.

A GRACE-FO-like linear midplane cavity was purchased from Stable Laser Systems for use in these validation tests. This flight-like cavity has a length of 77.7 mm, a free spectral range of 1.933 GHz, a Finesse of approximately 10 000, and a zero-crossing temperature of 36.74°C. The mean linear coefficient of thermal expansion of the ultra-low expansion (ULE) glass is typically 0 ± 30 ppb/° from 5° to 35°, with a maximum variation of 10 ppb/° [19].

C. Performance test configuration

The test configuration is illustrated in Fig. 3. A 1064-nm non-planar ring oscillator (NPRO) laser was stabilized to the linear cavity using the PDH locking technique [20]. For this PDH control loop, a modulation frequency of 1.38 MHz provided by an external function generator was used to drive the GHz electro-optic modulator (iXblue; two parts were used: NIR-MPX-LN-02 and NIR-MPX-LN-05). The cavity-reflected light was detected and digitized using an analog-to-digital converter and processed using a control algorithm implemented on an FPGA. Actuation was frequency shaped and fed back to the laser to hold its frequency to a particular cavity resonance fringe.

The development SFU generated a phase-modulated GHz tone matched to the cavity free spectral range (approximately 1.93 GHz) and combined this tone with the PDH modulation signal using analogue electronic combination. The SFU also digitized and demodulated the same cavity-reflected signal to obtain an error signal.

The primary laser was also interfered with a secondary independently stabilized 1064-nm NPRO laser on a high-bandwidth photodetector. The relative frequency of the two lasers was tracked with a digital phasemeter implemented on a Liquid Instruments Moku:Lab.

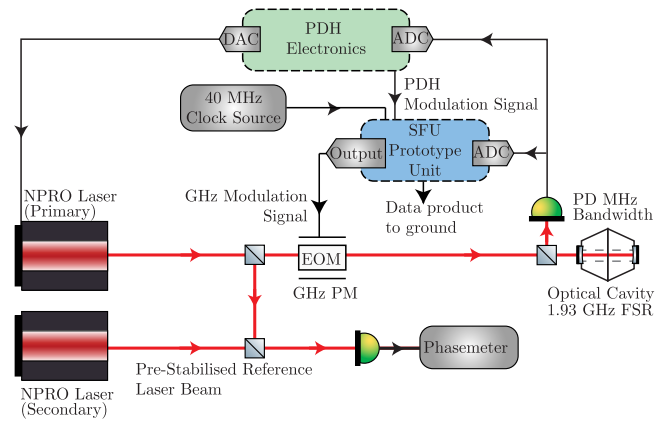


FIG. 3. Test configuration using the development SFU and a midplane cavity. A 1064-nm non-planar ring oscillator (NPRO) laser was stabilized to the midplane cavity using the PDH technique. The PDH modulation signal was passed to the SFU, where it was combined with a phase-modulated GHz tone. The combined modulation signal was then used to drive the EOM. The cavity-reflected light was split between the PDH controller and the SFU, with each unit independently digitizing and demodulating the signal for use in their respective digital control or readout systems. The laser was also interfered with a second 1064-nm NPRO laser on a high-bandwidth photodetector, with the second laser independently stabilized. The beatnote between these two lasers was then tracked with a digital phasemeter (Liquid Instrument Moku:Lab).

IV. RESULTS

A. Long-term stability and cavity ageing

The GRACE-C mission is planned to operate for at least five years, with previous missions operating for 10–15 years. Long-term stability of this FSR technique is therefore crucial and has not previously been demonstrated.

To investigate the long-term stability of the FSR readout, semiregular spot-check measurements were taken between April 2023 and October 2025. The data shown in Figure 4 show the laser frequency determined by measuring the beatnote of the cavity-stabilized laser with an iodine-referenced laser, as well as the measured cavity FSR over a subset of this time. The FSR measurements have been converted to absolute laser frequency by multiplying the FSR by the mean mode number (145 652.8116), calculated by dividing the laser frequency by the measured FSR for N measurements.

The data are closely fitted over this period using a function that includes an exponential and a linear term as [21,22]: $f(t) = -0.942 \text{ MHz} \times \exp(-t/55 \text{ days}) + 7.30 \text{ kHz/day} \times t + 281.629\,735\,554\,601 \text{ THz}$.

The lower plot in Fig. 4 shows the residuals of the laser frequency measurement with respect to the fitted curve in blue, and the residuals between the laser frequency and the FSR measurements (converted into laser frequency) in red. The residuals of the laser frequency measurement with

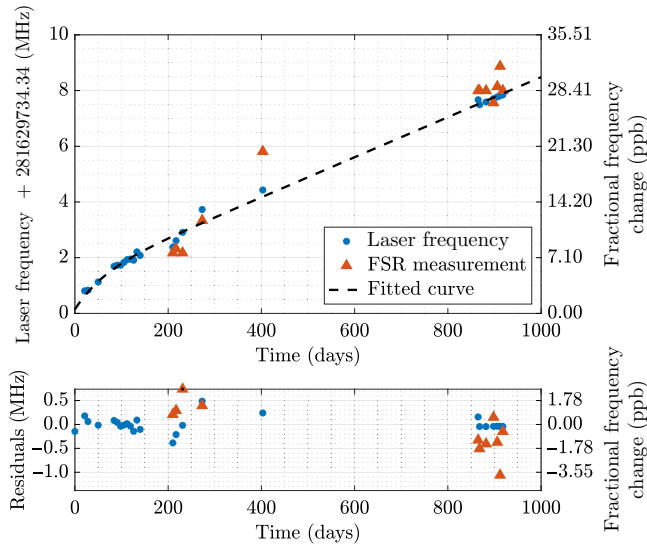


FIG. 4. Laser frequency measurements taken between April 2023 and October 2025, comparing the laser with an iodine referenced laser (blue). The cavity FSR measurements are also plotted (in red), converted to laser frequency by the mean calculated mode number, 145 652.8116. Finally, the function $f(t) = -0.942 \text{ MHz} \times \exp(-t/55 \text{ days}) + 7.30 \text{ kHz/day} \times t + 281.629\,735\,554\,601 \text{ THz}$ is also plotted. The lower plot shows the residuals. In blue is the residual between the laser frequency measurement and the fitted model. In red is the residual between the laser frequency measurement and the converted FSR measurement. The right-hand axes convert the absolute frequency into a fractional frequency in parts per billion.

respect to the fitted model show a maximum deviation of 0.5296 MHz and a standard deviation of 0.171 MHz. The errors in the laser frequency measurement are likely composed of residual amplitude-modulation errors caused by alignment errors through the iodine cell resulting in frequency shifts, as well as residual amplitude modulation generated by the EOM itself [23].

The residuals of the laser frequency measurement and the converted FSR measurement have a maximum deviation of 1.383 MHz and a standard deviation of 0.6395 MHz. The errors in the SFU measurement are likely due to residual spurious etalons in the optical path between the EOM and the cavity and calibration errors in the IQ modulation signal generated by the development SFU. Both of these cause residual amplitude modulation, resulting in dc offsets and offsets to the zero-crossing point of the error signal.

B. Etalon limitations

Parasitic or spurious etalons are a concern in any laser-stabilization scheme [24]. As the FSR readout is scaled by the mode spacing, any errors or limitations seen in a PDH readout appear approximately 150 000 times larger

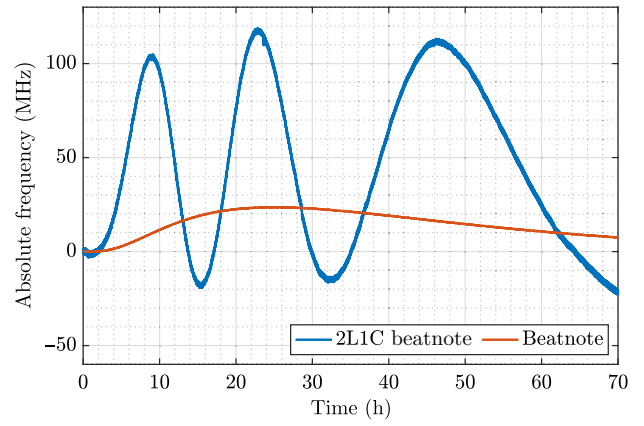


FIG. 5. Beatnotes between two lasers locked to adjacent longitudinal modes of the same cavity (2L1C: two lasers one cavity) and with a third independently stabilized laser. The cavity temperature was changed from 20 to 50 °C. The flat cavity mirror substrate (ULE glass) refractive index has a temperature coefficient of $10.68 \times 10^{-6}/\text{K}$ which, for a temperature change of 30 K, corresponds to an effective length change of 4.05 μm , and would result in the observed etalon response in the 2L1C beatnote.

in the FSR readout, making this error source particularly problematic for this measurement scheme. An initial temperature step of the optical cavity showed a clear spurious etalon in the FSR readout measured by tracking the beatnote of two lasers locked to adjacent cavity modes (referred to as 2L1C: two lasers one cavity). The data, recorded over approximately 3 days, are shown in Fig. 5, along with a beatnote with an independently stabilized laser. These data were taken in July 2022, before the long-term trend in Fig. 4 began.

Characterization of the etalon and investigation of possible contributors identified that the cavity mirror substrates' temperature-dependent change in refractive index had a corresponding change in length that matched the observed etalon behavior. As delivered, the cavity had plano-plano mirrors. Calculations showed that wedging of the cavity mirrors by the standard 0.5° would sufficiently angle the wavefronts to reduce the visibility of the spurious etalon by a factor of 1×10^6 .

The cavity was reworked to have 0.5° -wedged mirrors before being reintegrated into the test configuration and the temperature step was repeated, giving the data shown in Fig. 8, where the FSR readout closely tracks the independent reference laser. This performance confirms that a standard 0.5° wedge angle on both cavity optics was able to eliminate the temperature-induced etalon effects discussed above, demonstrating that an industry-standard wedge angle is sufficient to achieve the required performance.

The error due to spurious back-reflections can be determined quantitatively using the usual error-signal

derivation [20,25]. The cavity discriminant or error-signal slope, D , is proportional to the laser input power, as follows:

$$D \sim \frac{2\mathcal{F}P_{\text{in}}}{\nu_{\text{FSR}}} \quad (\text{W/Hz}), \quad (2)$$

where $\mathcal{F}$ is the cavity finesse, P_{in} is the laser input power, and ν_{FSR} is the cavity free spectral range.

For a finesse of 10 000, an input power of 100 μW , and an FSR of 1.93 GHz, the discriminant is $1.034 \times 10^{-9} \text{ W/Hz}$.

The power in the spurious etalon is also proportional to the laser input power and the return loss ϵ :

$$P_{\text{AM(peak)}} = 2\sqrt{\epsilon}P_{\text{in}} \quad (\text{W}). \quad (3)$$

The maximum frequency deviation due to a spurious etalon compared to the discriminant is therefore

$$\nu_{\text{offset}} = \frac{P_{\text{AM(peak)}}}{D} = \frac{\sqrt{\epsilon}\nu_{\text{FSR}}}{\mathcal{F}} \quad (\text{Hz}). \quad (4)$$

From this equation, we can see that the sensitivity to etalons is directly proportional to the cavity free spectral range and the square root of the return loss (ϵ), and inversely proportional to the cavity finesse.

The etalon's peak-to-peak amplitude can be equated with the error-signal amplitude, giving the power reflectivity required to generate the spurious etalon:

$$\epsilon = \left(\frac{D\nu_{\text{offset}}}{2P_{\text{in}}} \right)^2 = \left(\frac{\mathcal{F}\nu_{\text{offset}}}{\nu_{\text{FSR}}} \right)^2. \quad (5)$$

This equation can be used to determine the maximum allowable return loss to give a deviation of a particular tolerable size.

An input power of 100 μW , a frequency deviation (ν_{offset}) of approximately 1 kHz (from Fig. 5, corresponding to an absolute frequency of 150 MHz divided by the cavity mode number of 150 000), and the discriminant as calculated above, gives a scatter reflectivity of 27 ppm. The antireflective coating on the optics has a reflectivity of approximately 46 ppm at a wavelength of 1064 nm, which is within a factor of 2 of this estimated scatter.

For future missions, a thorough assessment of all potential etalon paths in the optical components and appropriate mitigation techniques, including wedging of cavity mirrors and angling of optical components, will be necessary to enable an accurate readout of the FSR and thus the laser absolute frequency.

C. Performance with cavity at static temperature

To determine the noise performance of the measurement technique as implemented on the development unit,

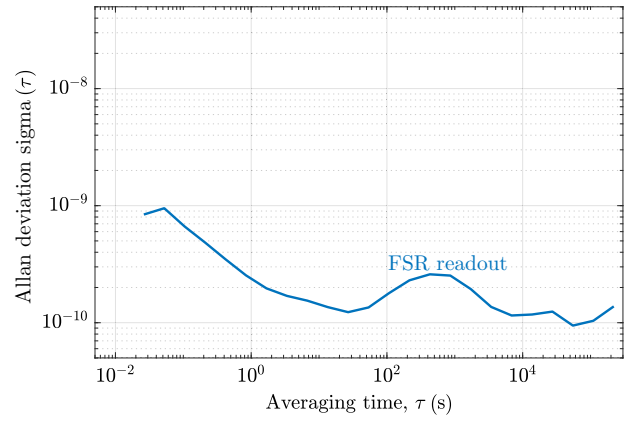


FIG. 6. Allan deviation of the development SFU readout over 12 days. The requirement is expected to apply for averaging periods of 12 h. Figure 7 plots the time series with the expected requirement.

a measurement was taken over 12 days. The laser stayed locked to the cavity for the duration of this measurement, and the cavity temperature was controlled to operate at the zero-crossing temperature (36.74 $^{\circ}\text{C}$). Figure 6 shows these data, presented as an Allan deviation.

The FSR readout was initially sampled at approximately 38 Sa/s. When the data are resampled to 0.038 Sa/s, the time series (Fig. 7) has an absolute peak-to-peak frequency change of 0.9268 MHz, a standard deviation of 0.14 MHz, and an rms value of 0.248 MHz. The requirement is expected to demand rms performance within ± 25 ppb (7 MHz) over a 12-h period.

Analog-to-digital converter (ADC) noise, pickup, and spurious etalons are the primary contributors to the total measurement noise. ADC noise and pickup limit performance at frequencies above approximately 10 MHz, while

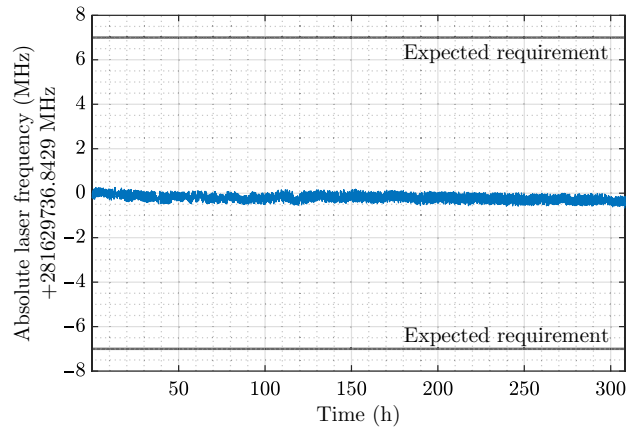


FIG. 7. Time series of the FSR readout data. Data were originally sampled at approximately 38 Sa/s and have been resampled using decimation to 0.038 Sa/s. The expected requirement at ± 7 MHz is also shown.

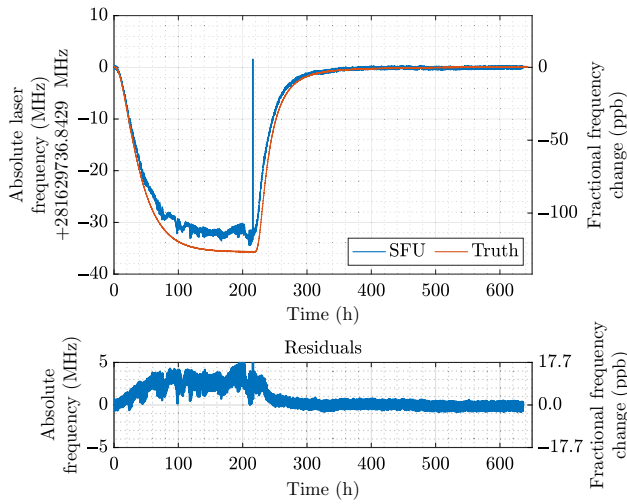


FIG. 8. FSR readout and beatnote recorded as the optical-cavity temperature is changed from 36 to 50 °C and back. The temperature change has induced a corresponding change in both the FSR readout and the beatnote as measured against an independently stabilized laser (“Truth”). The spike in the upper plot occurred as a result of the PDH laser controller being deliberately reset after 9 days to ensure measurement continuity. When reset, the GHz tones are no longer resonant and the FSR readout goes to zero. When the laser controller is re-engaged, the readout returns to its previous position. The lower plot shows the residuals of the two data traces, calculated by subtracting the beatnote from the FSR readout. The mean residual frequency deviation is 0.9061 MHz, with a standard deviation of 1.32.

spurious etalons dominate below 10 mHz. A full analysis of noise sources is provided in Ref. [26].

D. Performance with cavity temperature step

To verify that the FSR readout technique was making a true measurement of cavity mode spacing, a deliberate temperature change was applied to induce a cavity length change. The GRACE missions units, while temperature controlled, do have temperature variations of the order of 20 °C over the life of the mission [1], so it is important to verify the FSR readout technique over a range of temperatures.

With one laser stabilized to the optical cavity using PDH and the SFU reading out the cavity FSR, a deliberate temperature change of 14 °C (from 36 to 50 °C) was applied to the optical cavity’s temperature controller. Once the cavity temperature had stabilized, the temperature was changed back to 36 °C. Figure 8 shows the resulting FSR readout, as well as a beatnote with a secondary independently stabilized laser. There is good agreement between the FSR readout and the beatnote, with the lower plot showing the residuals, calculated by subtracting the beatnote from the FSR readout, which remain within the requirement bounds of ± 7 MHz or 25 ppb. The differences in noise performance after the temperature change could be from a

number of sources. For example, with the SFU operating in open-loop mode, the temperature step offsets the SFU error signal from zero. A nonzero offset of the SFU error signal couples laser intensity variations linearly into the error. For this reason, we are pursuing a closed-loop implementation in upcoming work.

V. CONCLUSIONS

The GRACE-Continuity mission, launching in 2028, will fly an SFU to read out the optical cavity FSR and provide knowledge of the laser’s absolute frequency. This work has advanced the development of the SFU technique by demonstrating, for the first time, compatibility with the mission cavity geometry, and by investigating systematics such as spurious etalons that could limit the performance of the technique. This paper has demonstrated tracking of the laser frequency change due to cavity ageing over 2.5 yr with errors smaller than 1 MHz (3.5 ppb) when compared to an iodine-stabilized laser. This result confirms the core functionality of the FSR readout technique for the SFU.

This work also presents the first results with a path-to-flight development unit, purpose-built to demonstrate compatibility with the GRACE mission. The results achieved show performance better than the requirement, with the rms deviation over a 300 h period being 28 times smaller than the requirement.

The development SFU will undergo further flight-readiness testing, including thermal cycling and shock and vibration tests. A system and performance test, including integration with existing flight hardware, will also be performed. This SFU would also be compatible with other cavity-stabilized laser systems, for example the LISA mission. Although the LISA mission does not have a tight absolute stability requirement, potential benefits from more accurate laser frequency knowledge should be investigated.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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