

Characterizing the phase-tracking limits of the GRACE follow-on flight laser

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(Received 20 January 2025; revised 30 April 2025; accepted 20 June 2025; published 8 July 2025)

The Gravity Recovery and Climate Experiment–Follow On (GRACE-FO) mission measures changes in the Earth’s gravitational field using intersatellite microwave and laser links. The received optical power at which these laser links operate robustly constrains mission parameters, such as spacecraft separation, optical beam divergence angle, and technical noise requirements. This work optimizes the phasemeter, a critical component of the link, for low-received optical power phase-tracking of the GRACE-FO flight spare laser. Experimental measurements and analytical modeling demonstrated that interferometric links using the GRACE-FO flight spare laser can be tracked down to 200 femtowatts (60 dB Hz), ten times lower than the 70-dB-Hz signal strength budgeted for the GRACE-FO laser link. Operating at this level affords an increase by a factor of 3.16 in the separation, divergence angle, or relaxation to technical noise requirements over current GRACE-FO design settings.

DOI: [10.1103/q62l-3684](https://doi.org/10.1103/q62l-3684)

I. INTRODUCTION

Intersatellite interferometers enable critical measurements unattainable using ground-based sensors. The Gravity Recovery and Climate Experiment–Follow On (GRACE-FO) mission monitors the Earth’s mass distribution, tracking global ice mass and groundwater movement [1–3]. GRACE-FO uses intersatellite microwave and laser links to detect nanometer changes in spacecraft separation over hundreds of kilometers, with the laser link included as a technology demonstrator. The GRACE-FO laser ranging instrument demonstrated displacement tracking with 10 times the precision of the microwave link, motivating next-generation Earth geodesy missions, such as GRACE-C (formerly the Mass Change Mission) [4] and the Next Generation Gravity Mission [5,6], to operate exclusively with laser links. Optical links offer improved precision over their radio counterparts due to their shorter wavelength but suffer greater divergence loss in transmission. Across the 220-km separation of GRACE-FO, the optical link suffers 70 dB of loss, resulting in some 2 nanowatts of light being captured at the far satellite [3].

Spacecraft separation is tracked by measuring the change in phase of the heterodyne interference signal between the incoming laser light and a local reference field. The incoming light must be bright enough for the intersatellite ranging system to recover the interferometric phase accurately. When the received optical field is too weak, the phasemeter, a digital system used to track interferometric phase changes, exhibits behavior that corrupts the geodesy measurement. The minimum signal strength requirement set for the GRACE-FO mission to guarantee robust phase-tracking is a carrier-to-noise density ratio of 70 dB Hz: 2 picowatts of input signal in shot-noise-limited detection [7]. This value constrains mission design parameters such as intersatellite separation, optical beam divergence angle, and noise contributions of nonshot-noise-additive sources (electronic noise and laser relative intensity noise). Increasing phasemeter operation robustness in tracking lower-power signals opens up new mission design spaces, increases margins for current missions, and relaxes requirements on other technical noise sources.

The phasemeter is a digital feedback loop that abstracts the phase information from the heterodyne signal (typically megahertz frequency [8] but also possible with dc-centered carriers [9]) for transfer to ground stations [8,10]. When the carrier-to-noise density ratio of the input signal is low, the phasemeter begins to cycle-slip, reporting integer jumps in the measured phase signal relative to the true phase [11]. Cycle slips corrupt the science measurement being performed with the instrument; their onset

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defines the minimum optical power level of the GRACE-FO mission, motivating study of low-optical-power phase-tracking [12–17]. A publication by the authors presented a method for optimizing phasemeter performance for low-optical-power tracking, demonstrating robust phase-tracking of a single femtowatt optical field between two independently stabilized lasers [17]. The work experimentally demonstrated that the minimum optical power at which an interferometric link can operate depends on the parameter tuning of the phasemeter and the frequency dynamics of the signal being tracked. For a transponder-type mission, like GRACE-FO, the signal dynamics of the link are dominated by the free-running laser noise [18].

This paper performs a series of phase-tracking measurements and phasemeter optimizations with the GRACE-FO flight spare laser, a laser with free-running performance representative of that onboard the GRACE-FO mission. Experimental measurements were combined with analytical models to explore the change in tracking error and cycle-slip rate as a function of the phasemeter’s bandwidth (sometimes also called the unity gain frequency). Using the results, the bandwidth was optimized for a 200-femtowatt signal, which was then tracked for 24 h without the phasemeter cycle-slipping. The measurements optimize phasemeter unity gain frequency and explore the minimum trackable optical power of the laser. Section II outlines the experimental system used to perform the phase-tracking measurement. Section III presents the measurements and

findings. Section IV discusses the implications of the findings for intersatellite interferometer design.

II. EXPERIMENTAL SYSTEM

Figure 1 displays the experimental system used to explore phasemeter performance tracking the flight representative laser. Two 1064-nm-wavelength lasers were used, the GRACE-FO flight spare laser (TESAT 25 mW NPRO) and a reference laser (Lumentum 25 mW NPRO 125), selected to have lower laser frequency noise than the flight spare laser in the band of 1 Hz to 10 kHz. Figure 2 displays the frequency amplitude spectral densities of the interference beatnote between the flight spare laser and the reference laser (red), and the reference laser with a second Lumentum NPRO 125 (blue), demonstrating that the laser frequency noise of the reference laser was below that of the flight spare laser. The carrier frequency of the reference laser was offset from the flight spare laser by 10 MHz.

Light from both lasers was passed through isolators and attenuated before being ported into an enclosed fiber test bed (pictured in Fig. 1). In the test bed, the light from the flight spare laser was split unevenly at a ratio of 99 to 1 to produce a bright field and a weak field. The weak field was further attenuated with a variable optical attenuator and a voltage-controlled optical attenuator. Light from the reference laser was split evenly and interfered with the bright and weak fields of the flight spare laser on two Insight

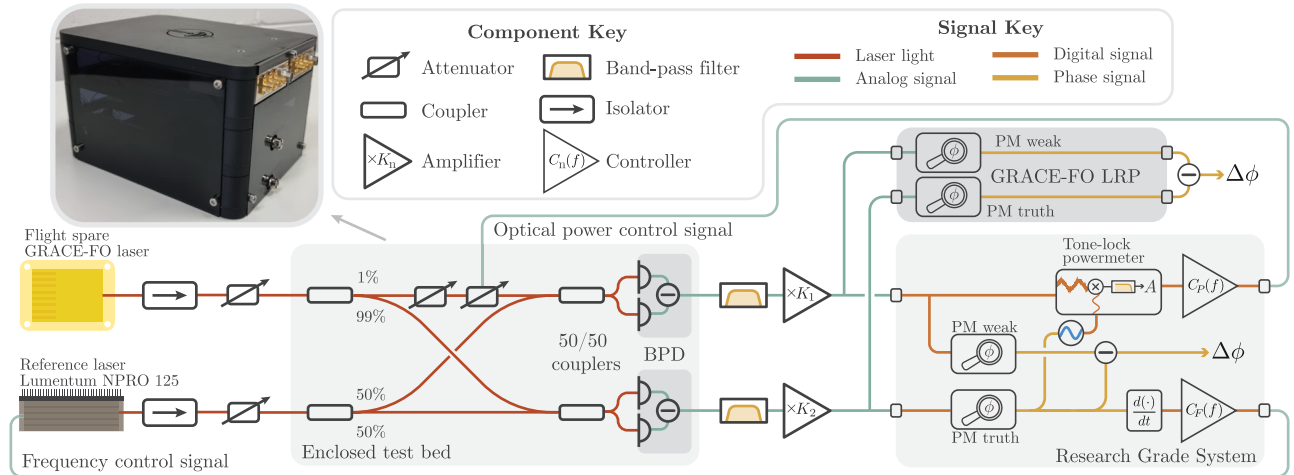


FIG. 1. Experimental system used to optimize phasemeter tuning for the GRACE-FO flight spare laser. Light from the GRACE-FO flight spare laser and a low-noise reference laser (Lumentum NPRO 125) was attenuated and passed into an enclosed test bed (pictured). The test bed split, attenuated, interfered, and detected the input fields at two balanced photodetectors (BPD) to produce two oscillating-voltage signals with the same phase information but different carrier-to-noise density ratios. The weak signal (top path) and truth signal (bottom path) were filtered and amplified before being digitized and passed into two digital systems: a research-grade filed programmable gate array running highly reconfigurable phasemeters and other control loops to support the experiment, and the GRACE-FO laser ranging processor (LRP). In both systems, the two signals were tracked using two independent phasemeters. The weak phasemeter (PM weak) unity gain frequency was varied to explore performance, while the truth phasemeter (PM truth) was held at 60 kHz to track the high-strength truth signal. Slow feedback loops were implemented on the research-grade system to suppress fluctuations in weak field optical power and keep the offset frequency between the two lasers around 10 MHz.

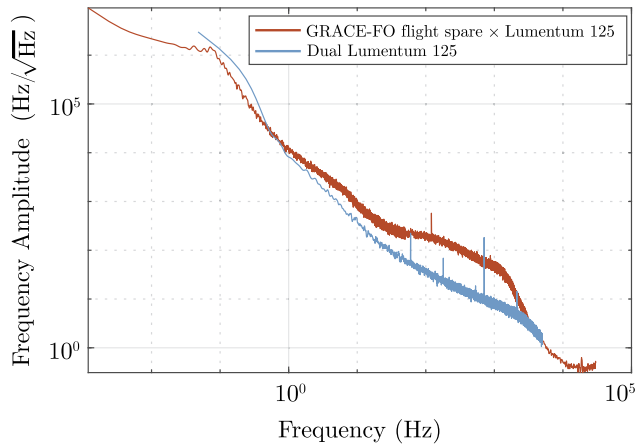


FIG. 2. Frequency amplitude spectral densities of the beat-note between the GRACE-FO flight spare laser and a Lumentum NPRO 125 laser (red) and two Lumentum NPRO 125 lasers (blue). The frequency noise of the flight spare laser is higher than the Lumentum NPRO in the band of 1 Hz to 50 kHz.

BPD-400 balanced photodetectors, producing a weak signal and a bright signal. The phase information of the two detected interference signals was dominated by the same laser phase noise. The weak signal was used to explore phasemeter performance, while the bright signal was used to make a robust high signal-to-noise ratio measurement, which is used as a truth measurement.

The voltage outputs of both detectors were band-pass-filtered with a pass range of 6.7 MHz to 20 MHz [19] before amplification, with the weak signal amplified by a gain of $\times 125$ and the reference signal $\times 25$. The resulting voltage signals were split and digitized by two field programmable gate array (FPGA) systems: GRACE-FO engineering model laser ranging processor (LRP) [10], a system running a clone of the GRACE-FO flight phasemeter and using representative hardware of the GRACE-FO flight model LRP, and a research-grade National Instruments FPGA system. The research-grade system was used to experimentally determine the optimal phasemeter tunings for low-optical-power tracking, while the GRACE-FO LRP was used to demonstrate the stability of the discovered phasemeter parameter tunings. The research-grade system consisted of an NI-5782 ADC card and an NI-7935R FPGA.

On both systems, two phasemeters were implemented to track the phase of the weak and truth signals. The unity gain frequency of the weak phasemeter (PM weak) was varied between 5 kHz and 50 kHz to explore tracking performance, while the reference phasemeter (PM truth) was held at a constant unity gain frequency of 60 kHz to track the high carrier-to-noise ratio reference field. For both phasemeters, the controllers consisted of proportional, single-integration, and double-integration components. The first integrator was tuned to cross the

proportional component, a factor of 10 below the unity gain frequency, and the second-order crossing was tuned a factor of 10 below that, as described in [17]. The phase measurements of the two phasemeters were different, producing a signal dominated by the tracking error in the weak phasemeter.

Two control loops were also run on the research-grade system to aid the experiment. The first, an optical power control loop, stabilized the optical power of the weak field. Power measurement of the weak field was made using a tone lock power meter [17]. This power measurement was used to generate an error signal and fed back to the voltage-controlled optical attenuator in the enclosed test bed. The unity gain frequency of the optical power control loop was 1 Hz, stabilizing slow drift in weak field optical power to approximately $\pm 5\%$. The second control loop, slow frequency control of the reference laser, kept the interference frequency within the operational bandwidth of the system (6.7–20 MHz, similar to the operational bandwidth of GRACE-FO). The unity gain frequency of the frequency control loop was about 0.1 Hz and kept the beat note frequency within ± 1 MHz of the lock point. The additional laser frequency noise suppression provided by this feedback loop had negligible impact on the results presented in Sec. III, as the loop unity gain frequency was significantly lower than the phasemeter bandwidths explored.

III. MEASUREMENTS AND RESULTS

The first measurement swept the weak phasemeter bandwidth (unity gain frequency) and measured the phasemeter tracking error and cycle-slip rate. Figure 3 (top) shows the phase difference between the weak and reference phasemeter measurements for optical power levels of 100 femtowatts (red) and 200 femtowatts (blue). Also plotted are analytical models for the phasemeter tracking error, as presented in [17], but with the measurement of laser frequency noise from Fig. 2 used for the laser frequency noise contribution. When the phasemeter unity gain frequency was lower than optimal tuning to minimize tracking error, the tracking error was dominated by untracked laser frequency noise. When the phasemeter unity gain frequency was higher than the optimal value, the tracking error was dominated by shot-noise-driven phase noise within the tracking band. Between these two regimes existed an optimal phasemeter unity gain frequency that balanced the contributions from both sources to minimize the tracking error. For the 100-femtowatt and 200-femtowatt optical signals, the analytical solutions for the optimal unity gain frequencies to minimize tracking error were 10.5 kHz and 14.5 kHz, respectively. The experimental measurements demonstrated consistency with these models.

Figure 3 (bottom) shows the observed cycle-slip rate as a function of unity gain frequency for the 100-femtowatt power optical signal, indicated by crosses. For the unity

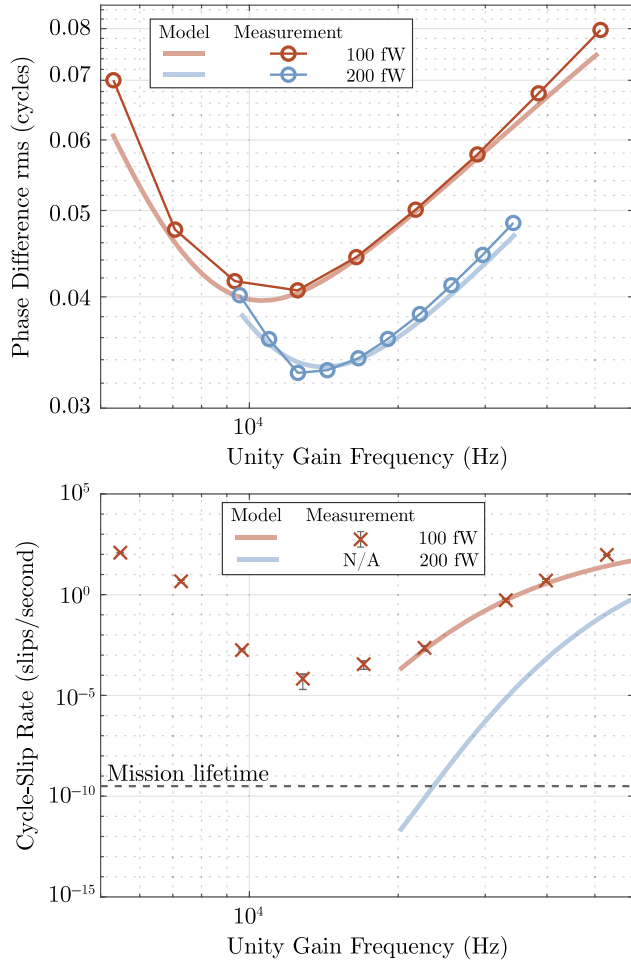


FIG. 3. Phasemeter tracking performance as a function of unity gain frequency for the GRACE-FO flight spare laser. Measurements were performed with the research-grade system. The top plot shows the root-mean-square (rms) of the phase difference, $\Delta\phi$ from Fig. 1, for a 100-femtowatt optical field (red) and a 200-femtowatt optical field (blue). Analytical models show the optimal unity gain frequencies for the 100-femtowatt and 200-femtowatt cases are 10 kHz and 14.5 kHz, respectively. The bottom plot shows the cycle-slip rate as a function of unity gain frequency for a 100-femtowatt optical field (red). No cycle-slip rates are presented for the 200-femtowatt case, as no cycle slips were observed within the measurement period. Error in cycle-slip rate estimated using Bayesian inference of Poissonian statistics [20]. Models for the cycle-slip rate from Viterbi *et al.* [21], Eq. (3) in [17], only valid in additive noise-dominated tracking.

gain frequencies explored here, the cycle-slip rates for the 200-femtowatt signals were too low to observe cycle slips within the measurement period. In the shot-noise-dominated regime, a model from Viterbi *et al.* [21], Eq. (3) in [17], for cycle-slip rates in phase-locked loops dominated by additive noise is also plotted for both 100-femtowatt and 200-femtowatt optical signals, indicated by the solid lines. The phasemeter unity gain frequency that minimized tracking error for the 100-femtowatt signal also

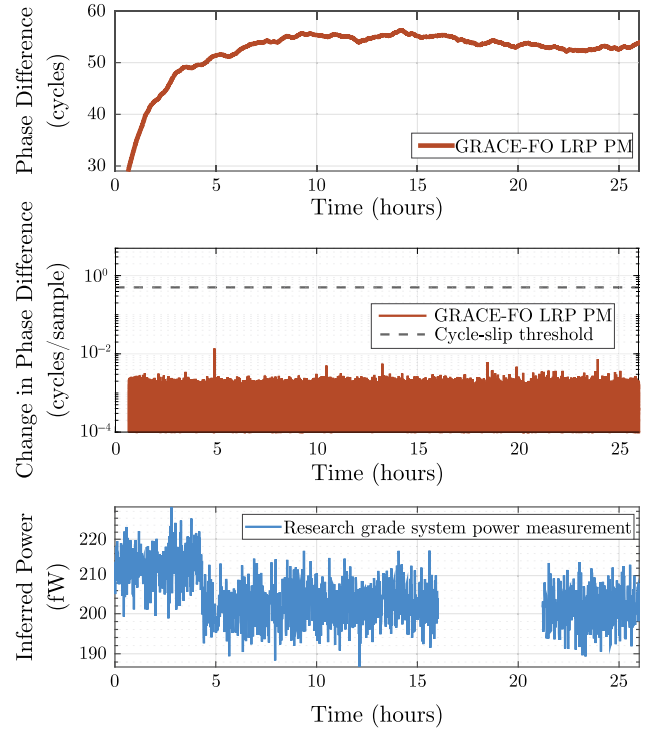


FIG. 4. Twenty-four-hour cycle-slip-free tracking of a 200-femtowatt optical field. Tracking was performed with phasemeters implemented on the GRACE-FO engineering model LRP (red), with weak-field phasemeter unity gain frequencies tuned to 16 kHz. The top plot shows the tracking error between the weak field and the reference field. The middle plot shows the change in the tracking error of the GRACE-FO LRP, a measurement used to inspect for cycle slips, which are characterized by a phase change less than 0.5 cycles per sample: none are present. The bottom plot shows the inferred optical power of the weak field measured across the time period. The gap in the research-grade system power measurement was due to data-saving limitations; the optical power control loop stayed locked through the entire period. The change in power at 4 h was due to the lock point being manually adjusted.

produced the lowest cycle-slip rate, at 6.7×10^{-5} slips per second. In the laser- frequency-dominated regime (unity gain frequencies below 10 kHz), the phasemeter cycle-slipped and lost lock of the signal significantly more than in shot-noise-dominated tracking (unity gain frequencies above 10 kHz) with the same tracking error. As such, the authors preferred to tune the phasemeter unity gain frequency to be slightly higher than the value that minimized tracking error to ensure the tracking error was dominated by the shot-noise contribution. The shot-noise-dominated model of the 200-femtowatt case suggests that, with a unity gain frequency of 16 kHz, the average cycle-slip rate will be less than one slip per 5 years, the lifetime of the mission.

To demonstrate the stability of the proposed phasemeter tuning, cycle-slip-free phase-tracking of an approximately 200-femtowatt optical signal was performed for 24 h. The

measurement used two phasemeters implemented on the GRACE-FO engineering model LRP [10]. The unity gain frequency of the phasometer tracking the 200-femtowatt field was tuned to 16 kHz, and the system was left to track for 24 h. Throughout this period, the research-grade system slow control loops were active. Figure 4 displays the tracking performance of the GRACE-FO LRP phasometer tracking an approximately 200-femtowatt signal. The top plot shows the cycle-slip-free phase difference between the two phasemeters implemented on the GRACE-FO LRP (red line). The phase difference between the weak and truth phasometer phase measurements places an upper bound on the weak phasometer tracking error. Over long timeframes, the phase difference was dominated by environmentally driven fluctuations in fiber path length rather than the phasometer dynamics. The phasometer noise floor has been verified to be significantly below the observed level [10]. The middle plot shows the change in the phase difference between samples (red line). Cycle slips in the weak phasometer would appear in this signal as differential phase error values greater than 0.5 cycles per sample (broken black line) [22], indicating sudden jumps in the tracking error. The phase difference change displays no such jumps, indicating that no cycle slips were detected in the GRACE-FO LRP weak phasometer tracking across the 24-h measurement. The bottom plot shows the optical power of the weak field (blue line), as measured by the research-grade system. The measurement shows that the weak field optical power had a mean value of 212 femtowatts until the 4-h mark, at which time the optical power lock point was adjusted, and a mean value of 202 femtowatts from 4 h to 25 h. Breaks in the data were due to the research-grade system resetting data capture, as its higher capture rate caused it to fill files. The LRP tracking measurement, slow frequency feedback, and optical power stabilization were uninterrupted over the 24-h measurement.

IV. IMPLICATIONS FOR INTERSATELLITE GEODESY

This section discusses the potential benefits to intersatellite geodesy missions afforded by the findings of this work. The GRACE-FO LRP was designed to operate down to

a carrier-to-noise density ratio of 70 dB Hz per channel. During initial operation, the observed total carrier-to-noise ratio (sum of the four channels) in GRACE-FO was 88 dB Hz [3], resulting in approximately 82 dB Hz in each channel. With the phasometer parameter tuning proposed here, the GRACE-FO LRP demonstrated robust tracking of a shot-noise-limited optical field of approximately 200 femtowatts: a carrier-to-noise density ratio of 60 dB Hz. This level is 10 dB below the carrier-to-noise density requirement of GRACE-FO and 22 dB below the observed carrier-to-noise density ratio during initial operation. The phasometer bandwidth tuning presented here enables various design changes that benefit the science measurement, ease acquisition, and relax mission constraints. For this work, we explore a 10-dB carrier-to-noise density ratio relaxation as a point of reference. The parameter changes afforded, outlined in Table I, leverage the relaxed carrier-to-noise density ratio requirement by 10 dB but maintain the current margins over the requirement. Further relaxation in nontransponder mission configurations could be explored as in Ref. [18].

Requirements on received power constrain multiple mission design parameters, such as the intersatellite separation and optical beam divergence. Increasing satellite separation to 900 km may increase point mass sensitivity by a factor of 2.5 [23], but result in increased optical loss due to beam divergence. The phasometer parameter tuning described here would enable missions to tolerate the additional optical loss in increasing the arm lengths by a factor of 3.16 over the maximum GRACE-FO armlength specification (270 km), extending armlengths to 853 km. Larger beam divergence angles simplify mission design, relax satellite pointing requirements, and reduce acquisition times. The divergence half angle of the GRACE-FO mission of 140 microradians could be increased to 440 μ rad while maintaining the mission's current margins. The results of this work could instead be used to relax requirements on GRACE-FO laser ranging instrument components. While the output optical power of the laser could be reduced by a factor of 10, a redesign of the GRACE-FO optical bench would be required to maintain sufficient optical power in the reference field used in heterodyne detection. The improvements in low-power

TABLE I. Relaxed mission parameters afforded by the phasometer tuning proposed here relative to GRACE-FO current parameters. The “GRACE-FO spec” column states the value of each parameter in the GRACE-FO mission. The “individual parameter relaxations afforded” column displays how much any one parameter can be relaxed while maintaining the current mission design margins after reducing the minimum trackable carrier-to-noise density ratio from 70 dB Hz to 60 dB Hz. Simultaneously relaxing the three parameters by the amounts shown is not possible. Smaller concurrent relaxations to the three parameters can be made, but the impact on the measurement carrier-to-noise density ratio must be balanced to still meet the 60-dB-Hz requirement.

Parameter	(GRACE-FO spec)	Individual parameter relaxations afforded
Spacecraft separation	(270 km [1])	853 km
Beam divergence	(140 μ rad [3])	440 μ rad
Tx laser power	(20 mW [3])	2 mW

tracking may instead be applied to relax technical noise requirements, such as electronic noise and laser relative intensity noise. The optical power improvement demonstrated here is equivalent to increasing the dominant noise source present in nominal GRACE-FO operation by a factor of 3.16, enabling the application of smaller size, weight, power, and cost lasers and photodetectors.

V. CONCLUSIONS

Interspacecraft interferometric link design is constrained by the minimum optical power at which robust measurement can be made. In Earth geodesy missions, such as GRACE-FO, the requirements on received optical power levels are set by the phasemeter. This work has performed a series of measurements with the GRACE-FO flight model laser to determine optimal phasemeter parameter tuning for low-optical-power tracking in the GRACE-FO mission. Experimental measurements determined that to minimize tracking error for optical signal strengths of 100 and 200 femtowatts, the required phasemeter unity gain frequencies are 10.5 kHz and 14.5 kHz, respectively. Under this optimal unity gain frequency tuning for a 100-femtowatt signal, a mean cycle-slip rate of 1 cycle slip every 4.1 h was observed. A phasemeter implemented on the GRACE-FO engineering model LRP with a unity gain frequency of 16 kHz was used to track a 200-femtowatt signal continuously for 24 h. In this period, no cycle slips were observed.

The findings of this work illustrate that the phasemeter tuning identified decreases the minimum carrier-to-noise density ratio requirement of the mission by 10 dB to 60 dB Hz. This enables GRACE-FO-like missions to operate at separations up to a factor of 3.16 larger (out to 853 km) or with an optical divergence angle a factor of 3.16 greater (up to 440 μ rad) while maintaining current mission design margins. These results enable future missions to be designed with longer arm lengths, larger beam divergence, or relaxed laser or technical noise requirements.

ACKNOWLEDGMENTS

ANU researchers were supported by the Australian Research Council Centre of Excellence for Engineered Quantum Systems (EQUS, CE170100009) through the Translational Research Program and the Australian Research Council Centre of Excellence for Gravitational Wave Discovery (OzGrav, CE230100016). K.M.'s contributions are partially funded by the SmartSat CRC supported by the Australian Government. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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