

Dual-quadrature phasemeter for space-based interferometry

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This letter presents a dual-quadrature phasemeter, an implementation of a phase-locked loop designed to track the phase of homodyne and heterodyne intersatellite laser links. Dual-quadrature phasemeters use dual-quadrature optical detection to enable an alternate phase readout scheme that operates with wider bandwidths and on signals with carrier-frequency differences down to dc. Analytical modeling demonstrates that dual-quadrature phasemeters overcome the bandwidth limitations of conventional phasemeters. Numerical simulations of noise linearity tests found that the phase-tracking error of the dual-quadrature phasemeter is less than $10 \text{ microcycle}/\sqrt{\text{Hz}}$ in the presence of nonlinear cyclic errors. The dual-quadrature phasemeter enables exploration of an optical configuration for retroreflector-based space geodesy missions with architecture similar to that implemented in the Gravity Recovery and Climate Experiment Follow-On mission. One such alternate configuration is proposed that is capable of tracking satellite separation without requiring a frequency offset between local and incoming light, eliminating the need for optical frequency shifters.

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I. INTRODUCTION

Phase-locked loops (PLLs) are control loops that enable real-time phase measurement of an oscillating signal. PLLs are widely used across modern electronics, including in wireless and optical data communications, clock synchronization, and frequency synthesis [1,2], largely due to their simplicity in implementation and versatility in application. PLLs have found further application in the field of optical metrology, where they are used to track phase changes in the interference between optical fields [3] and phase-lock optical sources. The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission is one such example, where intersatellite laser links spanning 200 km are tracked with a phasemeter, a digitally implemented phase-locked loop, to measure changes in the Earth's ice mass and groundwater movement [4,5]. The phasemeter is uniquely suited to the extraction of phase information from weak-amplitude and high-frequency carrier signals on device, converting the mission data into a form that can be practically transferred to Earth [3].

Phasemeters place design constraints on future Earth geodesy missions. One example is an alternate optical configuration proposed for the European Space Agency's

Next Generation Gravity Mission (NGGM), named the retroreflector configuration [6], in which the optical payload of one satellite is replaced by a retroreflecting optic. This architecture simplifies optical design but brings with it several technical challenges. Double passing the optical link results in the divergence loss being incurred twice, making it challenging to meet received optical power requirements set by the phasemeter. Previous research undertaken by the present authors, however, has shown that the optical power requirements of retroreflector configurations are lower than those of active transponder configurations, making these losses tolerable [7]. In the retroreflector configuration, science measurement is made by interfering the return light with local light from the same laser, resulting in a dc-centered interference frequency that varies with intersatellite Doppler shifts ($\pm 1 \text{ MHz}$). This signal is not suitable for standard phasemeter tracking, as the carrier frequency is outside the phasemeter's specified frequency input range (for GRACE-FO, 4–16 MHz [5]). When the carrier frequency of the tracked signal falls below the internal filter corner frequency of the PLL, upshifted harmonics from the internal mixer dominate the phase output, corrupting measurement. Retroreflector designs accommodate this requirement by including a frequency shifter, making such designs incompatible with the current GRACE-FO optical bench [6].

While traditional PLLs are not suited to tracking the phase of dc-centered signals, feedback-loop-based phase estimators for optical homodyne architectures have been developed in the field of optical communications. Taylor [8,9] presented a phase-estimation loop that used a 90°

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hybrid detection scheme to interrogate both quadratures of the incident optical field for demodulation of information encoded via phase-shift keying. Taylor's scheme has since been proposed in ground-satellite optical communication schemes [10]. Sutton *et al.* [11] applied a variant of the same concept in the context of homodyne digital interferometry, where a homodyne PLL used a coordinate rotation digital computer (CORDIC) arctangent algorithm and feedback combined to measure displacement with a noise floor of $0.8 \text{ pm}/\sqrt{\text{Hz}}$.

In this letter, we present a dual-quadrature phasemeter, a form of homodyne PLL designed for phase metrology in homodyne and heterodyne systems. This implementation leverages dual-quadrature optical detection to modify the internal structure of the PLL. Dual-quadrature phasemeters have two key advantages over heterodyne phasemeters. Specifically, they can track (1) with a larger bandwidth than equivalent heterodyne PLLs, and (2) signals with any carrier frequency between the positive and negative Nyquist frequencies of the capture rate. These benefits make them suitable for both homodyne and heterodyne detection schemes and enable tracking of higher-frequency dynamics. An interferometric architecture for future Earth geodesy missions is proposed that leverages the tracking-frequency range of the dual-quadrature phasemeter, resulting in a retroreflector-based mission with a GRACE-FO-like optical bench. The dual-quadrature phasemeter extends the class of optical signals that can be interrogated with real-time phase-tracking techniques.

II. PHASE-LOCKED-LOOP ARCHITECTURE

A. Heterodyne phasemeter

Figure 1(a) shows a block-diagram schematic of a heterodyne phasemeter implemented with a phase-locked loop. Two optical fields are interfered and detected through photodetection. The output voltage signal is digitized,

resulting in a periodic signal with angular frequency ω and phase information $\phi(t)$. The signal is mixed with a digital reference oscillator at the same carrier frequency ω and phase information $\tilde{\phi}(t)$. This operation results in an upshifted component at the sum of the two mixed frequencies and a downshifted component at their difference:

$$\begin{aligned} M_{\text{out}}(t) &= \sin(\omega t + \phi(t)) \times \cos(\omega t + \tilde{\phi}(t)) \\ &= \sin(\phi(t) - \tilde{\phi}(t)) + \sin(2\omega t + \phi(t) + \tilde{\phi}(t)). \end{aligned} \quad (1)$$

For a small difference in phase between the two oscillations, (2) can be approximated as

$$M_{\text{out}}(t) \approx \Delta\phi(t) + \sin(2\omega t + \phi(t) + \tilde{\phi}(t)), \quad (3)$$

where $\Delta\phi(t) = \phi(t) - \tilde{\phi}(t)$ is the phase error between the two input signals. The upshifted component at 2ω is filtered by the in-loop second-harmonic filter, leaving the phase-error term, which is fed back to update the reference oscillator. With insufficient filtering, the upshifted term is also fed back, driving the reference oscillator and compromising measurement. As such, the carrier frequency of the tracked signal, ω , must be sufficiently larger than the corner frequency of the in-loop second-harmonic filter. The in-loop second-harmonic filter cutoff also constrains the maximum stable bandwidth, as the total PLL latency is typically dominated by the delay of the in-loop second-harmonic filter. These restrictions limit the scope of PLL applications in optical tracking to heterodyne sensing architectures with bandwidths below the cutoff frequency of the in-loop second-harmonic filter and interference frequencies above.

B. Dual-quadrature phasemeter

Figure 1(b) shows a block-diagram schematic for a dual-quadrature phasemeter. The interference between two

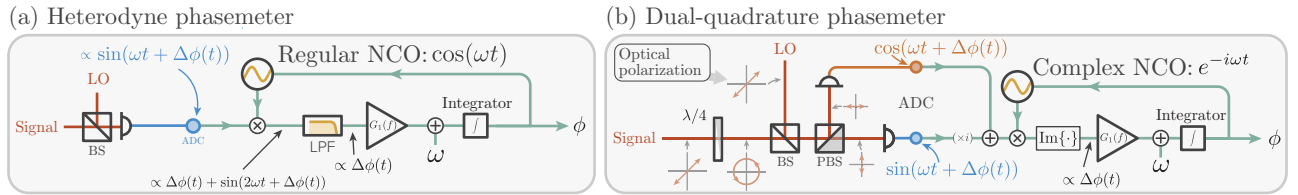


FIG. 1. Block-diagram schematic of heterodyne and dual-quadrature phasemeter. (a) A heterodyne PLL detects the interference between two optical fields and mixes the digitized signal with a reference oscillator consisting of a single numerically controlled oscillator (NCO). Mixing results in an output with upshifted and downshifted components. The higher-frequency component is filtered, and the downshifted component, which is proportional to the phase error between the reference and the input signal, is fed back to update the reference oscillator. (b) A dual-quadrature phasemeter combines the two input optical fields in a dual-quadrature detection scheme that interrogates both quadratures of the interference signal. The quadrature inputs are digitized and combined to form a complex waveform before being mixed with a complex reference oscillator. The output of the complex mixing operation is only proportional to the phase error between the reference and the input, removing the need for an in-loop second-harmonic filter. The error signal is fed back to update the complex reference oscillator.

optical fields is detected using a dual-quadrature detection scheme [9,12–14]. The resulting quadrature components of the detected signal are combined to form a complex input signal. This input signal is then mixed with a complex NCO, seeded at the negative of the input tone carrier frequency, $-\omega$, resulting in a mixer output of

$$M_{\text{out}}(t) = e^{i(\omega t + \phi(t))} \times e^{-i(\omega t + \tilde{\phi}(t))} \quad (4)$$

$$= \cos(\Delta\phi(t)) + i \sin(\Delta\phi(t)), \quad (5)$$

which, for small phase errors, simplifies to

$$M_{\text{out}}(t) \approx 1 + i\Delta\phi(t). \quad (6)$$

The imaginary component of the mixer output is passed through a controller and used to update the reference oscillator. As both components of mixing are complex, we perform single-sideband demodulation, resulting in only a downshifted term proportional to the phase error between the input signal and the reference oscillator. As such, the in-loop second-harmonic filter is no longer required to ensure PLL linearity, removing the aforementioned restrictions it placed on the PLL.

C. Frequency-response comparison

Figure 2 shows a Bode plot for a dual-quadrature phasemeter (red) and two heterodyne phasemeters, with in-loop second-harmonic filter cutoffs of $f_s/40$ (yellow) and of $f_s/1000$ (green). The frequency is given as a proportion of the digital clock rate of the PLLs, f_s . The phasemeter's open-loop gains were modeled as

$$H_\tau(s) = e^{-s\tau} \left(\frac{2\pi f_{\text{ug}}}{s} + 0.1 \times \left(\frac{2\pi f_{\text{ug}}}{s} \right)^2 \right), \quad (7)$$

where $s = i2\pi f$ is the Laplace parameter, f_{ug} is the unity-gain frequency of the phasemeter, and τ is the propagation delay in the phasemeter feedback loop. For a phasemeter with an in-loop second-harmonic filter implemented as a cascade integrator-comb filter, the shortest possible time delay achievable by the loop is $\tau = (N + 1)/f_s$, where N is the decimation rate of the in-loop second-harmonic filter (also the ratio between the in-loop second-harmonic filter cutoff and the PLL update rate, f_s). This analysis assumes that, aside from the delay imposed by the in-loop second-harmonic filter of the heterodyne phasemeter, the total propagation delay in the phasemeter feedback loop is limited to a single clock cycle. This generalization is made to emphasize the decoupling of the in-loop delay from the feedback-loop components.

The controllers of each phasemeter were tuned to maximize the unity-gain frequency while maintaining a 60° phase margin. The unity-gain frequency of the dual-quadrature phasemeter was only limited by the update rate

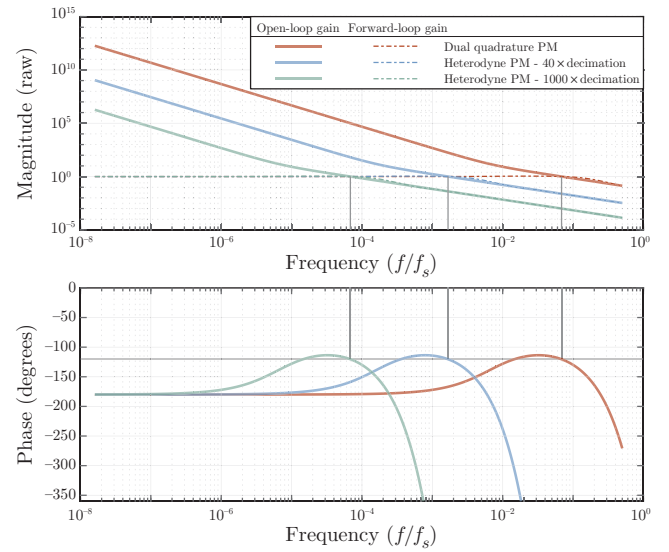


FIG. 2. Bode plots of a dual-quadrature phasemeter and two heterodyne phasemeters with internal filter corner frequencies of $f_s/40$ and $f_s/1000$. The upper plot shows the magnitude, and the lower plot shows the phase of frequency response. The controller gains of the phasemeter are tuned to maximize the unity-gain frequency while maintaining a 60° phase margin. The maximum bandwidth of the two heterodyne phasemeters were constrained by the in-loop second-harmonic filter delay. The dual-quadrature phasemeter bandwidth was only limited by the propagation delay in the feedback loop, enabling it to track signals with higher-frequency dynamics.

of the phasemeter (which in an idealized case is $\tau = 1/f_s$), whereas the maximum unity-gain frequencies of the two heterodyne PLLs are limited by the delay imposed by their in-loop second-harmonic filters. For the heterodyne PLL, the in-loop second-harmonic filter also defines the minimum trackable frequency of the PLL. As such, there is a trade-off between how low a frequency the heterodyne PLL can track and how large a bandwidth it can track. This limitation is not present in the dual-quadrature phasemeter. Higher bandwidths enable the dual-quadrature phasemeter to track signals with higher-frequency dynamics, extending the class of signals it can track beyond the heterodyne phasemeter.

D. Practical implementation

One drawback of dual-quadrature phasemeters over heterodyne phasemeters is their susceptibility to cyclic errors: errors caused by dc offsets or differences in the relative amplitudes or phase of the in-phase and quadrature signal components [12]. Cyclic errors insert unsuppressed upshifted mixing components into the feedback signal, resulting in nonlinear errors in phase measurement. Extensive literature exists on the correction of cyclic errors, as they are present in all quadrature-detection measurement schemes [12,15,16]. Earth geodesy missions require

the contribution of phasemeter nonlinear tracking error to be below $1 \text{ nm}/\sqrt{\text{Hz}}$ [5]. As such, the following numerical simulations explore the performance of the dual-quadrature phasemeter in the presence of static cyclic errors both in isolation and when implemented with a cyclic correction algorithm based on that presented in Ref. [16].

III. LINEARITY TEST

A phasemeter linearity test used by Shaddock *et al.* in Ref. [3], named the three-noise test, was used to explore the phase-tracking performance of the dual-quadrature phasemeter. The three-noise test uses three phasemeters to track numerically generated laser frequency noise and combines the phasemeter measurements to remove the input signals, leaving only the noncommon nonlinear tracking errors. Cyclic errors in the dual-quadrature phasemeter cause harmonics at multiples of the carrier frequency to be modulated onto the internally generated reference, mixing any signals at these frequencies into the phasemeter's measurement. When the carrier frequency of the signal is greater than the bandwidth of the phasemeter, any mixing harmonics caused by cyclic errors are suppressed by the frequency response of the phasemeter. As such, cyclic-induced nonlinear errors worsen when the carrier frequency of the tracked signal is within the phasemeter bandwidth range around dc.

Figure 3 presents a block-diagram schematic of the phasemeter three-noise test. Laser frequency noise was simulated as frequency noise with a $10 \text{ Hz}/\sqrt{\text{Hz}} \times 1 \text{ Hz}/f$ amplitude spectral density. The laser frequency noise was simulated with deliberately low amplitude to keep the tracked beatnotes within the 10-kHz phasemeter bandwidth of dc for the majority of each test, increasing the impact of nonlinear errors on measurement. The carrier frequencies of the three signals were varied between simulations to explore performance in two cases: with the initial beatnote frequency at 1 MHz and with the initial frequency at 0 Hz (dc). The first case is an idealized one, in which the carrier frequency is far from dc. The second case is a more challenging tracking environment, notably, a worse case than Earth geodesy missions, in which intersatellite-induced Doppler shifts pull the carrier frequencies away from dc (between $\pm 1 \text{ MHz}$ for GRACE-FO).

The simulated laser frequency noise was used to generate two quadrature components of the input signal. In signal generation, a constant randomized phase offset (within ± 0.1 cycles), amplitude scaling (within $\pm 10\%$), and dc offsets (within $\pm 10\%$ of amplitude) were included to simulate static cyclic errors. After generation, each signal was passed through a cyclic correction algorithm based on Ref. [16]. After correction, each complex signal was tracked with an independent dual-quadrature phasemeter. The phase outputs of the three phasemeters were linearly

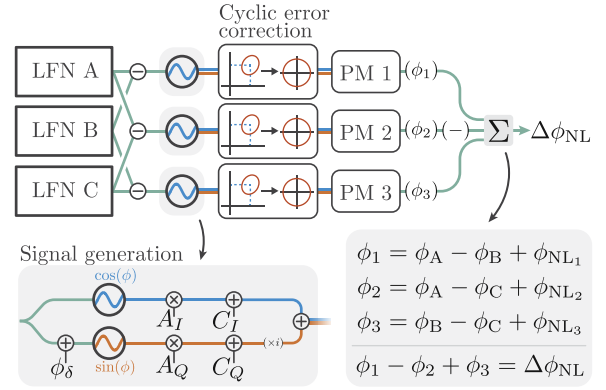


FIG. 3. Phasemeter three-noise test performed with three dual-quadrature phasemeters. Laser frequency noise of $10 \text{ Hz}/\sqrt{\text{Hz}} \times 1/f$ was numerically generated in three separate instances before being combined to form three linearly independent signals. The three signals drove numerically controlled oscillators where cyclic errors were inserted in the form of dc offsets, amplitude mismatches, and phase errors. The complex output signals were fed through a cyclic-error-correction procedure from Ref. [16] to suppress the impact of the inserted cyclic errors. The resulting signals were tracked with three separate dual-quadrature phasemeters, each with a unity-gain frequency of 10 kHz. The outputs of the three phasemeters were combined to determine the total nonlinear tracking error present.

combined to remove the simulated laser phase noise, leaving only nonlinear tracking errors and the tracking noise floor of the phasemeters. Three cases were explored with the simulation:

- (i) **dc cyclic:** dc-centered tracking with cyclic errors and no corrections applied; exploring worst-case tracking error.
- (ii) **dc corrected:** dc-centered tracking with cyclic errors and corrections applied, determining the impact of the corrections on improving measurement.
- (iii) **1-MHz tracking:** 1-MHz-centered tracking with no cyclic errors to provide a baseline for performance in ideal conditions.

Figure 4 displays the results of the three-noise tests: the top panel shows the frequencies of the three signals tracked by the three phasemeters for a single measurement; the middle panel shows the nonlinear phase error (three-noise test output) for the dc-corrected measurement of the signals displayed in the top plot; the bottom panel shows the phase amplitude spectral densities of the three tracked phase signals as well as the residual errors of three different cases.

The tracking performance varied between the three cases explored. The 1-MHz tracking measurement demonstrates that the noise floor of the phasemeter in ideal cyclic conditions is $1 \text{ microcycle}/\sqrt{\text{Hz}}$. This performance

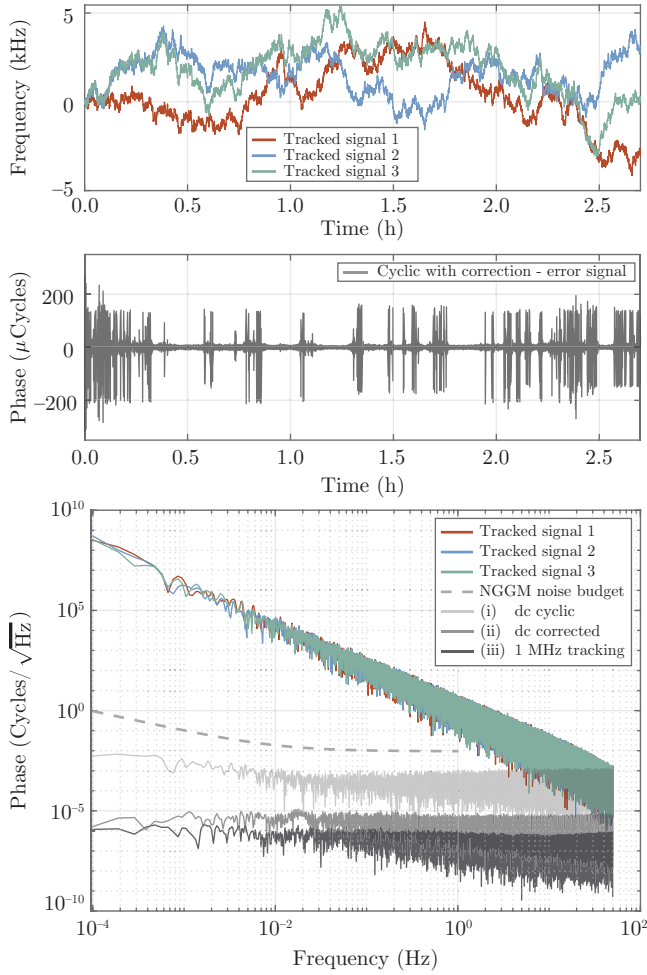


FIG. 4. Results from the phasemeter three-noise test performed on the dual-quadrature phasemeter. Top: tracked frequency signals by the three phasemeters. Middle: nonlinear tracking error for a dc-centered signal with cyclic errors present and cyclic correction active. Bottom: phase amplitude spectral density of the three tracked signals and tracking error for the three cases explored: dc-centered signal with cyclic error (light grey), dc-centered signal with cyclic correction applied (dark grey) and 1-MHz-centered ideal tracked signal (black). The noise level of the dc-centered signal with cyclic corrections present was 30 dB below the NGGM noise requirement [17], demonstrating the initial feasibility for a dual-quadrature-phasemeter-based measurement scheme.

is equivalent to the noise level observed by Shaddock *et al.* [3] in evaluating a phasemeter for the Laser Interferometer Space Antenna (LISA). Introducing cyclic errors into the tracked signal raised the phasemeter noise floor by 3 orders of magnitude relative to the 1-MHz tracking case, and it increased further at frequencies below 10 mHz. With correction, however, the impact of these cyclic errors could be reduced to below $10 \text{ microcycle}/\sqrt{\text{Hz}}$ ($10 \text{ pm}/\sqrt{\text{Hz}}$ with a 1064-nm-wavelength carrier), well below the $1 \text{ nm}/\sqrt{\text{Hz}}$ phasemeter performance requirement for

geodesy missions. The amplitude spectral density (ASD) of the tracking error in the corrected case is largely dominated by spurs of noise that occur when one of the tracked signals is within 100 Hz of dc. This suggests that with either improved cyclic error correction or in an environment where less time is spent within 100 Hz of dc, the phasemeter performance could be further improved. In the case of GRACE-FO, the Doppler-induced frequency shift remains within $\pm 100 \text{ Hz}$ during four 1-s intervals in each 90-min orbit.

IV. IMPLEMENTATION IN EARTH GEODESY MISSION

Figures 5(a) and 5(b) illustrate a simplified GRACE-FO-type optical mission architecture and an alternate architecture that enables the application of the dual-quadrature phasemeter, respectively. This alternative architecture allows a GRACE-FO-like laser ranging interferometer to function without a frequency offset between the local and incoming light, thereby enabling retroreflector-based schemes to operate without including a frequency shifter. The authors note that they do not see any benefit to using this optical architecture in a transponder scheme, such as that implemented in GRACE-FO.

In the GRACE-FO optical configuration [Fig. 5(a)], an incoming weak field is interfered with a bright reference

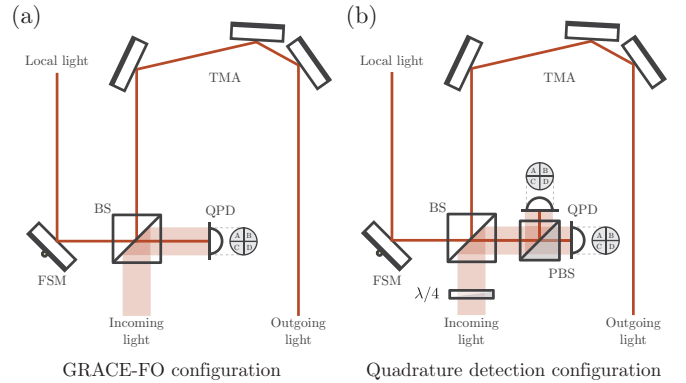


FIG. 5. Optical configuration for a geodesy mission using the dual-quadrature phasemeter. (a) Simplified GRACE-FO optical bench structure. Local light is steered with a fast-steering mirror (FSM) before being interfered with incoming light on a 90-10 beam splitter (BS). The transmitted port is split on a 50-50 BS and detected on a quadrant photodetector (QPD). The reflected port is redirected through a triple-mirror assembly and transmitted to the far satellite. (b) Alternate optical configuration that enables dual-quadrature coherent detection and application of the dual-quadrature phasemeter. Incoming light is passed through a quarter-wave plate before interference with local light on the same 90-10 BS. The BS is replaced with a polarizing beam splitter (PBS) and two quadrant photodetectors to interrogate the in-phase and quadrature components of the incident optical field.

field on an uneven beam splitter and detected using a single quadrant photodiode. On the other output of the beam splitter, the bright field is redirected by the triple-mirror assembly (TMA) and transmitted to the far satellite. In the second configuration [Fig. 5(b)], the incoming weak field is passed through a quarter-wave plate, circularly polarizing the light. This delays one polarization component by $\lambda/4$ relative to the other, enabling dual-quadrature detection [18]. The weak field is then interfered with the bright local light (which needs to be vertically polarized at 45° relative to the polarizing beam splitters) on a 90-10 beam splitter (90% reflected). The transmission path for the local light is further split through a polarizing beam splitter and detected with two quadrant photodiodes. At this detection point, two quadrant photodiodes measure the I and Q components of the signal. The second output (reflected path for the local oscillator) is redirected by the TMA and transmitted to the second satellite. This alternate configuration enables quadrature coherent detection while leaving much of the pre-existing GRACE-FO optical configuration unchanged.

This design facilitates the exploration of missions that feature a simplified second satellite that uses a passive retroreflector. An asymmetric retroreflector-based intersatellite interferometer, as investigated in Ref. [6,19], can achieve full system redundancy, a significant strength over the current GRACE-FO architecture; however, less explored asymmetric designs may present opportunities for further reductions in cost and mission complexity. For instance, the second satellite could operate without an onboard accelerometer, employing the accelerometer-transplant method demonstrated by GRACE-FO [20]. Furthermore, such a mission could leverage the lower optical power and frequency dynamic tracking requirements of retroreflector-based systems, as shown in Ref. [7], to eliminate the need for higher-power lasers and enable the application of C-band lasers.

While these results suggest the feasibility of the dual-quadrature phasemeter for space-based interferometric missions, there are several other factors that need to be considered. Without added frequency shifters, the operational frequency band of the mission would be a dc-centered range extending to the maximum Doppler-induced frequency shift in both the positive and negative directions. This imposes noise requirements on the laser's relative intensity noise (RIN), photodetector dark noise, and analog-to-digital converter noise in this dc-centered frequency band. While a space-based interferometric geodesy mission has not previously been designed to operate in this band, meeting the GRACE-FO RIN and electronic noise requirements [6] in a dc-centered band is possible with consumer-grade components. The authors find no compelling reason to suggest that this system would fail, thereby justifying further investigation.

V. CONCLUSIONS

This letter presents a phase-locked loop designed specifically for implementation in homodyne and heterodyne optical metrology, referred to here as the dual-quadrature phasemeter. By redesigning the structure of a PLL around a coherent detection scheme, dual-quadrature phasemeters can track optical signals with higher-frequency dynamics and with relaxed carrier-frequency requirements. Analytical modeling showed that the technique overcomes the bandwidth limitations present in heterodyne phasemeters. Numerical simulations demonstrated that, when paired with correction techniques, the tracking error present in a dual-quadrature phasemeter in the presence of cyclic errors was below $10 \text{ microcycle}/\sqrt{\text{Hz}}$ for a simulated dc-centered signal. This technique enables a retroreflector-based sensing architecture for intersatellite laser links that operates without requiring an optical frequency shifter, making it more compatible with a GRACE-FO-like optical bench.

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The authors declare no conflicts of interest.

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