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Reconstruction and Separation Method of Ranging and Communication Phase in Beat-Note for Micro-Radian Phasemeter

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Abstract

The primary measurement involves detecting tiny (picometer-level) pathlength fluctuations between satellites using heterodyne laser interferometry for space-based gravitational wave detection. The interference of two laser beams with a MHz-level frequency difference produces a MHz beat-note, in which the gravitational wave signal is encoded in the phase of the beat-note. The phasemeter then performs micro-radian accuracy phase measurement and communication information demodulation for this beat-note. To mitigate the impact of phase modulation, existing solutions mostly alleviate it by reducing the modulation depth and optimizing the structure of the pseudo-random noise (PRN) codes. Since the phase modulation is not effectively separated from the phase of the beat-note phase measurement, it has a potential impact on the phase extraction of the micro-radian accuracy of the beat-note. To solve this problem, this paper analyzes the influence mechanism of phase modulation on beat-note phase measurement and proposes a method to separate the modulated phase based on complex rotation. The beat-note is processed by complex conjugate rotation, which can effectively eliminate the PRN modulated phase. Simulation and analysis results demonstrate that this method can significantly enhance the purity of the measured phase in the beat-note while maintaining the ranging and communication functions. Targeting the application of the micro-radian phasemeter in space-based gravitational wave detection, this study presents the reconstruction and separation method of the ranging and communication phase in beat-note, which also provides a new direction for the final selection of modulation depth in the future.

Keywords: space-based gravitational wave detection; laser interferometer; phasemeter; ranging and communication



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1. Introduction

In 2002, Heinzel first proposed the application of Direct Sequence Spread Spectrum (DS/SS) modulation to space-based gravitational wave detection, enabling million-kilometer-scale laser ranging and data communication (inter-spacecraft data transmission for synchronization, control, and scientific information in gravitational wave detection) tasks [1]. In recent years, multiple tests conducted by Laser Interferometer Space Antenna

(LISA) have verified the feasibility and robustness of this technology. Currently, the DS/SS scheme has become an integral part of the design of LISA. Laser heterodyne interference signals include the main beat-note using 89% of the optical power, two sideband beat-notes using 10% of the optical power, and the ranging and communication codes using 1% of the optical power (corresponding to approximately 0.1 rad modulation depth) [2–4]. The ranging and communication codes perform Binary Phase Shift Keying (BPSK) phase modulation of a PRN sequence onto the optical beam carriers. This modulation appears in the main beat-note as a result of the interference between phase modulated beams. The ranging and communication system is integrated into the phasemeter that is the critical beat-note phase measurement payload. Therefore, the impact of phase modulation on beat-note phase measurement must be carefully considered. Previous experiments conducted by LISA have demonstrated that the phase fidelity required for scientific signals is not affected by low-depth phase modulation. Consequently, 1% of the optical power is used to implement ranging and communication [5]. This design has been internationally recognized for both the Taiji and TianQin missions, which adopted LISA's signal structure and the low-modulation-depth strategy to preserve phase fidelity in their ranging and communication systems. Related scientific experiments have already been conducted, achieving significant results [6]. In 2022, Shuang Han and colleagues developed an FPGA-based signal simulation system capable of generating three channel beat-note signals, performing PRN-coded spread spectrum communication modulation, and injecting noise. The system achieved spurious suppression of -53 dBc and second harmonic suppression of -47 dBc, successfully simulating the key characteristics of the laser heterodyne interference signal over the 2–20 MHz band, thus providing a reliable signal source for phasemeter ground tests [7]. In 2023, Rujie Deng, Yibin Zhang, and their team conducted research focused on the inter-satellite communication and ranging requirements of the Taiji program. They developed a ground-based electronics verification system based on an FPGA platform, establishing a processing flow comprising BPSK spread spectrum modulation, Phase Locked Loop (PLL) demodulation, Delay Locked Loop (DLL) code synchronization, and centroid-based ranging. Using a hybrid modulation of a 1024-bit Weil sequence and a 16-bit information code, the system achieved a ranging accuracy better than 1.6 m within a 60 m baseline, thus verifying the feasibility of the ranging architecture and processing algorithms. Subsequently, the team proposed and implemented an inter-satellite laser communication system. Designed with an 80 MHz system clock, the system operated at a communication rate of 19.5 kbps and a PRN code rate of 1.25 Mbps, with a phase modulation depth of 0.4 rad, corresponding to approximately 4% of the optical power. Performance was validated through electronic and optical platforms, demonstrating interferometric measurement capability while maintaining a communication bit error rate better than 10^{-6} . The system exhibited excellent stability and practicality, laying a solid foundation for the construction and future deployment of the Taiji inter-satellite link [8,9]. Given the integration of the ranging and communication system into micro-radian phasemeter, the potential noise introduced during phase modulation processes must be carefully analyzed, as it poses a significant concern for high-precision gravitational wave detection. In 2023, Yamamoto et al. reported that BPSK phase modulation introduces a DC component that increases the noise of the main lobe, thereby degrading phase tracking accuracy and inducing errors in ranging measurements. Under conditions of a modulation depth of 0.1 rad (approximately 1% carrier power) and a 1.6 MHz PRN code rate, the resulting phase noise was measured at $158 \mu\text{rad}/\text{Hz}^{1/2}$, which is two orders of magnitude higher than LISA's design target of $1 \text{ pm}/\text{Hz}^{1/2}$ (equivalent to $5.9 \mu\text{rad}/\text{Hz}^{1/2}$) [10]. In 2024, Hongyu Long et al. incorporated balance considerations into the design of PRN codes and proposed an optimization method based on bit balanced sequences, resulting in six pairs

of bit-balanced PRN codes. Experiments demonstrated that the designed sequences were insensitive to random data and achieved dynamic bit balancing, effectively suppressing the introduction of DC components. This design provides a novel optimization approach for PRN sequences in space-based gravitational wave detection missions [11].

Currently, the design of gravitational wave ranging and communication systems has become increasingly sophisticated. The suppression of modulation-induced noise is typically achieved by reducing the modulation depth and optimizing the PRN code structure. However, under the stringent beat-note phase measurement requirements at the micro-radian level, the modulation phase remains directly superimposed onto the measured phase, making its impact non-negligible. Moreover, the commonly adopted modulation depth of approximately 0.1 rad faces certain challenges in deep space communication applications. If effective separation of the modulation phase can be achieved, allowing the extraction of a pure measurement signal, it would enable the maintenance of micro-radian measurement accuracy while providing the possibility of increasing the modulation depth. Based on this motivation, this paper proposes a modulation phase separation method utilizing complex conjugate rotation. By demodulating the received signal and reconstructing the modulation component, a complex conjugate rotation can be performed to effectively eliminate the embedded pseudo-random modulation phase from the measured signal, thereby enhancing the phase purity of the heterodyne signals. This method contributes to improving the beat-note phase measurement accuracy in space-based gravitational wave detection missions and enhances the overall robustness and interference resistance of inter-satellite ranging and communication systems.

2. Modulation Phase Impact

The Direct Sequence Spread Spectrum (DS/SS) modulation scheme enables the simultaneous continuous measurement of inter-satellite distances and clock synchronization while allowing encoded information to be transmitted along with the ranging signal, requiring only a small fraction of the laser power. Consequently, this scheme is integrated into the precision heterodyne interferometers used for gravitational wave detection. The heterodyne signals consist of the main beat-note and two sideband beat-notes, where clock noise information, the PRN sequence, and communication data are phase modulated onto the main and sideband beat-notes via Electro-Optical Modulators (EOMs) with different modulation depths. Figure 1 illustrates the inter-satellite laser interferometry systems adopted by missions such as LISA and Taiji, both of which employ a triangular constellation of three spacecraft. Each spacecraft houses two Optical Assemblies (OAs), each containing a laser, a telescope, a freely floating test mass, and an optical bench for interference. By jointly measuring the distance variations between test masses located in different spacecraft over million-kilometer baselines through laser heterodyne signals, it is possible to reconstruct the strain induced by gravitational waves [12,13].

During the measurement process, under ideal conditions, the laser heterodyne interference signal received by a single quadrant of the satellite's Four-Quadrant Photodiode (QPD) can be expressed as defined in Equation (1) [14,15]:

$$S(t) = G_t J_0^2(m_{sb}) \cos[2\pi(f_{main} + f_D)t + \varphi_{main} + m_{prn} \sum_{n=-\infty}^{\infty} c_n p(t - nT_c)] \\ + G_t J_1^2(m_{sb}) \cos[2\pi(f_{up} + f_D)t + \varphi_{up}] \\ + G_t J_1^2(m_{sb}) \cos[2\pi(f_{down} + f_D)t + \varphi_{down}] \quad (1)$$

The total gain of the Trans-Impedance Amplifier (TIA) is given by $G_t = \frac{\eta G_{TIA} \sqrt{\gamma P_S P_L}}{N}$, where G_{TIA} is the TIA gain, P_S and P_L are the received signal power and the local laser power, γ is the heterodyne detection efficiency, and N is the number of photodiodes (QPD):

$N = 4$). $J_n(m)$ denotes the n th-order Bessel function, and m_{sb} is the sideband beat-notes modulation index, approximately 0.45 rad. The control index under this modulation function takes the J_0 and J_1 terms. f_{main} , f_{up} , and f_{down} represent the main beat-note frequency and the upper sideband beat-note frequency and lower sideband beat-note frequency, respectively. f_D refers to the Doppler frequency shift, and φ_{main} , φ_{up} and φ_{down} correspond to the phase shifts of the main beat-note and the upper sideband beat-note and lower sideband beat-note, respectively. The PRN code modulation index m_{prn} is approximately 0.1 rad, c_n represents the PRN code in binary form, its pulse shape is $p(t)$, and T_c is the period.

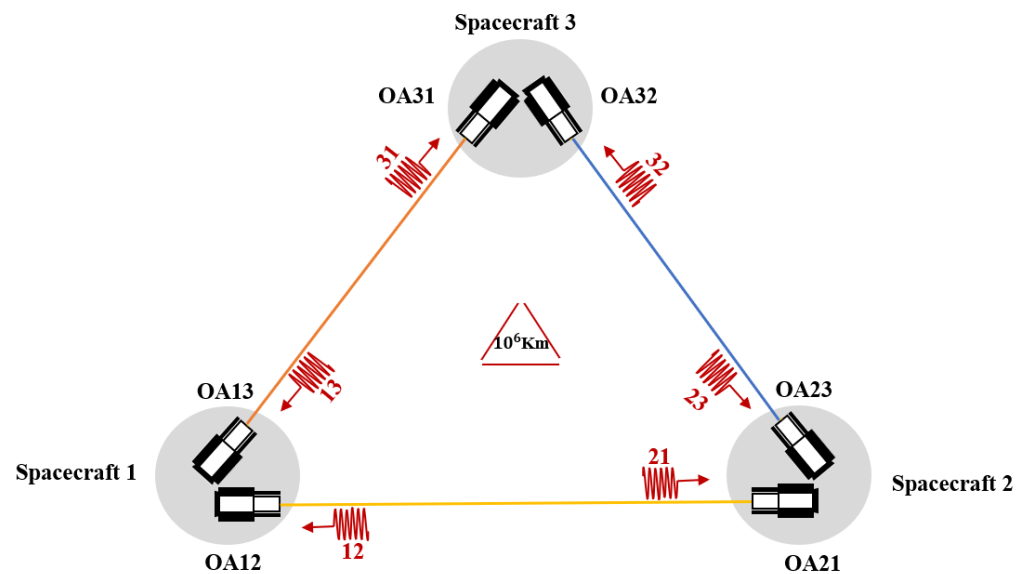


Figure 1. A conceptual diagram of the three-spacecraft constellation for space-based gravitational wave detection.

In relation to the above expression, it can be seen that BPSK modulation introduces phase jumps $\pm m_{prn}$ into the signal phase. Since the PRN code is a pseudo-random sequence, rapid phase reversals are observed during beat-note phase measurements, which can adversely affect the measurement accuracy. Neglecting the contributions from the upper and lower sideband beat-notes, as well as signal amplitude variations, the input signal corresponding to the main beat-note after Analog-to-Digital Conversion (ADC) can be expressed as in Equation (2):

$$S_{main}(t) = \cos[2\pi(f_{main} + f_D)t + \varphi_{main} + m_{prn} \sum_{-\infty}^{\infty} c_n p(t - nT_c)] \quad (2)$$

Here, the primary point of concern lies in the modulation phase φ_{mod} , represented by $m_{prn} \sum_{-\infty}^{\infty} c_n p(t - nT_c)$. In previous studies, the distinction between low-modulation-depth BPSK modulation and the conventional modulation of BPSK has not been considered. In traditional communication systems, as shown in Equation (2), conventional BPSK modulation has a modulation depth m_{prn} of π , and under this condition, the modulation phase $\varphi_{mod(\pi)}$ can be described as in Equation (3):

$$\varphi_{mod(\pi)} = m_{prn} \sum_{-\infty}^{\infty} c_n p(t - nT_c) = \pm \pi \sum_{-\infty}^{\infty} p(t - nT_c) \quad (3)$$

In the current ranging and communication system designs for gravitational wave detection, in order to reduce the impact of modulation on signal phase measurement, m_{prn}

is typically set to 0.1 rad. Under this condition, the signal's $\varphi_{\text{mod}(0.1\text{rad})}$ can be expressed as in Equation (4):

$$\varphi_{\text{mod}(0.1\text{rad})} = m_{\text{prn}} \sum_{-\infty}^{\infty} c_n p(t - nT_c) = \pm 0.1 \sum_{-\infty}^{\infty} p(t - nT_c) \quad (4)$$

It can be seen that at a low modulation depth, the modulation phase φ_{mod} of the main beat-note directly couples into the measured scientific phase $\varphi_{\text{mod}(\pi)}$, causing a phase offset of approximately ± 0.1 rad in the signal due to the modulation. The characteristics of signals under different modulation depths are simulated below, as shown in Figure 2.

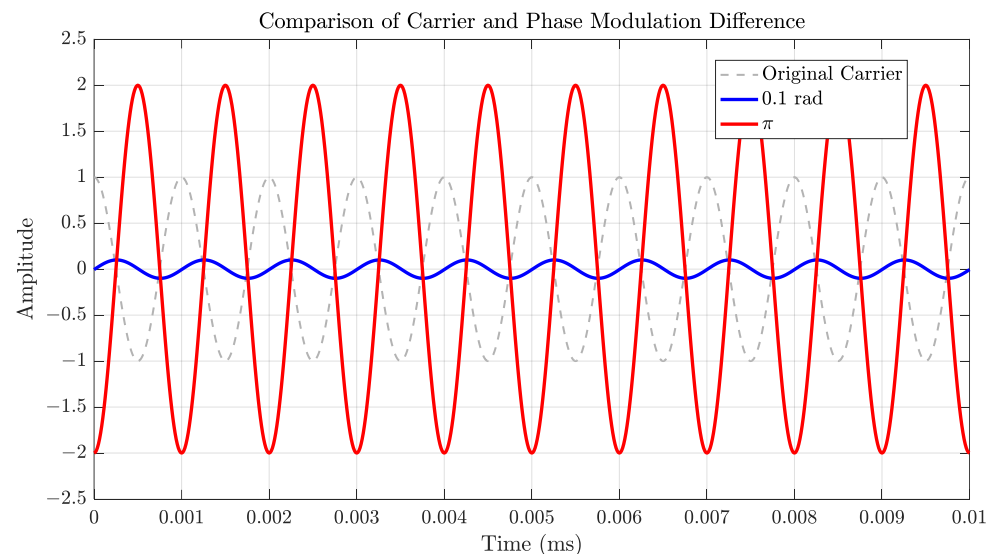


Figure 2. Comparison of carrier and phase modulation differences.

Figure 2 illustrates the differences between modulation depths of 0.1 rad and π with respect to the original carrier. The original carrier signal (gray dashed line) is a standard sinusoidal waveform. For the π modulation depth (red solid line), due to the abrupt phase transition of π at modulation jumps, the signal undergoes a polarity reversal in amplitude, but the corresponding instantaneous phase change is discrete and does not form continuous phase drift along the phase trajectory. In contrast, for the modulation depth of 0.1 rad (blue solid line), the modulation component acts as a small continuous offset superimposed on the carrier phase, leading to slight but continuous deviations in the instantaneous phase trajectory relative to the original carrier. In this modulation form, a cumulative tiny phase drift develops over time, effectively altering the phase evolution process of the signal. Thus, in gravitational wave detection, although the modulation depth is only 0.1 rad, the induced phase offset is superimposed onto the measured scientific phase. Considering that current domestic efforts have not yet achieved multiple signal coupling, beat-note phase measurement accuracy for signals incorporating ranging communication modulation or sideband modulation has not yet reached the design target of $1 \text{ pm}/\sqrt{\text{Hz}}$ in the 0.1 mHz to 1 Hz frequency band [16]; thus, it is necessary to address and mitigate the impact of low-modulation-depth phase modulation on beat-note phase measurement accuracy.

3. Modulation Component Reconstruction and Separation

Based on the above analysis, it is evident that at the current low modulation depth, the modulation phase is directly superimposed onto the measured phase, affecting the accuracy of beat-note phase measurement and increasing the difficulty of coupling ranging and communication codes into the signal. Therefore, this paper proposes a solution to

preprocess the modulation component of the signal prior to scientific measurements to remove the modulation term and eliminate its impact on signal phase measurement. Figure 2 illustrates the signal processing flow within the phase meter. The optical heterodyne signal is captured by a QPD and converted into an electrical signal. It is synchronized with the pilot tone (PT) and digitized via an ADC before being input to a field-programmable gate array (FPGA). Inside the FPGA, multiple PLLs are employed to extract the phase and frequency information of the signal, and a DLL is used for absolute inter-satellite ranging and communication data demodulation. The system uses an 80 MHz system clock to provide synchronized driving signals for both the ADC and the FPGA, while the pilot tone is used to suppress timing jitter introduced during ADC sampling, thereby improving the stability and accuracy of beat-note phase measurements. In the current processing flow, phase and frequency extraction via PLLs is performed prior to demodulation. However, as discussed in the previous section, the modulation phase adversely affects the accuracy of phase extraction. Thus, this paper proposes a modification to the FPGA internal signal processing flow to mitigate this effect, as shown in the red dashed box in Figure 3. An Interference Signal Recovery (ISR) module is inserted before the signal enters the PLL. This module performs demodulation, modulation component reconstruction, and modulation phase removal.

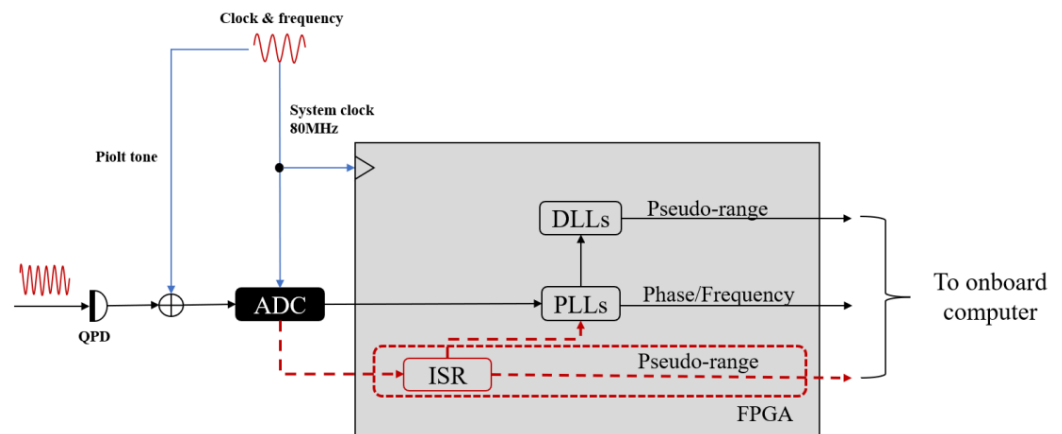


Figure 3. Phasemeter processing procedure.

The ISR module is developed on the basis of the principle of modulation, leveraging the structural characteristics and reconstruct ability of the modulation component. It introduces an approach that separates the modulation term through modulation phase inversion and cancelation. By demodulating the signal and synchronously generating the corresponding PRN sequence, the structure of the modulation phase can be extracted and reconstructed, thereby enabling a more precise removal of the modulation phase. The core idea lies in the fact that the modulation process itself is a controlled operation driven by a pseudo-random sequence, rendering the modulation component deterministic and reproducible. Through code synchronization techniques on the receiver side, a local PRN sequence identical to that at the transmitter can be accurately generated, enabling the reconstruction of the modulation phase and its subsequent inversion and compensation. The reconstruction of the modulation component is achieved by demodulating the received signal and applying code synchronization techniques to regenerate the PRN sequence identical to the transmitted one, thus enabling the reconstruction of the modulation phase.

After demodulation, the receiver generates a locally synchronized PRN code $R_I(t)$ as in Equation (5):

$$R_I(t) = \sum_{-\infty}^{\infty} c_n^I p(t - nT_c) \quad (5)$$

The c_n^l represents the reconstructed local PRN. We calculate the correlation function between the local $R_l(t)$ and the received signal $R_r(t)$ as in Equation (6):

$$S_{PRN}(t) = \int_{t-T}^t R_l(t) \cdot R_r(t) \quad (6)$$

When the PRN codes are aligned, the correlation peak reaches its maximum and the component of the local PRN modulation phase at this time can be expressed as in Equation (7):

$$\varphi_{\text{mod}}^l(t) = m_{prn} \sum_{-\infty}^{\infty} c_n^l p(t - nT_c) \quad (7)$$

The $\varphi_{\text{mod}}^l(t)$ represents the reconstructed local modulation phase. After reconstructing the modulation component, complex rotation is applied to cancel it from the signal, thereby removing the modulation phase from the original signal:

$$S'(t) = S(t) \cdot \exp(-j\varphi_{\text{mod}}^l(t)) \quad (8)$$

which is equivalent to

$$S'(t) = \Re(e^{j(2\pi(f_{\text{mian}} + f_D)t + \varphi_{\text{main}})} \cdot e^{j\varphi_{\text{mod}}} \cdot e^{-j\varphi_{\text{mod}}^l(t)}) \quad (9)$$

When $\varphi_{\text{mod}}^l(t) \approx \varphi_{\text{mod}}(t)$ is satisfied, effective separation of the modulation phase can be achieved.

To obtain a synchronized PRN code and achieve signal reconstruction, this paper employs a Costas loop for carrier synchronization and a DLL loop for demodulation. The overall process of the ISR module is shown in Figure 4. During the carrier synchronization stage, the Costas loop internally generates local reference signals for the in-phase component $\cos(2\pi f_c^l t + \varphi_l(t))$ and the quadrature component $\sin(2\pi f_c^l t + \varphi_l(t))$, which are mixed with the input signal to be obtained as in Equation (10):

$$\begin{aligned} I(t) &= s(t) \times \cos(2\pi f_c^l t + \varphi_l(t)) \\ Q(t) &= s(t) \times \sin(2\pi f_c^l t + \varphi_l(t)) \end{aligned} \quad (10)$$

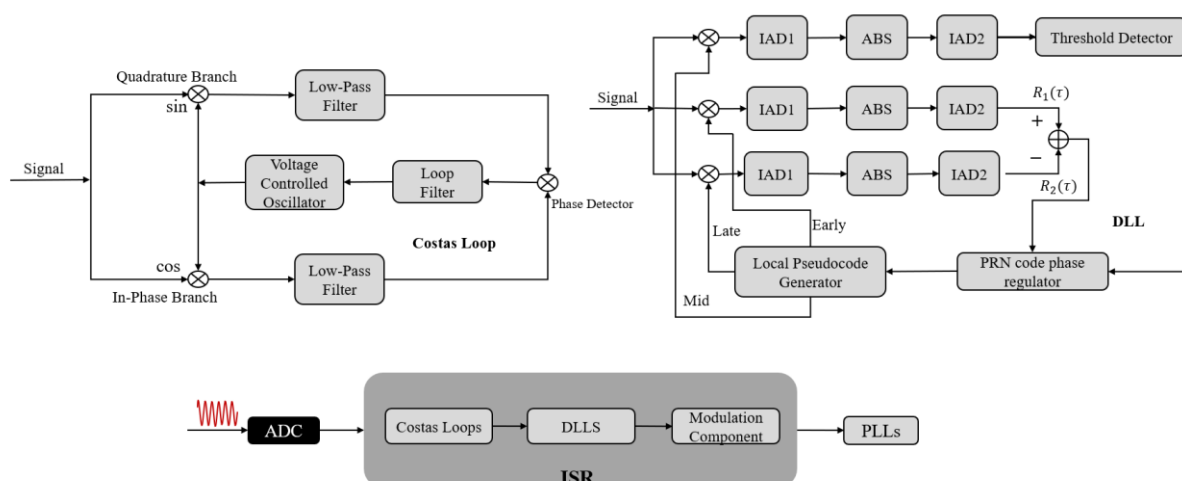


Figure 4. The processing flow of the ISR module.

In this expression, f_c^l and $\varphi_l(t)$ represent the local frequency and phase. After passing through a low-pass filter, only the components near zero frequency around the beat-note are retained, resulting in Equation (11):

$$\begin{aligned} I(t) &\approx \frac{1}{2} \cos(\Delta\varphi(t) + \varphi_{\text{mod}}(t)) \\ Q(t) &\approx \frac{1}{2} \sin(\Delta\varphi(t) + \varphi_{\text{mod}}(t)) \end{aligned} \quad (11)$$

Here, $\Delta\varphi(t) = (2\pi(f_{\text{main}} - f_c^l)t) + (\varphi_{\text{main}} - \varphi_l(t))$ represents the phase difference between the input signal and the local signal. The $I(t)$ and $Q(t)$ components, after passing through the low-pass filter, are mixed within the phase detector to generate the error function as in Equation (12):

$$e(t) = I(t) \cdot Q(t) = \frac{1}{8} \sin(2\Delta\varphi(t) + 2\varphi_{\text{mod}}(t)) \quad (12)$$

The error function can be approximated as

$$e(t) \approx \frac{1}{8} [\sin(2\Delta\varphi(t)) + 2\varphi_{\text{mod}}(t) \cos(2\Delta\varphi(t))] \quad (13)$$

The error signal $e(t)$ is fed into the loop filter, which controls the local Voltage-Controlled Oscillator (VCO) to perform frequency and phase modulation, thereby achieving carrier synchronization [17].

After carrier synchronization is completed and the demodulated ranging communication code signal is obtained, the DLL enters the acquisition phase. As shown in Figure 4, the received signal is multiplied by three locally generated PRN codes (early, mid, and late), and the resulting correlation signals are fed into the First-level Integrate and Dump filter (IAD1), which performs sample integration within each data code period and resets periodically. The output of IAD1 is then processed by an absolute value operation (ABS) to remove sign information and retain only the correlation magnitude. This output is subsequently passed to the Second-level Integrate and Dump filter (IAD2), whose integration window spans an entire PRN code cycle. The output of IAD2 represents the correlation strength between each PRN replica and the received signal, serving as the decision metric for DLL acquisition. In the system architecture, the acquisition and tracking loops are integrated into a unified structure that jointly achieves PRN code synchronization. This design enables a seamless transition from initial acquisition to stable tracking, ultimately allowing data readout once the punctual PRN code is synchronized with the incoming signal, thereby forming a complete ranging code synchronization mechanism [18,19]. Once PRN synchronization is established, the modulation signal can be reconstructed and separated according to Equations (8) and (9).

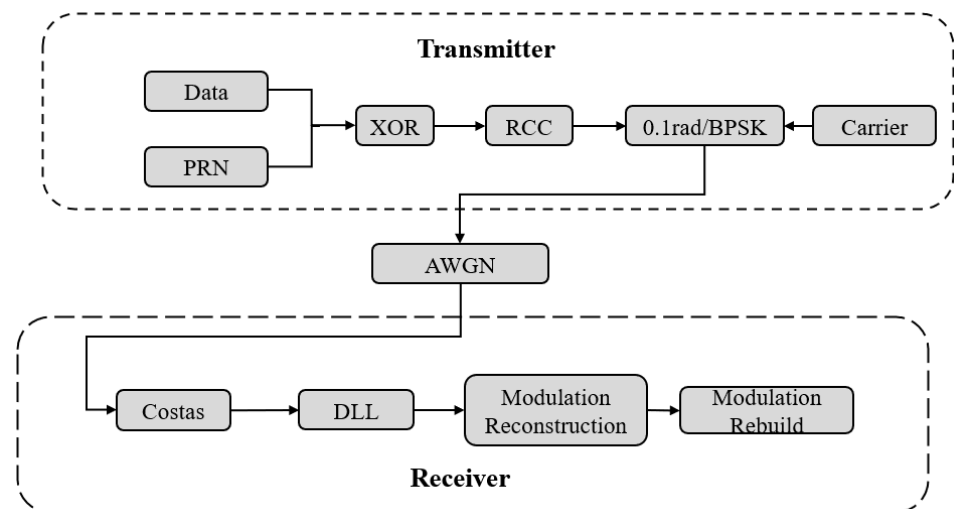
4. Simulation Experiment Verification

To verify the effectiveness of the modulation phase reconstruction and separation method proposed in this paper and considering that the method relies on the accurate synchronization and reconstruction of the modulation sequence at the receiver, a signal modulation and demodulation system for DS/SS signals with low modulation depth was developed on the MATLAB R2016a platform. A systematic simulation verification was carried out using the parameter settings listed in Table 1. The system sampling frequency was set to 80 MHz, the PRN rate f_{chip} was set to 1.6 MHz, the data code rate f_{data} was set to 25 kbps, and the PRN code length was 1024 [11], with a modulation depth of 0.1 rad.

Table 1. System parameters for modulation and demodulation of DS/SS signals with low modulation depth.

Type	Value	Remarks
System frequency f_s	80 MHz	Gravitational wave design
PRN code rate f_{chip}	1.6 MHz	According to reference [11]
Samples per chip	50	
spreading factor	64	
data rate f_{data}	25 KHz	
PRN sequence length	1024	
Carrier frequency f_{main}	5 MHz	5~25 MHz interference measurement band
Modulation depth m_{prn}	0.1 rad	Gravitational wave design

After the system parameters are determined, the simulation process illustrated in Figure 5 mainly consists of two parts: the transmitter and the receiver. The transmitter performs spread spectrum modulation for ranging and communication and transmits the signal, while the receiver carries out signal demodulation. The PRN code is shaped using a Root-Raised-Cosine (RRC) filter to suppress inter-symbol interference and ensure signal transmission quality. To simulate the real transmission environment, Additive White Gaussian Noise (AWGN) is introduced into the signal. On the receiver side, carrier synchronization is achieved using a Costas loop, followed by PRN code synchronization via a DLL, modulation term reconstruction, and demodulation phase removal.

**Figure 5.** System simulation process.

The established BPSK modulation and demodulation system with low modulation depth is validated, and the results are shown in Figures 6–8.

As shown in Figure 6, under noise-free conditions, the modulation component was first reconstructed to remove the modulation phase. The resulting instantaneous phase error remained consistently at zero, indicating that the modulation component reconstructed after the Costas loop and DLL demodulation introduced no phase deviation during the restoration process, thus achieving the complete recovery of the pure carrier. Figure 7 presents a time domain comparison between the demodulated carrier and the original modulated signal. The two signals exhibit high consistency in frequency, amplitude, and phase, with a high degree of waveform overlap, further confirming the accuracy of the modulation/demodulation process, the precision of modulation term reconstruction,

and the effectiveness of the demodulation removal. To further evaluate the robustness and stability of the proposed method under practical conditions, additive AWGN was introduced into the signal, and an in-depth analysis of the demodulated results was conducted. The corresponding results are shown in Figure 8.

The figure presents a comparison of signal spectra under three different modulation depths (0.1 rad, 1 rad, and π). The left column shows the spectra of the phase-modulated signals, while the right column displays the spectra after demodulation using complex conjugate rotation. It can be observed that as the modulation depth increases, the spectrum of the modulated signal gradually broadens, with more pronounced sidelobes beyond the main lobe and energy spreading over a wider bandwidth. In contrast, after demodulation, the spectral component at the carrier frequency becomes significantly enhanced and energy is reconcentrated, indicating that the complex rotation effectively removes the modulation components embedded in the phase. Notably, even at a modulation depth of π where spectral broadening is the most prominent, the carrier frequency component is still clearly recovered after demodulation, demonstrating the robustness and effectiveness of the method at high modulation depths. Overall, the results confirm that complex conjugate rotation is an efficient means of removing modulation phase, significantly improving the spectral purity of the recovered carrier and providing a cleaner input signal for subsequent frequency extraction and phase-locked processing.

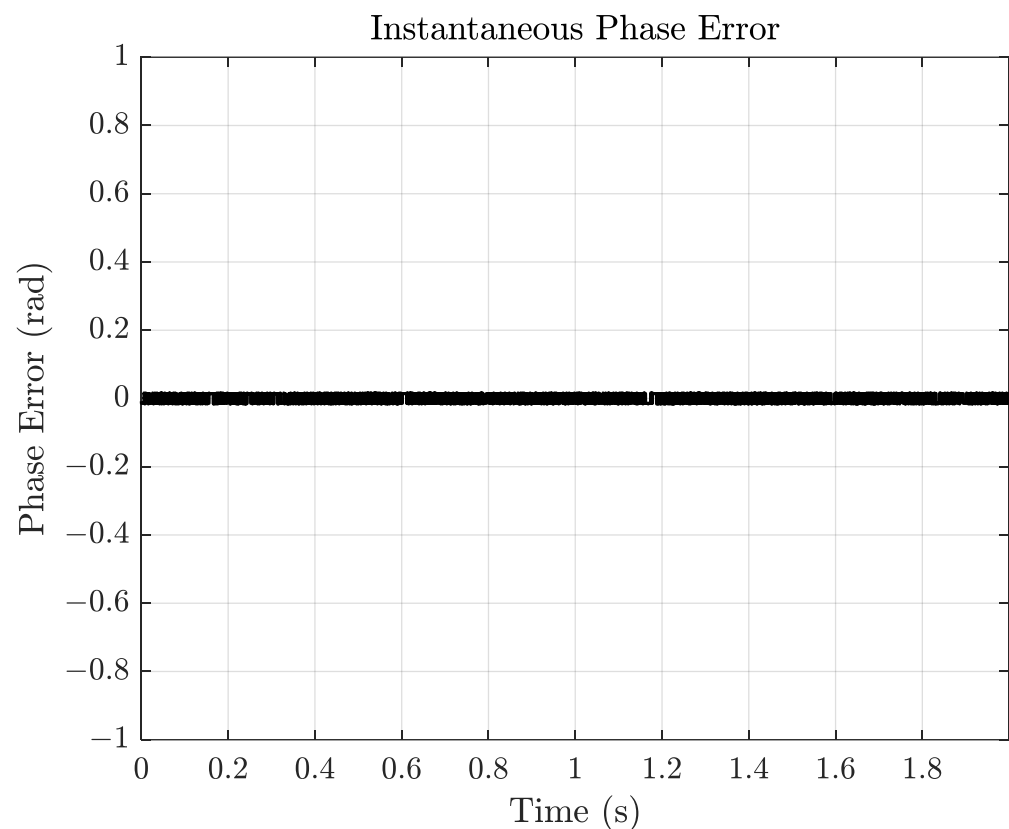


Figure 6. Residual phase error between demodulated carrier and modulated phase.

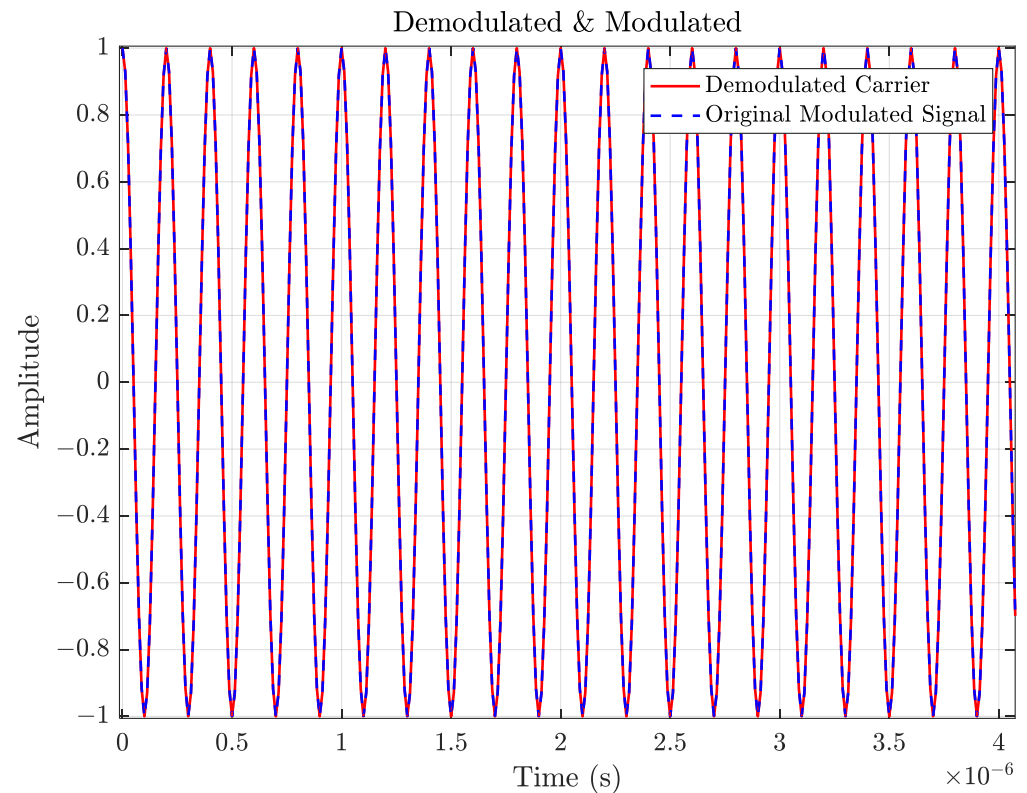


Figure 7. Comparison of demodulated carrier and original modulated signal.

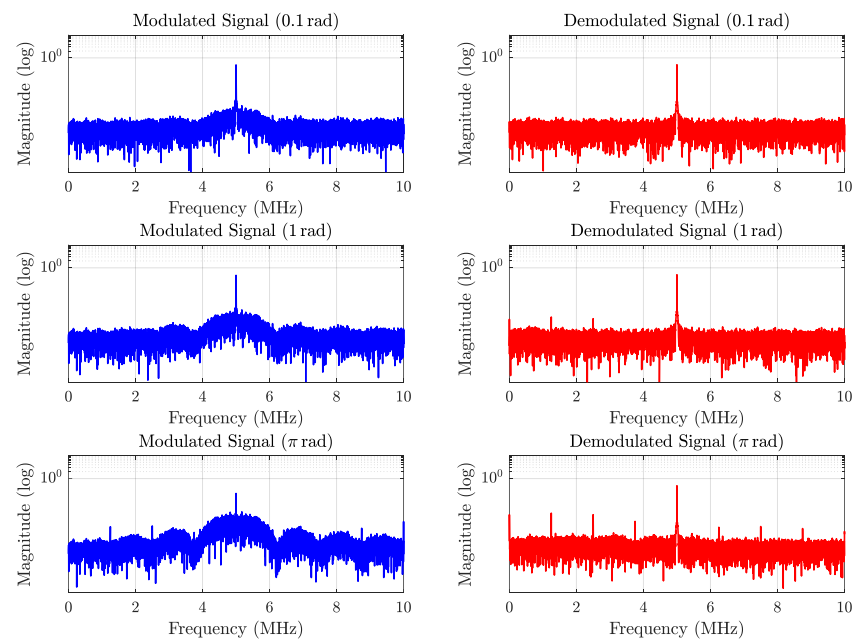


Figure 8. Comparison before and after signal processing.

5. Conclusions and Outlook

This paper addresses the impact of low depth phase modulation on measurement accuracy in the ranging and communication system designed for a micro-radian phasemeter. A modulation phase separation method based on complex rotation is proposed. Simulation analysis results demonstrate the strong effectiveness of the method. By demodulating the received signal, reconstructing the modulation component, and applying complex conjugate rotation, the pseudo-random modulation phase embedded in the signal can be effectively eliminated, significantly enhancing the phase purity of the heterodyne signals.

This is of great importance for achieving micro-radian-level phase measurements in space-based gravitational wave detection. Unlike traditional approaches that rely on reducing the modulation depth to suppress modulation induced interference, the proposed method actively separates the modulation phase without affecting the original measurement signal. It provides a scalable and high-precision strategy for enabling multi signal coupling scenarios, including ranging, communication, and scientific measurements. This method not only improves the purity of the measured phase but also creates the possibility of further increasing the modulation depth in ranging and communication systems, aiming to lay a solid technical foundation for achieving integrated and highly robust signal processing architectures in space-based interferometric missions.

It is important to emphasize that the method proposed herein offers a novel solution to mitigate the effects of low modulation depth on the demodulation bit error rate and the influence of modulation-induced noise on phase measurements in space-based gravitational wave detection systems. Currently, this approach cannot be directly applied to inter-spacecraft interferometry due to inherent limitations. A principal challenge arises from the receiver's ability to acquire, in real time, the PRN information transmitted by remote spacecraft, which critically impacts the accurate reconstruction and subsequent removal of modulation components. Future research will prioritize the development of parallel demodulation decision architectures aimed at enhancing the real-time processing capability for communication bit decoding. Additionally, predictive schemes leveraging historical data will be investigated to forecast potential modulation states proactively. Complementarily, buffering strategies involving the deliberate design of delay lines and memory resources will be incorporated to ensure adequate temporal allowance for demodulation decisions and modulation component elimination. Collectively, these methodological advancements are anticipated to furnish viable engineering solutions that enable the extension and practical implementation of the proposed approach in inter-spacecraft interferometric applications while maintaining system real-time performance and manageable hardware resource demands.

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Data Availability Statement: The data presented in this study are not publicly available due to privacy, and access can be requested from [yut@ciomp.ac.cn] upon reasonable request.

Conflicts of Interest: The author of the current study has no conflicts of interest to declare.

References

1. Heinzel, G. Ranging with pseudo-random noise. In Proceedings of the LISA International Science Team (LIST) Meeting, Philadelphia, PA, USA, 3–8 November 2002; p. 17.
2. Pollack, S.E.; Stebbins, R.T. A demonstration of LISA laser communication. *Class. Quantum Gravity* **2006**, *23*, 4201. [[CrossRef](#)]
3. Heinzel, G.; Esteban, J.J.; Barke, S.; Otto, M.; Wang, Y.; Garcia, A.F.; Danzmann, K. Auxiliary functions of the LISA laser link: Ranging, clock noise transfer and data communication. *Class. Quantum Gravity* **2011**, *28*, 094008. [[CrossRef](#)]
4. Esteban, J.J.; García, A.F.; Barke, S.; Peinado, A.M.; Cervantes, F.G.; Bykov, I.; Heinzel, G.; Danzmann, K. Experimental demonstration of weak-light laser ranging and data communication for LISA. *Opt. Express* **2011**, *19*, 15937–15946. [[CrossRef](#)] [[PubMed](#)]

5. Delgado, J.J.E.; Marin, A.F.G.; Bykov, I.; Heinzl, G.; Danzmann, K. Free-space laser ranging and data communication. In Proceedings of the 2009 6th Workshop on Positioning, Navigation and Communication, Hannover, Germany, 19 March 2009; IEEE: Piscataway, NJ, USA, 2009; pp. 275–281.
6. Liu, H.S.; Gao, R.H.; Luo, Z.R.; Jin, G. Laser ranging and data communication for space gravitational wave detection. *Chin. Opt.* **2019**, *12*, 486–492.
7. Han, S.; Tong, J.; Wang, Z.; Yu, T.; Sui, Y. Simulation system of a laser heterodyne interference signal for space gravitational wave detection. *Infrared Laser Eng.* **2022**, *51*, 20210572.
8. Deng, R.J.; Zhang, Y.B.; Liu, H.S.; Luo, Z.R. Ground electronics verification of inter-satellites laser ranging in the Taiji program. *Chin. Opt.* **2023**, *16*, 765–776.
9. Zhang, Y.B.; Deng, R.J.; Liu, H.S.; Luo, Z.R. Parameter design and experimental verification of taiji program inter-satellite laser communication. *Chin. J. Lasers* **2023**, *50*, 2306002.
10. Yamamoto, K. *Intersatellite Clock Synchronization and Absolute Ranging for Gravitational Wave Detection in Space*; Leibniz Universität Hannover: Hannover, Germany, 2023.
11. Long, H.Y.; Yu, T.; Xue, K.; Wang, Z. Design of Ranging Communication Coding and Noise Suppression Methods in Space Gravitational Wave Detection. *Symmetry* **2025**, *17*, 40. [[CrossRef](#)]
12. Reinhardt, J.N.; Staab, M.; Yamamoto, K.; Bayle, J.B.; Hees, A.; Hartwig, O.; Wiesner, K.; Shah, S.; Heinzl, G. Ranging sensor fusion in LISA data processing: Treatment of ambiguities, noise, and onboard delays in LISA ranging observables. *Phys. Rev. D* **2024**, *109*, 022004. [[CrossRef](#)]
13. Sweeney, D. Laser Communications for LISA and the University of Florida LISA Interferometry Simulator. Ph.D Thesis, University of Florida, Gainesville, FL, USA, 2012.
14. Jiang, Q.; Dong, P.; Liu, H.S.; Luo, Z.R. Ground-based principle verification of clock noise transfer for the Taiji program. *Chin. Opt.* **2023**, *16*, 1394–1403.
15. Gao, X.; Yi, Z.; Lian, J.; Long, W.; Li, Z. Communication reliability analysis of inter-satellite laser link based on transmission parameters. In Proceedings of the 4th Optics Young Scientist Summit (OYSS 2020), Ningbo, China, 4–7 December 2020; SPIE: Bellingham, WA, USA, 2021; Volume 11781, pp. 485–494.
16. Liu, H.S.; Luo, Z.R.; Gang, J. The development of phasemeter for Taiji space gravitational wave detection. *Microgravity Sci. Technol.* **2018**, *30*, 775–781. [[CrossRef](#)]
17. Shachi, P.; Mishra, R.; Jatoth, R.K. Coherent BPSK demodulator using Costas loop and early-late gate synchronizer. In Proceedings of the 2013 Fourth International Conference on Computing, Communications and Networking Technologies (ICCCNT), Tiruchengode, India, 4–6 July 2013; IEEE: Piscataway, NJ, USA, 2013; pp. 1–6.
18. Bhatti, B.A.; Umer, M.; Ahmed, W.; Tariq, M.H.; Ali, U. Carrier and symbol synchronization in digital receivers using feedback compensation loop and early late gate on FPGA. In Proceedings of the 2014 International Conference on Robotics and Emerging Allied Technologies in Engineering (iCREATE), Islamabad, Pakistan, 22–24 April 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 146–150.
19. Han, S. Design and Implementation of Phasemeter Test System for Space Gravitational Wave Detection. Master's Thesis, University of Chinese Academy of Sciences (Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences), Changchun, China, 2022.

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