

The phasemeter of Taiji-1 experimental satellite

Zi-Ren Luo^{*,†,‡,**} Tao Yu^{§,**} and He-Shan Liu^{*,†,¶}

**Center for Gravitational Wave Experiment,
National Microgravity Laboratory, Institute of Mechanics,
Chinese Academy of Sciences (CAS), Beijing 100190, China*

*†Taiji Laboratory for Gravitational Wave Universe (Beijing/Hangzhou),
University of Chinese Academy of Sciences (UCAS), Beijing 100049, China*

‡Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China

*§Changchun Institute of Optics, Fine Mechanics and Physics,
CAS, Changchun 130033, China*

¶liuheshan@imech.ac.cn

||On behalf of The Taiji Scientific Collaboration

Received 15 September 2020

Revised 16 October 2020

Accepted 30 October 2020

Published 25 February 2021

Taiji-1 is the first demonstrated experimental satellite of Taiji program in China. Phasemeter is one of the key components of the laser interferometer which is responsible for phase extraction of the heterodyne signals. In this paper, we present the architecture and implementation of Taiji-1 phasemeter. The DPLL architecture is used in Taiji-1 which is generally regarded as the best choice for space missions. We test the phasemeter on the ground and the results show that the phasemeter reaches the sensitivity of $600 \mu\text{rad}/\sqrt{Hz}$ in the frequency range of 0.01–1 Hz. It is further shown that it can reach the accuracy of $30 \mu\text{rad}/\sqrt{Hz}$ in the frequency range of 0.1–1 Hz, both of which are within the technical requirements of Taiji-1 mission.

Keywords: Phasemeter; DPLL; Taiji-1.

1. Introduction

Taiji-1 is the first demonstrated technology satellite of Taiji program which utilizes the laser interferometer to detect the gravitational waves in space.^{1,2} The interferometer transfers tiny displacements between the test masses to the phase of a heterodyne signal. For a $1 \text{ pm}/\sqrt{Hz}$ sensitivity, the phase should be extracted with a

**Equally contribute to this work.

¶Corresponding author.

||For more details, please refer to article 2102002 of this Special Issue.

precision of $2\pi \mu\text{rad}/\sqrt{Hz}$ in the frequency range of 0.1 mHz–1 Hz. Several methods exist for extracting the phase including zero-crossing,³ Single Bin Discrete Fourier Transform (SBDFT)⁴ and⁵ Digital Phase-Locked Loop (DPLL). In Taiji mission, due to the orbital drift, the frequency of a heterodyne signal fluctuates by several MHz (depending on the final orbit selection). Moreover, due to the other necessary functions, the laser beam of Taiji should modulate extra tones such as clock jitter, ranging and communication code.⁶ Therefore, the phasemeter requires to track multi-frequencies tones. To track the frequency fluctuations of the signal, DPLL uses the NCO to get locked to the tested signal. Assigning different initial NCO values enables DPLL to follow different tones in the heterodyne signal. This is the reason DPLL architecture is selected for the phase extraction in Taiji mission.

Similar to the LISA pathfinder (LPF), Laser Interferometer Space Antenna,^{7,8} Taiji-1 focuses on the technologies of single satellite, such as the local laser interferometer, Gravity Reference Sensor (GRS), micro-thruster, and the satellite platform. For phase extraction, in contrast to the LPF which uses SBDFT, Taiji-1 adopts DPLL. The required phase sensitivity for Taiji-1 is $100 \text{ pm}/\sqrt{Hz}$ ($\approx 600 \mu\text{rad}/\sqrt{Hz}$).

In the following, we present the architecture and implementation of the phasemeter in Sec. 2. Then in Sec. 3, the detailed ground tests of the phasemeter are presented and the obtained results are discussed.

2. Architecture and Implementation

Similar to the LPF, the optical bench of Taiji-1 is focused on the local interferometer consisting of four interferometers. Two interferometers have unequal arms and are used for the stability detection of the optical bench, and the other two have equal arms for test mass motion monitor. Each interferometer has two Quadrant Photo Detector (QPDs) on both sides of the ending Beam Splitter (BS), named as the main part, and backup part, respectively. Therefore, the main and backup parts each have four QPDs with 16 analog output channels for independent measurement. In Taiji-1, the electronic part of the interferometer is called Interferometer Electronic Control Box (IECB) and consists of the phasemeter, the secondary power supply, and other accessory boards. The diagram of the IECB is shown in Fig. 1.

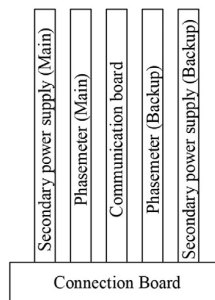


Fig. 1. The diagram of the IECB.

As it is seen in Fig. 1, here are main and backup parts for the QPDs. The IECB also contains two phasemeters each with 16 channels, two secondary power supplies for the corresponding phasemeters, one communication board for communication and control, and one connection board for other board connection. The backup part of the phasemeter is a cold standby design which is turned on or off by the upload command control.

The phasemeter hardware mainly consists of four Analog to Digital Converter (ADCs), AD9253, four channels and an Field Programmable Gate Array (FPGA), Xilinx K7-325t chips. Four ADCs are also considered for digitalization of 16 analog signal channels. The FPGA is also used for software realization of 16 DPLLs. The ADC and FPGA are driven by the temperature compensation crystal oscillators with the relative frequency stability lower than 10^{-8} . Although the heterodyne frequency is 1 kHz, the primary frequency of the FPGA is set to 80 MHz to compatible with the following missions. For the success of Taiji-1 and as a backup of the DPLL phasemeter, the IECB stores the data of ADCs (8 kHz sampling rate), and the data can also be post-processed on the ground. The physical picture of IECB is shown in Fig. 2.

2.1. Analog front-end

To decrease the heat generation, only the photodiode of the QPD is installed in the optical bench of Taiji-1. The Transimpedance amplifier (TIA) is then integrated with the analog front-end of the phasemeter. The diagram of the phasemeter analog front-end is illustrated in Fig. 3.

The analog front-end of the phasemeter mainly contains the transimpedance amplifier, voltage amplifier, low pass filter, and differential amplifier. AC signal is



Fig. 2. The IECB of Taiji-1 interferometer assembled together with the modulated part of the interferometer which also contains AOMs and an optical fiber beam splitter.

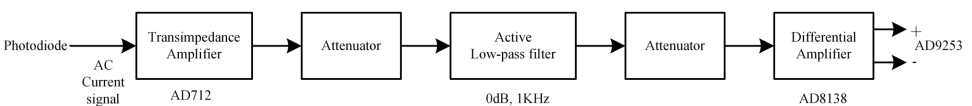


Fig. 3. The diagram of the phasemeter analog front-end.

converted by the photodiode and it is proportional to the interferometer beams power. The transimpedance also converts the current to voltage. Because the laser power is sufficient, the second amplifier is not used in Taiji-1. The main function of the first attenuator is impedance matching and to prevent signal waveform distortion. The cut-off frequency of the low pass filter is set to 5 kHz to remove the noise and also act as anti-aliasing. The differential amplifier also converts its input to a differential signal which is then provided to the ADC as its input. The analog signal is then quantized by the ADC into the digital signal.

2.2. Software

The architecture of the phasemeter is based on DPLL and the code is written in Very-High-Speed Integrated Circuit Hardware Description Language (VHDL). The VHDL code of DPLL is optimized for the aerospace standards. The diagram of the phasemeter code is presented in Fig. 4.

As it is seen in Fig. 4, the developed software is composed of the ADC driven code, 16-channel DPLL, the down-sampling part, and the communication part. The output of the 16-channel ADC is directly delivered to DPLL. For independent measurement, the output of the ADC is also transmitted to the ground after getting down-sampled to 8 kHz. In the DPLL, the digital data is then separately processed for each channel. All the information is then transferred to the communication board of the IECB.

The DPLL includes the NCO, multiplier, LPF, PI controller and anti-aliasing filter. The algorithm of the DPLL has been presented in our previous research. The frequency and phase information are then obtained using frequency readout and PA readout, separately. The frequency readout is suitable for the large orbital drift, such as scientific interferometer. The PA readout is suitable for tiny phase different situations, such as the reference interferometer, TM interferometer and Wavefront

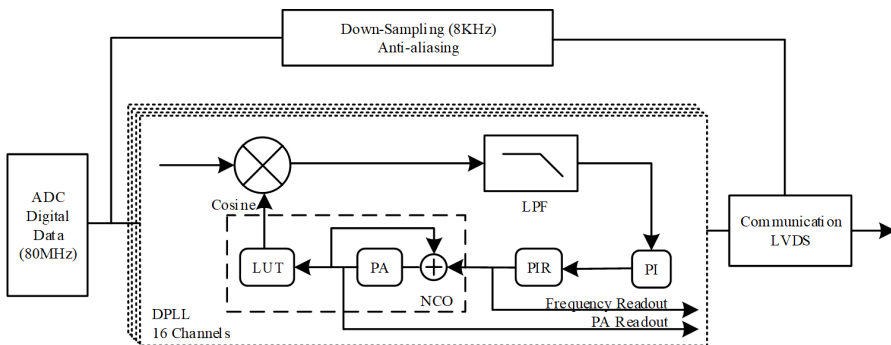


Fig. 4. The diagram of the phasemeter software. LUT: Look-up Table, PA: Phase Accumulator, NCO: Numerically Controlled Oscillator, PIR: Phase Increment Register, PI: Proportional Integral, LPF: Low Pass Filter, LVDS: Low Voltage Differential Signal.

Differential Sensing (DWS) signal. Therefore, the phasemeter of Taiji-1 needs two readout schemes.

3. Tests and Results

The phasemeter is always tested in the zero measurement,⁹ where one signal is split into two and directly connected with the two channels of phasemeter. In this condition, the phase error between the detected signals remains zero, hence, the obtained information reflects the phasemeter's noise. In this paper, the zero measurement is adopted as the test method. The tested signals are generated by analog and optical signals and the results are shown in the following.

3.1. Analog signal test

The signal of the first test is generated by a commercial functional generator (RIGOL 1032, two channels). The typical result of the test is shown in Fig. 5.

Figure 5 shows that the sensitivity of the phasemeter satisfies the requirement of Taiji-1 mission in the frequency range of 0.01–1 Hz, which is $600 \mu\text{rad}/\sqrt{\text{Hz}}$. Moreover, the phasemeter can reach the sensitivity of $30 \mu\text{rad}/\sqrt{\text{Hz}}$ in the frequency range of 0.1–1 Hz. The sensitivity is slightly decreased in the frequencies below 0.1 Hz.

The interferometer of Taiji-1 should be capable of timely readout of the related position as well as its fluctuation. In this condition, the frequency readout is not suitable for the phase readout and instead the PA readout provides a better choice. In the second test, the results of the frequency readout and the PA readout are compared. The signal of this test is then generated by the commercial functional generator (RIGOL 1032), where the phase modulation function is opened with a frequency of 0.1 Hz. The typical result is shown in Fig. 6.

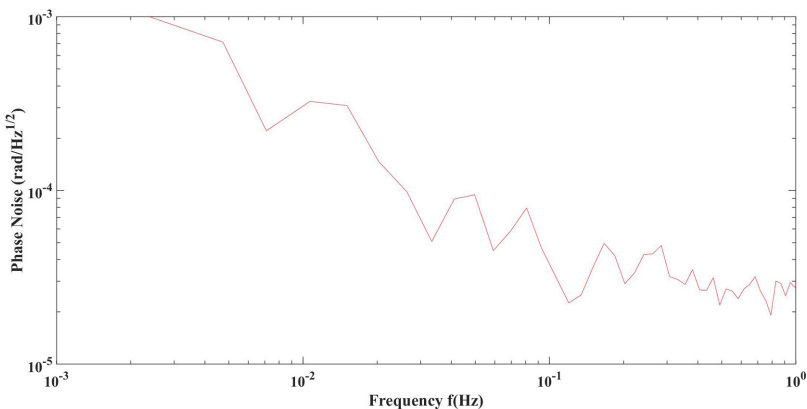


Fig. 5. The typical result of the analog signal test in zero measurement condition.

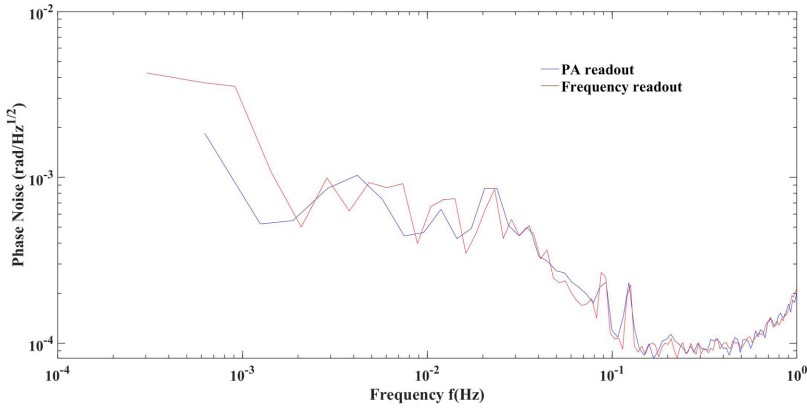


Fig. 6. The comparison of the frequency readout and the PA readout.

From Fig. 6, the frequency readout and the PA readout demonstrate good consistency in the whole frequency range. The phase-modulated signal is also clearly seen at 0.1 Hz. Comparing with Fig. 5, the sensitivity here is however decreased. This is because the signal-to-noise ratio is reduced by opening the phase modulation function.

3.2. Optical signal test

In the optical signal test, the heterodyne signal is generated by the optical fiber interferometer. The signal has two beams with 1 kHz frequency difference from the AOMs. The beams are directly imported to a 2×2 optical fiber beam combiner. In this condition, the two beams have interfered in an ideal way. The heterodyne signal besides the combiner is regarded as the zero signal and can be utilized as the tested signal. The typical result of the test is shown in Fig. 7.

From Fig. 7, it is seen that the sensitivity of the interferometer reaches $30 \mu\text{rad}/\sqrt{\text{Hz}}$ in the frequency range of 0.3–1 Hz. In the frequency range of 0.02–1 Hz, the interferometer satisfies the requirement of Taiji. However, compared with the results presented in Fig. 5, the sensitivity is significantly increased. The reasons are as follows: (1) Although the optical fiber interferometer prevents the fussy alignment and assembly process, the optical fiber is easily affected by environmental factors such as temperature and vibration. Therefore, the heterodyne signal of the optical fiber may encounter extra noise comparing with the optomechanical structure; (2) The tested situation is the normal atmospheric environment. Therefore, compared with the vacuum, the thermal drift and air turbulence are more complex in this test scenario.

Furthermore, Taiji-1 phasemeter is thoroughly tested for both analog and optical signals. In both the test conditions, the phasemeter reaches the sensitivity of $600 \mu\text{rad}/\sqrt{\text{Hz}}$ in the frequency range of 0.01–1 Hz.

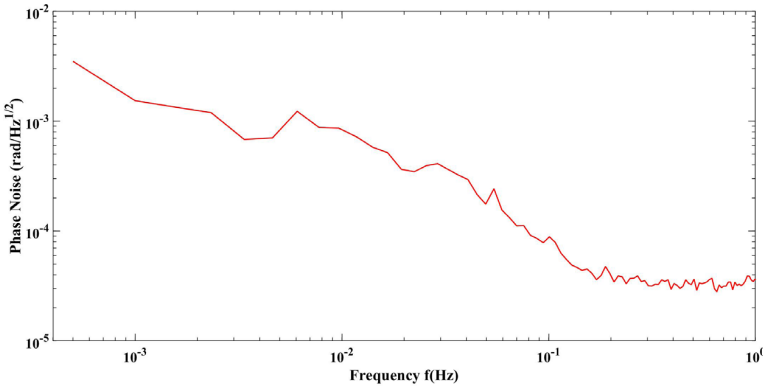


Fig. 7. The typical result of the optical signal test.

4. Conclusion and Outlook

Taiji-1 is the first technology demonstration satellite for space gravitational wave detection in China. As the readout equipment of the laser interferometer, here, we present the phasemeter of Taiji-1. In this paper, the main part and backup part of the phasemeter, each with 16 channels, have been introduced and tested in detail. The tested signals are generated by the function generator and the optical fiber interferometer. This provides an all-round analysis of the phasemeter. The tested results showed that the phasemeter can reach the sensitivity of $600 \mu\text{rad}/\sqrt{\text{Hz}}$ in the frequency range of 0.01–1 Hz. Moreover, the accuracy reaches $30 \mu\text{rad}/\sqrt{\text{Hz}}$ in the frequency range of 0.1–1 Hz. In the following mission of Taiji, the phasemeter not only requires high sensitivity but also has more complex functionalities compared with Taiji-1. Nevertheless, the phasemeter of Taiji-1 provides us with more confidence to be used in the following mission.

Acknowledgments

This work was financially supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (Grant Nos. XDA1502070304, XDA1502070902 and XDB23030000).

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