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Laser Interferometer Used for Satellite–Satellite Tracking: an On-Ground Methodological Demonstration *

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A Chinese satellite gravity mission called SAGM (Space Advanced Gravity Measurements) is now taken into consideration. To meet its designed requirement, the measurement precision of the laser ranging system used to measure the inter-satellite distance change has to be better than 100 nm/Hz$^{1/2}$ within a broad bandwidth from 0.1 mHz to 1 Hz. An equal arm heterodyne Mach–Zehnder interferometer has been built on ground to demonstrate the measurement principle of a laser ranging system, which potentially can be used for both SAGM and future GW (gravitational wave) space antennas. Because of the equal arm length, the laser frequency noise has been significantly suppressed in the interferometer. Thus, the sensitivity better than 1 nm/Hz$^{1/2}$ in a frequency range of 0.15 mHz–0.375 Hz has been achieved. The result shows that the proposed methodology has very promising feasibility to meet the requirements of SAGM and of GW space antennas as well.

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The idea of using a laser interferometer to measure the change of the relative distance between two satellites has been considered for various uses, e.g. gravitational wave (GW) space antennas,[1−6] as well as GRACE-type (Gravity Recovery and Climate Experiment) satellite gravity missions.[7−11]

The GW is a direct prediction of Einstein's theory of general relativity and known as a product of violent astronomical phenomena. Therefore, detection of a GW is of great significance to assess the validity of Einstein's theory. More importantly, the GW can serve as a new probe to explore the physical universe besides electromagnetic radiation.[12,13] The Satellite Gravity Mission uses satellites to map the gravity field distribution of the Earth. Mapping data of high temporal and special resolution can enable us to better understand our planet, such as ocean circulation, sea level change, water balance, ice sheet mass balance, atmosphere, solid earth, ocean tides, etc.[14]

The laser interferometer for LISA, a space GW antenna, is under development,[15,16] while an engineering mode for LISA pathfinder, an LISA science and technology demonstrating satellite, has already been built.[17,18] An on-ground test shows that the noise level of 10 pm/Hz$^{1/2}$ at the frequency band 0.01 Hz–1 Hz can be reached. As for the GRACE-follow-on mission, studies of the laser ranging system has already been carried out by several groups.[9,10,19,20] Within a narrow frequency band around 0.1 Hz, the measurement precision about 10 nm/Hz$^{1/2}$ is achieved.

Supported by the Chinese SAGM mission, a prototype of the laser ranging system has been built on an ordinary aluminum-alloy optical table. To eliminate the measurement error caused by laser frequency instability, a Mach–Zehnder interferometer with equal arms has been employed. Without any thermal control, measurement precision better than 1 nm/Hz$^{1/2}$ has been obtained in a broad frequency band from 0.15 mHz to 0.375 Hz. The result shows that the proposed methodology is very promising for meeting the requirements of the SAGM mission, and could potentially be used for future GW space antennas.

Laser frequency instability would cause a measurement error: $\delta L = (\delta v/v) \cdot \Delta L$, where δL, δv, v and ΔL are the measurement error, the laser frequency instability, the laser frequency, and the arm length difference, respectively.[1] To reduce the measurement error of the laser frequency instability, a heterodyne laser interferometer prototype with equal arms is employed in the experiment (the arm length difference $\Delta L \approx 2$ cm). The temperature of the laboratory is controlled in a range of 25 ± 2℃, and the interferometer is put on an optical bench enclosed by a cuboid acrylic cage to prevent air convection. The optical bench is set up on an isolation basis to avoid environmental vibration, and the resonant frequency of the basis is about 7.8 Hz.

The schematic diagram of the laser interferometer prototype is shown in Fig. 1, and the prototype layout is shown in Fig. 2. Acousto-optical modulators (AOMs) are used to generate an offset frequency Δf between the two beams of the laser. The beat frequencies used in the experiment are 1, 10, 100, 300, and 500 kHz. Photo-detectors are used to register the beat signals of interferences, and the phases of the signals are read by a phase meter. The relationship between the phase change and the relative distance change is given by $\delta L = (\Delta\theta/2\pi) \cdot \lambda$.

The data are analyzed with a method called power spectrum density (PSD). Two different algorithms are used to calculate the PSD, see Figs. 3(a) and 3(b).

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Figure 3(a) is given by direct discrete Fourier transformation, with Fig. 3(b) given by Welch's overlapping segments average (WOSA). Both (a) and (b) can be used to characterize the results. While the curve given by the WOSA method is smoother and neater, so that in Figs. 4 and 5 only WOSA curves are given.

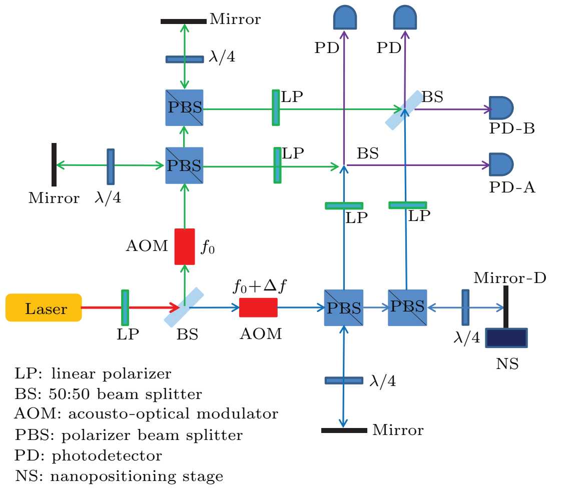

Fig. 1. Schematic diagram of the laser interferometer prototype.

Fig. 2. Layout of the laser interferometer prototype.

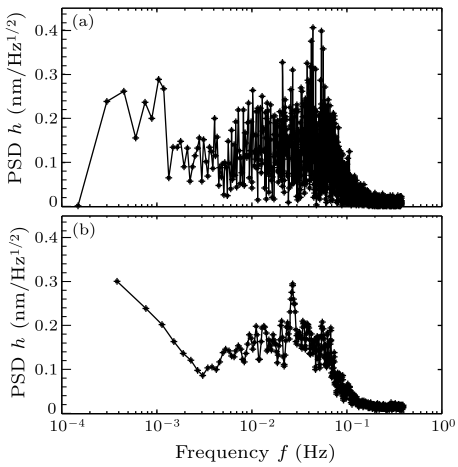

Fig. 3. The noise power spectrum density of the laser interferometer prototype under static measuring mode: (a) calculated by direct discrete Fourier transformation; and (b) given by the WOSA method.

The laser adopted in the experiment is fabricated by Melles Griot: the output power, the wavelength, the frequency stability, and the beam divergence are 1 mW, 632.8 nm, ±2 MHz for 1 h and 1.60 mrad, respectively. The AOM is developed by the China Electronics Technology Group Corporation 26th Research Institute: the central frequency, the frequency shift range and the relative frequency stability are 100 MHz, ±1 MHz and 10^{-7}, respectively. All the optical components are commercially available and fabricated by CVI Melles Griot, with the transmitted wave-front error of $\lambda/10$ at 633 nm. The photodetectors were purchased from Hamamatsu, and are type C5331-12: the frequency bandwidth, the active area and the photosensitivity were 4 kHz–40 MHz, Φ = 3.0 mm and 0.42 A/W (λ = 620 nm), respectively. The phase-meter is developed by Powertek: the frequency range, the measurement accuracy and the resolution are 0.1 Hz–700 kHz, ±0.25° (100 kHz–700 kHz) and 0.001°, respectively. In order to simulate the inter-satellite distance change, a nano-positioning stage fabricated by Physik Instrumente is adopted, on which the mirror-D is installed. The type of the stage is P-611.Z, which is operated under closed-loop control to obtain better positioning, and the closed-loop travel, the closed-loop resolution, and the linearity are 120 µm, 2 nm and 0.1%, respectively.

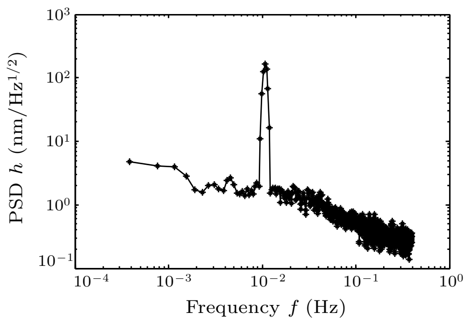

Fig. 4. The noise power spectrum density of the laser interferometer prototype under dynamic measuring mode.

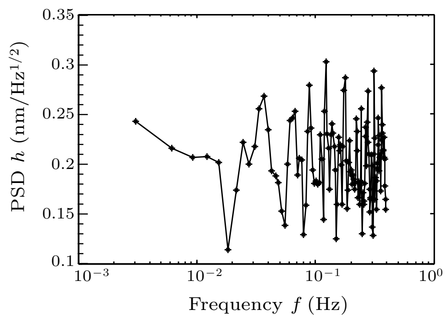

Fig. 5. The noise power spectra density of the nano-positioning stage itself.

To better understand the measurement error of the heterodyne laser interferometer prototype, two measuring programs are employed: (1) the static measuring mode: mirror-D is fixed and the environmental conditions are kept as stable as possible, then the measuring data are recorded by using a remote computer while the system is running; (2) the dynamic measuring mode: mirror-D is moved by the nano-positioning stage in a form of sine wave (the amplitude of sine wave does not exceed $\lambda/2$), then keeping the environmental conditions as stable as possible, and the measuring data are also recorded by using a remote computer.

Under the two measuring modes, the results show that the system measurement error is the same while the beat frequency of the interferometer varies from 1 kHz to 500 kHz. Thus, a 300 kHz beat frequency is adopted in the experiment for the easy analysis.

The noise PSD of the laser interferometer prototype under the static measuring mode is shown in Fig. 3. The noise level is 0.1–0.5 $\mathrm{nm/Hz^{1/2}}$ within the frequency band between 0.15 mHz and 0.375 Hz. The noise mainly results from: (1) the breathing motion of the optical bench driven by environmental temperature drift, which occurs in the lower frequency band ($\leq$0.01 Hz); (2) the seismic vibration noises in higher frequency band (0.1 Hz–0.01 Hz), which results from the effect of the ocean tides colliding with the mainland. Lu *et al.* reported that the vibration frequency of North China is from 10 s to 32 s,[21] which is consistent with our experimental results; (3) the instrument noise, including the laser frequency noise, the photodetector noise, the phase-meter noise etc. However, these noises are insignificant in comparison with the above two noises.

Figure 4 shows the noise PSD of the laser interferometer prototype under the dynamic measuring mode, and the noise PSD of nano-positioning stage itself is shown in Fig. 5 while it is moving in a sine equation. The period and the amplitude of the modulated signal are 100 s and 210 nm, respectively. The highest peak corresponding to 0.01 Hz in Fig. 4 is about 180 $\mathrm{nm/Hz^{1/2}}$, which has resulted from the modulated signal. However, the PSD peak value of modulated signal is inconsistent with the amplitude of the sine. The deficiency of the detected signal's amplitude compared to the modulated signal comes from the frequency instability of the nano-positioning stage itself, since the power of the modulated signal has been divided and distributed to other frequencies near the modulated frequency of 0.01 Hz. In addition, when using the WOSA method, the choice of the window function and its normalization also influence the peak value. In the higher frequency band ($\geq$0.1 Hz), from the comparisons and the analysis of Figs. 3–5, it is indicated that the noise PSD of the laser interferometer prototype under the dynamic measuring mode is dominated by the noise resulting from nano-positioning stage itself. As the same as the static measuring mode, in the lower frequency band ($\leq$0.1 Hz), the noise of the laser interferometer prototype under the dynamic measuring mode mainly comes from the seismic vibrations and the temperature drift. According to the temperature measurement, the temperature fluctuation of environment (near the optical bench) is about 0.1℃ under the static measuring mode, but about 0.3℃ while under the dynamic measuring mode, which leads to a higher noise level in the latter mode within the frequency band $\leq$0.01 Hz.

In summary, an on-ground methodological demonstration of a laser ranging system has been carried out, which can be used in the SAGM mission or future GW space antennas. To eliminate the noise caused by the laser frequency instability, a heterodyne laser interferometer prototype is employed with equal arms. Preliminary error sources of the laser ranging system have been analyzed, and it has been found that the measurement error of the system is unchanged while the beat frequency of the interferometer has been changed from 1 kHz to 500 kHz. A noise level of 0.1–0.5 $\mathrm{nm/Hz^{1/2}}$ within the frequency band between 0.15 mHz and 0.375 Hz is obtained under the static measuring mode, which has met the requirements of the SAGM mission. Under the dynamic measuring mode, the noise level is 1–3 $\mathrm{nm/Hz^{1/2}}$ within the frequency band between 0.15 mHz and 0.01 Hz, and the greater temperature drift will lead to the worse performance below 0.01 Hz. However, the measuring noise does not exceed 1 $\mathrm{nm/Hz^{1/2}}$ within the higher frequency band from 0.01 Hz to 0.375 Hz, in which the noise in this frequency band is mainly contributed by the laser interferometer measuring noise and the nano-positioning stage itself. Therefore, in our experiment the major noise source comes from the environmental temperature drift. A certain scheme to stabilize the thermal environment and low expansion material will be used in our future work. A great improvement of the system performance can be expected.

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