Inter-satellite range-finding method with high precision and large range based on optoelectronic resonance

Bin Chen (陈 斌)[1,2], Jinlong Yu (于晋龙)[1], Ju Wang (王 菊)[1,*], Tianyu Li (李天宇)[1], Wenrui Wang (王文睿)[1], Yang Yu (于 洋)[1], and Tianyuan Xie (谢田元)[1]

[1]*School of Electronic Information Engineering, Tianjin University, Tianjin 300072, China*

[2]*College of Biomedical Engineering & Instrument Science, Zhejiang University, Hangzhou 310027, China*

**Corresponding author: wangju@tju.edu.cn*

Received June 22, 2016; accepted September 30, 2016; posted online November 8, 2016

As microsatellite technology develops, precise inter-satellite measurement shows its significance in distributed satellite systems. In this Letter, a novel technique is proposed for measuring the inter-satellite distance, which adopts optoelectronic resonance and has a function of self-referencing. Resonance cavities have a high spectral purity and a high oscillation frequency. By utilizing the accumulative amplification principle to convert the measurement of distance to that of the frequency, high accuracy is achieved. In the experiment, this measuring scheme has a large measuring range between 1 and 6 km (can be potentially larger), and the accuracy is better than 1.5 μm. The relative accuracy reaches the level of 10^{-10}.

OCIS codes: 060.5625, 150.5670, 120.0120.

doi: 10.3788/COL201614.110608.

As microsatellite technology develops, its applications broaden constantly. Distributing the functions of traditional satellites to various microsatellites has become a new operating mode, which is turning into a hotspot of aerospace area rapidly[1–3].

Developed jointly by the National Aeronautics and Space Administration (NASA) and the German Space Agency, the Gravity Recovery and Climate Experiment (GRACE) satellite is composed of two satellites which are 200 km apart. Their orbit altitude is 500 km. The fundamental principle of gravity measurement is inverting the accurate measurement of the distance change and relative velocity between two satellites into the variations of the gravitational field. Therefore, range-finding accuracy in double-satellite systems is a basic premise as well as an important guarantee for the spatial resolution of Earth's gravitational field[4]. An accuracy as high as 10 μm is required to play an important role in studying the global water cycle and the exchange process of the atmosphere, hydrosphere, and oceans[5,6]. It was reported that Shanghai Astronomical Observatory had utilized one-way laser ranging to successfully measure a navigational satellite whose orbital altitude was 36000 km in 2013. A measurement accuracy of 10 cm was obtained, which meant its relative accuracy was 10^{-9}[7]. GRACE has reached an accuracy of 10 μm[8]. Its relative accuracy is 10^{-11}. Moreover, the GRACE follow-up satellite will carry a laser interference measurement system to further increase the detecting accuracy of the gravitational field, making the expected range-finding accuracy reach the level of nanometers[9].

In order to achieve high-precision observations or measurements on the basis of multi-satellite coordination, the high-precision inter-satellite range-finding method (with high precision and a large range) should be first solved. Inter-satellite range-finding methods include laser radar range finding, infrared tracking range finding, microwave radar range finding, and GPS range finding. Laser radar technology is growing more mature. However, no laser range-finding device developed independently in China has been applied to small-satellite flying formations. The measuring accuracy of infrared tracking ranging would be affected significantly by the device itself. Microwave radar range-finding technology can be conducted an independent search and measurement. However, the measuring accuracy is not high enough to satisfy the demands of moonlets. Meanwhile, the application of GPS is limited since part of the ranging codes is kept secret.

In this Letter, a novel technique is proposed for measuring the inter-satellite distance that adopts optoelectronic resonance and has the function of self-reference. Resonance cavities have a high spectral purity and high oscillation frequency. By utilizing the accumulative amplification principle to convert the measurement of distance to the measurement of frequency, record measuring accuracy can be achieved by common measuring instruments. In the experiment, this measuring scheme has a large measuring range between 1 and 6 km (can be potentially longer), and the accuracy is better than 1.5 μm. The relative accuracy reaches the level of 10^{-10}.

Most methods aiming at measuring the absolute distance with a large range and high precision convert the measurement of distance to the measurement of time (time-of-flight method) or phase (phase measurement method or interference method), making the results more accurate by means of improving the measurement resolution continually. The requirement of resolution brings technical difficulty and sensibility to other factors.

Actually, there is another effective measuring method that magnifies the deviation before it is measured: the accumulative amplification principle. In this way,

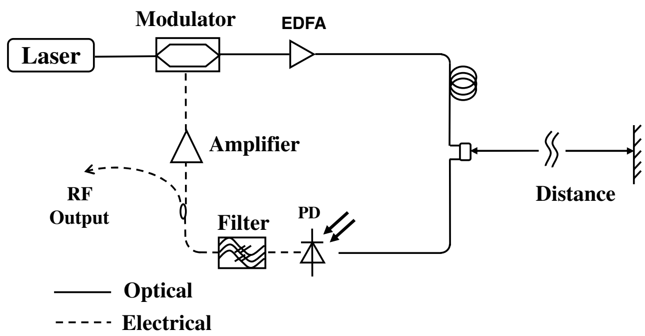

Fig. 1. Fundamental schematic diagram of OEO.

high-precision measuring results can be obtained by low-resolution measuring instruments, such as the classic test of the pendulum cycle.

Optoelectronic oscillators (OEOs) are one kind of new optoelectronic resonance oscillator that has developed rapidly in recent years[10–13]. A long resonant cavity is required to provide plenty of stored energy so the measured distance can serve as one part of the cavity. OEOs generally oscillate at a dozen to a few tens of GHz, and hence, higher harmonics could be detected to guarantee sufficient magnification. The spectral purity of their output is as high as the level of mHz, which is better than the minimum required frequency resolution (decided by the measuring accuracy). Therefore, in this Letter, a measuring method with a large range and high precision based on optoelectronic resonance was proposed for the absolute distance measurement.

OEOs are a new microwave signal generator that utilize long fibers to store energy. Their fundamental schematic diagram is shown in Fig. 1. The positive feedback loop is composed of a laser, an electro-optical modulator, an optical amplifier, a long fiber, a photoelectric detector, a microwave filter, and a microwave amplifier. The length of the resonance cavity is usually at the level of kilometers, which is long enough for most distance measurements conditions. In other words, the measured length can serve as a part of the cavity of OEO, so the change of the distance is transformed to the change of the cavity length, affecting the resonant frequency of the oscillator.

The interval of oscillation modes, which means the basic frequency, is decided by signal delay of the loop

$$f_b = \frac{1}{\tau}, \tag{1}$$

where delay time τ consists of two parts: the constant delay τ_0 caused by the electric circuit and fixed optical fiber and delay $\tau_L = nL/c$, which is decided by the measured distance L. In inter-satellites, refractive index $n = 1$. c refers to the speed of light in a vacuum. Therefore,

$$L = \frac{c}{f_b} - c\tau_0, \tag{2}$$

and all the integer-time frequencies of f_b could oscillate in an OEO. The actual oscillation frequency f_m of the OEO is selected by a microwave filter, and it is

$$f_m = Nf_b, \tag{3}$$

where N represents integer numbers. The oscillation frequency f_m is N times as high as basic frequency f_b (N is at the level of 10^5). As a result, the basic frequency variation caused by the distance is amplified N times. It is obvious, based on the premise of the same observation condition and the same test precision, that the accuracy of f_b measured directly is far lower than that of f_b calculated after measuring f_m and N. Thus, the measuring errors are reduced significantly. The measured distance L can be calculated by

$$L = \frac{Nc}{f_m} - c\tau_0, \tag{4}$$

so in this way, measured distance L actually depends on two factors: the accuracy of f_m and N[14].

The system's stability (which decides τ_0) plays an important role in the process of acquiring the length of the measured distance. As OEO system adopts a long optical fiber to store energy, and the cavity length is easily affected by the environment's temperature, stress, and so on. The resulting basic frequency variation would lead to serious drift or even mode hopping of the high frequency (f_m). Any impact contributing to the physical length will be reflected by a time delay that can be measured, while the time delay will be reflected by oscillating the frequency shift of the OEO[15]. The accuracies of the measured frequency and time delay ensure the accuracy of this range-finding method. But without any stabilizing methods, not only accurate τ_0 but also an exact value of the measured distance is not obtainable.

In order to ensure the stability of τ_0, which denotes the self-referencing function, two wavelengths are adopted to build two OEO systems, as shown in Fig. 2. In this system, the OEO built by λ_1 is used for testing; its loop length includes the cavity length of test system (decide τ_0) and the measured distance (L). The OEO built by λ_2 acts as a stabilized OEO and merely includes the constant cavity length of the test system. The stabilized loop built by λ_2 adopts the principle of a phase-locked loop. When the cavity length drift of the test system causes frequency variations, the phase-locked loop detects the error signal and compares it with one time base, the stability of which is at the level of 10^{-11}. The error signal feedback to control the cavity length of the test OEO and thus the stability of the test system are ensured.

Based on the above principle analysis, experimental research was carried out to prove the proposed scheme. The experimental scheme is shown in Fig. 3.

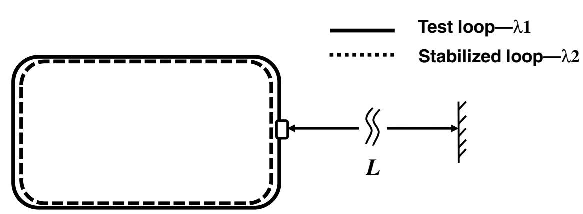

Fig. 2. Realization of self-referencing function.

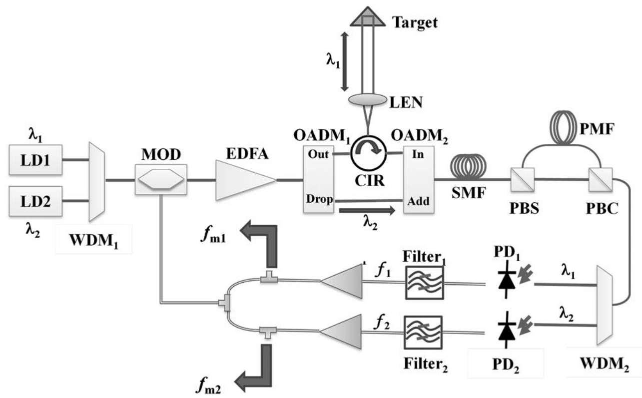

Fig. 3. Inter-satellite ranging system based on optoelectronic resonance.

The wavelengths of the continuous lights emitted by laser devices LD1 and LD2 are λ_1 and λ_2. These two continuous lights are coupled together after going through a WDM (WDM1). The coupled lights enter into an electro-optical modulator (MOD), and the modulated signal (after being amplified by an erbium-doped fiber amplifier, EDFA) goes into the IN port of an optical add–drop multiplexer (OADM). Wavelength λ_1 is selected at the OUT port of the OADM and λ_2 is at DROP of the OADM. λ_1 passes into 1 port of one circulator (CIR) and travels through the distance to be measured from 2 port of the circulator. After reaching the target, λ_1 reflects back to 2 port of the circulator, passes through 3 port of the circulator, and goes into the IN port of the second OADM, while λ_2 goes directly to the ADD port of the second OADM. λ_2 comes out along with λ_1 from the OUT port of the second OADM and goes through long single-mode fiber (SMF), polarization beam splitter (PBS), and polarization beam combiner (PBC) together. A polarization-maintained fiber (PMF) is placed on one arm of the PBS/PBC to suppress the side mode[16,17]. Before converting to microwave signals, two lights of different wavelengths are divided by a WDM, conduct photoelectric conversion separately, and amplify and couple together again to drive a $LiNbO_3$ modulator. After such repeated feedback oscillations, two OEO oscillation loop systems will be built. Their output oscillation frequencies are f_{m1} and f_{m2}, decided by the center frequencies of filter1 and filter2.

The phase-locked loop is utilized to precisely control the stability of the cavity length of the stabilized cavity loop built by λ_2, so as to precisely distinguish the loop length decided by the test OEO and variations of the measured distance[14].

Although the above scheme compensates for the vast majority of cavity length drifts of the test OEO, OEO loops with different wavelengths go through different devices and microwave lines when they pass the microwave amplifier and filter. The phase-locked loop can guarantee the stability of the cavity length of the loop built by λ_2. Moreover, the microwave loop drifts are tiny relatively (the cavity length of optical fiber is at the level of a kilometer; the microwave cavity length is about 10 cm by integration) and are not taken into consideration.

In this range-finding system, a long SMF is placed in the loop to emulate long distances in space; it should have been placed on the path of the measured distance. However, the fiber length varies greatly with the temperature (1 μm/°C/m), so there is no way to verify the measuring accuracy of the test system. If the long fiber is placed on the measured path, it is equivalent to continuous variations of the measuring distance. Therefore, the long fiber is placed on the public loop of the test loop and stabilized cavity loop. In this way, long fiber drifts can be compensated by the stabilized cavity loop so as to measure distance variations precisely.

In this experimental system, an ODL-650 optical fiber delay line produced by Ozoptics is used to change the measured distance precisely. Its range is 50 mm, equal to a round trip of a 25 mm light path. The accuracy of the fiber delay line is less than 1 μm. The accuracy of the measuring system can be verified by testing 16 points along the 25 mm optical path.

In order to test the measurement range of the absolute distance test system based on the OEO, we change the length of the ordinary single-mode fiber in the public loop from 1.5 to 8 km to emulate the spatial distance from 1.1 to 6 km. In each test, 16 points are selected at a range of 25 mm and the tests are performed there. At every location, the tests are performed 30 times, and the results are averaged and compared with the distance variation caused by the delay line. Errors in the test results are shown in Fig. 4. “Distance change” displayed on the X-axis is provided by the optical fiber delay line, whose accuracy is higher than 1 μm. The left Y-axis refers to the “measured distance,” which is provided by the measuring scheme based on the OEO. As is shown in Fig. 4, two sets of data have the character of good linear matching. The error curve displayed on the right Y-axis is the errors between the distance variation measured by the OEO and the distance variation provided by the ODL-650 optical fiber delay line. We emulate different spatial distances at every fiber length and compare all the distance test results based on the OEO with the results of the ODL-650. Their errors are less than 1.5 μm (including the air turbulence), while standard deviations of each set of 30 tests are less than 4 μm. The measuring accuracy can be improved further in space conditions.

In this way, a measuring accuracy that is higher than 1.5 μm is obtained from a multipoint test on an emulative spatial distance from 1.2 to 6 km. It is proven that this experimental system is able to get a high measuring accuracy with such a large range. Meanwhile, the relative measuring accuracy reaches $|\frac{\Delta L}{L}| = \frac{1.5\ \mu\text{m}}{6\ \text{km}} = 2.5 \times 10^{-10}$. What is worth mentioning is that these measuring results are acquired under the circumstance that the system parameters are not optimized completely. If the system parameters are further optimized, it is expected that a

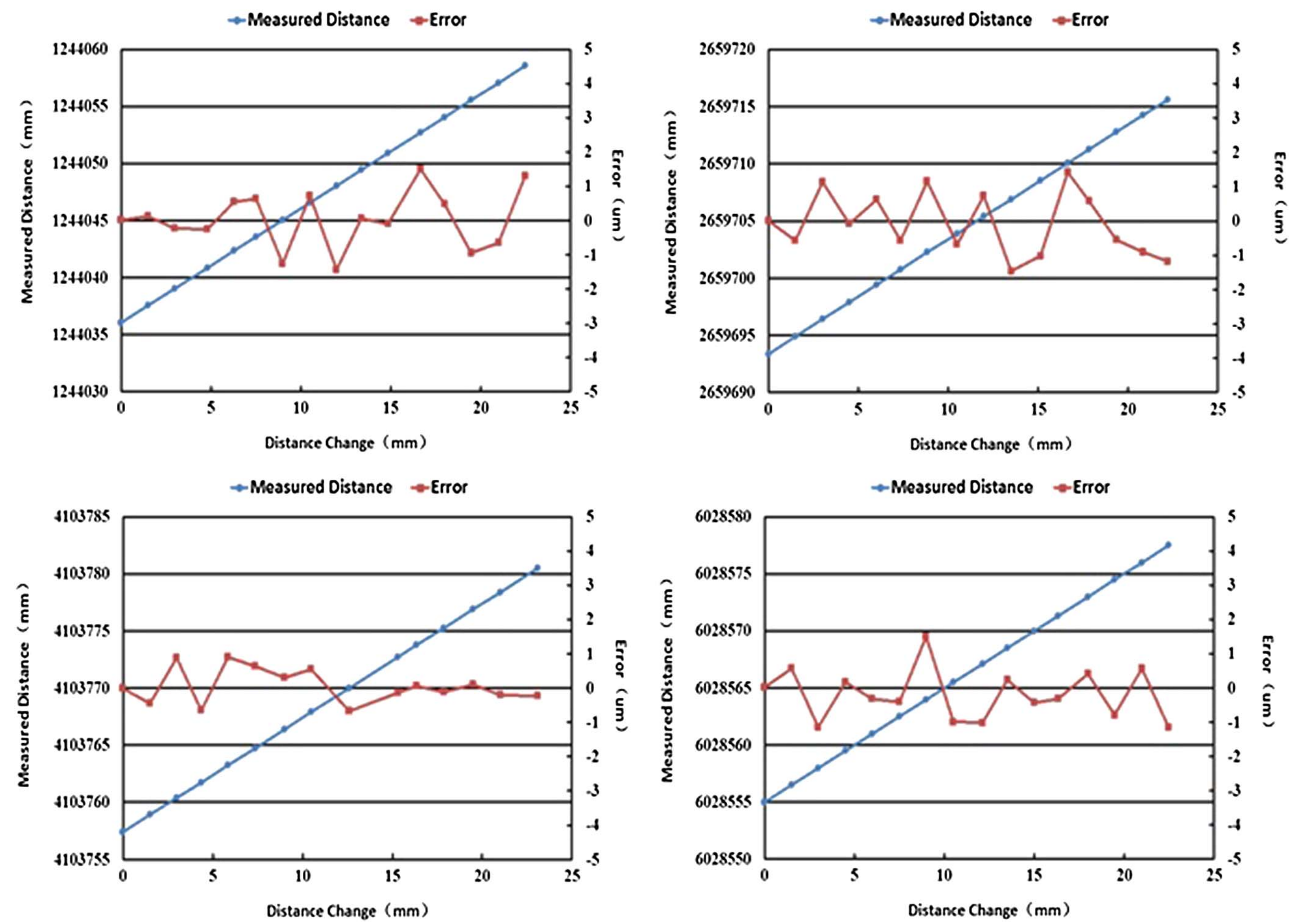

Fig. 4. Test results of measuring system.

higher measuring accuracy and a larger range can be achieved.

Although optical loss caused by special propagation is high and the inter-satellite environment is complicated, the line of sight between satellites could be made available by applying the appropriate pointing, acquisition, and tracking technique. In practice, propagating through a long distance will cause high optical losses, which would broaden the linewidth of the OEO and decrease the measurement accuracy. In order to imitate a practical measurement environment, another experiment for measuring the OEO linewidth under high optical loss was performed. The experimental setup is shown in Fig. 5.

Figure 5 shows a schematic of an OEO system to evaluate the dependence of the system performance on optical losses. The length of the SMF was about 8 km. A variable optical attenuator (ATT) was utilized to generate optical loss. Meanwhile, an optical amplifier with automatic power control (APC-EDFA) was placed in front of the photodetector (PD) to compensate for this loss. The output microwave signal of the oscillator was recorded by an electrical spectrum analyzer (ESA). The spectral linewidth of the OEO was measured when varying the attenuation of the ATT from 10 to 45 dB with a step of 5 dB. The results are shown in Table 1.

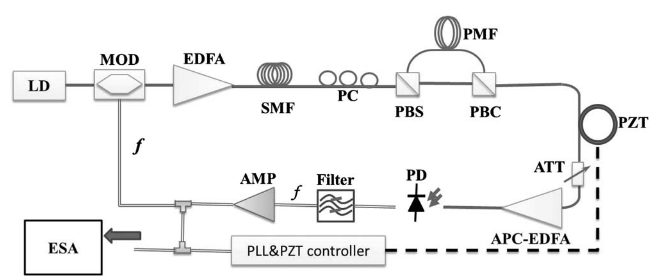

Fig. 5. Experimental setup for measuring the OEO linewidth under high optical loss.

As shown in Table 1, the linewidth of the OEO is less than 1 Hz (due to the 1 Hz resolution bandwidth of the ESA) under optical losses ranging from 10 to 45 dB. There is no observable change in the spectral linewidth of the OEO. It is clear that the use of an APC-EDFA can effectively compensate for the optical loss and maintain the desired linewidth and measuring accuracy. In a space situation, the proposed range-finding method can have a large dynamic range of optical losses.

An inter-satellite range-finding method with a large range and high precision based on optoelectronic

Table 1. Results of the Linewidth Measurement of the OEO

Attenuation (dB)	Linewidth (Hz)		
10	1	1	1
15	0	1	1
20	1	1	1
25	1	1	1
30	1	1	1
35	1	1	1
40	1	1	1
45	1	0	0

resonance is proposed. It utilizes the characteristics of a long resonant cavity, high spectral purity, and high oscillation frequency of an OEO to magnify the measured distance variation 10^5–10^6 times. Its measuring accuracy is higher than 1.5 μm, and the relative measuring accuracy reaches the level of 10^{-10}. High-precision inter-satellite range-finding technology has great significance for applications such as satellites flying formations, satellite coordination, satellite gravity field measurements, autonomous orbit determination of navigational satellites, and so on.

This work was supported in part by the Chinese National Natural Science Foundation (Nos. 61427817 and 61405142) and the Independent Innovation Fund of Tianjin University (No. 1601).

References

1. M. Navabi, M. Barati, and H. Bonyan, in *Proceeding of International Conference on Recent Advances in Space Technologies*, 277 (2013).
2. B. D. Tapley, S. Bettadpur, J. C. Ries, P. F. Thompson, and M. M. Watkins, Science **305**, 503 (2004).
3. B. Lu, F. Wei, Z. Zhang, D. Xu, Z. Pan, D. Chen, and H. Cai, Chin. Opt. Lett. **13**, 091402 (2015).
4. K. Jeongrae and D. Byron, J. Spacecraft Rockets **40**, 419 (2003).
5. C. Reigber, R. Schmidt, F. Flechtner, R. König, U. Meyer, K.-H. Neumayer, P. Schwintzer, and S. Y. Zhu, J. Geodynamics **39**, 1 (2005).
6. D. Schutze, G. Stede, V. Muller, O. Gerberding, C. Mahrdt, B. Sheard, G. Heinzel, and K. Danzmann, in *Proceeding of LISA Symposium*, 285 (2012).
7. H. Zhang, W. Meng, Z. Wu, J. Chen, and Z. Zhang, Chin. J. Lasers **40**, 0308005 (2013).
8. J. Shen, S. She, K. Wang, D. He, and Y. Huang, Chin. J. Space Sci. **27**, 342 (2007).
9. B. S. Sheard, G. Heinzel, K. Danzmann, D. A. Shaddock, W. M. Klipstein, and W. M. Folkner, J. Geodesy **86**, 1083 (2012).
10. X. Yao and L. Maleki, Electron. Lett. **30**, 1525 (1994).
11. X. Yao and L. Maleki, J. Opt. Soc. Am. B **13**, 1725 (1996).
12. X. Yao, L. Maleki, and D. Eliyahu, IEEE MTT-S Int. Microw. Symp. Dig. **1**, 287 (2004).
13. Y. Jiang, G. Bai, L. Hu, H. Li, Z. Zhou, J. Xu, and S. Wang, IEEE Photon. Technol. Lett. **25**, 382 (2013).
14. J. Wang, J. Yu, W. Miao, B. Sun, S. Jia, W. Wang, and Q. Wu, Opt. Lett. **39**, 4412 (2014).
15. X. Zou, X. Liu, W. Li, P. Li, W. Pan, L. Yan, and L. Shao, IEEE J. Quantum Electron. **52**, 1 (2016).
16. Y. Jiang, J. Yu, Y. Wang, L. Zhang, and E. Yang, IEEE Photon. Technol. Lett. **19**, 807 (2007).
17. S. Jia, J. Yu, J. Wang, W. Wang, Q. Wu, G. Huang, and E. Yang, IEEE Photon. Technol. Lett. **27**, 213 (2015).