Research on Weak-Light Phase Locking

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Abstract: The weak-light phase locking is an important module of the inter-satellite laser in terferometric ranging technology, which can amplify the power of the weak-light signal rece ived through a long distance and transmit it back with the same phase. The article introduc es and analyzes the principle, research status and noise analysis of weak-light phase locking, providing a reference for further research on weak-light phase locking.

1. Introduction

In the field of gravitational-wave detection and gravitational measurement, inter-satellite laser interferometric ranging technology can provide higher ranging accuracy and meet higher mission requirements. Although collimated laser beams are used in inter-satellite laser interferometry, the beam size of the emitted laser that propagates over a longer inter-satellite distance becomes much larger than that of the satellite. Because the divergence angle of the laser beam is determined by the diffraction limit, and the propagation distance is very long, about 105 to 106 kilometers [1]. As a result, the optical power received by the target satellite is very weak, and the power attenuation of the inter-satellite laser beam is so severe that the typical solution of the Michelson interferometer with only a mirror is not suitable for inter-satellite laser interferometry. To solve this problem, weak-light phase locking technology is used instead of simple reflection. The optical phase-locked loop can lock the phase of the local (slave) laser to the phase of the received light. In this way, the light emitted from the laser has the same phase as the light received, but the optical power is much greater.

2. The basic principle of weak-light phase locking

The weak-light phase locking is realized by the optical phase-locked loop. The difference from the general optical phase-locked loop is that the light received is very weak. The optical phase-locked loop is essentially a phase-locked loop system in the optical frequency band. The input of the loop is signal light and the output of the loop is local oscillator light. The function of the optical phase-locked loop is to use electrical feedback technology to achieve phase locked and tracking phase difference between signal light and local oscillator light. The structure of a standard optical phase-locked loop is shown in Figure 1, which consists of the following parts: optical phase detector (OPD), loop filter (LF) and optical voltage-controlled oscillator (OVCO). The optical voltage-controlled oscillator is a laser in fact.

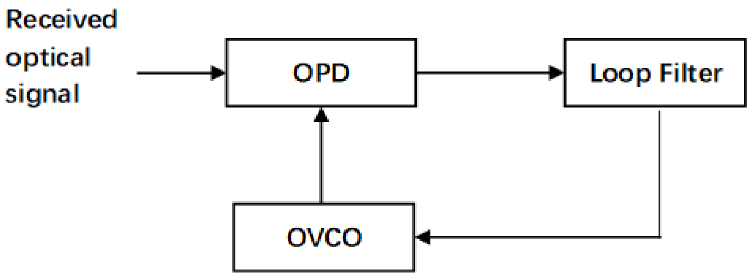

Figure 1. Schematic of OPLL

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Similar to the working principle of the traditional phase-locked loop, the optical phase detector detects the phase difference between the received light and the local oscillator light, and outputs the corresponding error signal. According to the need of the loop, the loop filter processes the error signal through filtering and integrating to generate a control signal to control the optical frequency output by the local oscillator laser. To realize closed-loop control, the optical carrier output from the local oscillator laser is fed back to the phase detector for phase detection.

In the closed loop, if the frequency difference between the local oscillator light and the signal light is less than a certain value, the frequency of the local oscillator light will gradually close to the received light frequency according to a certain rule. This process is called "frequency pulling". In the traction process, there will be some cycle slips. When the frequency of the local oscillator light and the frequency of the signal light are close enough, the local oscillator light only needs to undergo a phase transient process to lock with the signal light, and there is no periodic slip during this process. This process is called phase capture. When the loop is locked, the local oscillator light and the signal optical carrier have the same frequency and phase, and theoretically the output of the optical phase detector is zero at this time.

When the signal light frequency changes, the local oscillator light will automatically track the signal light frequency within a certain range due to the effect of the loop, so as to realize the synchronization of the optical carrier, the transmission of coherence and the flexible control of the light frequency.

3. Research status of weak-light phase locking

Enloe and Rodda [2] used homodyne phase-locked technology to manufacture two single-frequency He-Ne (He-Ne) lasers in 1965. The lasers oscillated at the same frequency and the phase difference is smaller than a third of one degree. After the 1990s, optical phase-locked loops have been widely used in the fields of optical communications, quantum optics, cold atom physics and laser interferometers [3-7]. The research laid the foundation for optical phase-locked technology. However, the research of weak-light phase locking faces new challenges, including quantum shot noise and phase noise at low frequencies, ranging from 0.1 mHz to 1 Hz.

Liao et al. proved that homodyne phase can be locked when the power of weak light is 2 pW. A neutral density filter is used to attenuate the laser, and a balanced detection method is used to eliminate laser intensity noise and improve the signal-to-noise ratio. The experimental result shows that the phase error is 290 mrad (rms) within 1.5 minutes of locking time [8].

Ye and Hall showed a high-performance optical phase-locked loop between two continuous wave Nd: YAG lasers. The feedback system uses the laser’s internal piezoelectric transducer (PZT) and external acousto-optic modulator (AOM). PZT (bandwidth approximately 20 kHz) corrects for slow but potentially large laser frequency drift, while AOM (bandwidth approximately 200 kHz) eliminates rapid frequency fluctuations. The residual phase noise is about 1μrad, and at 1 Hz and above, the phase noise outside the loop is about $0.6\mu\text{rad/Hz}^{1/2}$ [9].

McNamara et al. reported an experiment with a frequency offset of 15 MHz. Using a weak light intensity of 17 nW, they obtained the smallest residual noise in the frequency range of 10~800 Hz[10]. On this basis, they improved the weak-light phase locking performance of LISA in 2005. Experimental results show that the residual phase noise of the slave laser reaches the shot noise limit ($0.13\mu\text{rad}/\text{Hz}^{1/2}$) above 0.4 Hz when the power of the weak light was attenuated down to 13 pW[1].

Diekmann et al. realized an analog optical phase-locked loop with an offset frequency of 20 MHz, in which the detected optical powers of the two lasers were 31 pW and 200 μW. The phase noise between the two lasers is twice the shot noise limit as low as 60 mHz, and the residual phase noise below 60 mHz mainly comes from the analog electronics of the phase meter. This article describes in detail the noise generated by photodetectors, such as shot noise of photodiodes, Johnson noise and equivalent current noise of transimpedance amplifiers[11].

Dick et al. [12] and Francis et al. [13] demonstrated weak-light phase locking, with optical power as low as 40 fW and 30 fW. In order to lock the two lasers with this weak optical power, the parameters of the loop filter must be optimized to balance the laser phase noise and shot noise, so that the cycle slip rate can be minimized.

4. Noise analysis of weak-light phase locking

The noise of a weak light phase-locked loop comes from three main parts of a typical phase-locked loop: laser, phase meter and photodetector. The sources of laser noise include frequency fluctuations and photon number fluctuations (shot noise). Since shot noise is the limit of quantum noise, the optimal design of the phase-locked loop must ensure that shot noise is dominant. In the case of only shot noise, the cycle slip in the phase-locked loop can be reduced to any desired level by reducing the loop bandwidth [14]. However, when the laser frequency (phase) noise cannot be ignored, the loop bandwidth should be optimized.

The measurement noise of the phase meter is caused by the sampling time jitter of the analog-to-digital converter (ADC), the quantization error of the ADC, and the thermal drift of some thermal electronic components. By using the pilot tone correction technology, the phase error caused by the jitter of the ADC sampling time can be reduced [15, 16].

In principle, reducing loop noise requires a higher control bandwidth. Conversely, reducing loop noise requires lower control bandwidth. Therefore, the control bandwidth (or loop gain) is a key parameter that should be optimized for weak-light phase locking. In addition, cycle (time) delay is another key parameter that should be carefully considered. The control bandwidth can be determined by considering the loop delay and laser frequency noise [3].

5. Conclusion

The weak-light phase locking is an important part in the inter-satellite laser interferometric ranging process. Through the analysis and investigation of the weak-light phase locking, this paper shows that the research of the weak-light phase-locked loop faces some challenges, including quantum shot noise and phase noise at low frequencies, ranging from 0.1 mHz to 1 Hz. The noise sources of weak-light phase-locked loop include: laser, phase meter and photodetector. The weak-light phase-locked loop should be optimized accurately according to analysis of the noise sources.

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