Study and simulation of heterodyne optical phase-locked loop for inter-satellite laser interferometer

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Abstract. Coherent transmission of optical signal is an important module of inter-satellite laser interferometer. Through heterodyne optical phase-locking technology, the coherent transmission of laser signals from the master spacecraft can be achieved. And in the case of ensuring the stability of the local laser frequency, amplifying of the optical output power is realized. This article introduces and analyzes the principle, modeling and simulation of heterodyne optical phase-locking technology, which provides a reference for the realization of laser signal’s coherent transmission from slave satellite.

Keywords: Heterodyne, phase-locked loop, optical frequency.

1. Introduction
The rapid development of space science and technology and the continuous advancement of inter-satellite high-precision ranging technology have laid a solid foundation for the detection of the earth's gravitational field and the detection of gravitational waves in the universe [1-3]. The development plan of the next generation of Earth's gravity field detection satellite and space gravitational wave detection satellite has made the inter-satellite laser interferometer gradually become a research hotspot in the field of high-precision inter-satellite ranging at home and abroad [4-8]. Using the laser carrier as the inter-satellite ranging signal, the relative motion between the satellites brings a MHz-level Doppler shift to the laser carrier [9] [10]. 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 [11]. 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, heterodyne optical phase-locking technology is used instead of simple reflection.

2. Study on Heterodyne Optical Phase Locking Technology

2.1. The principle of heterodyne optical lock-in technology.
Optical phase-locked loop (OPLL) is a specific application of phase-locked loop. There are two models of optical phase-locked loops, one is a homodyne optical phase-locked loop, and the other is a heterodyne optical phase-locked loop. Both of these optical phase-locked loops are designed to use the
beat signal of the optical signal emitted from the remote laser and the optical signal output by the local laser. The homodyne optical phase-locked loop uses the phase-locking principle to lock the two lasers at the same frequency, and the beat frequency is zero. The heterodyne optical phase-locked loop locks the two lasers at a frequency with a fixed frequency difference $\Delta f$ (heterodyne frequency), but keeps the phase change consistent.

Generally, heterodyne optical phase-locked loops are mainly used in occasions with Doppler frequency shift. Calculated by the low and low tracking gravity satellite orbit height, the Doppler caused by the motion of the double satellites is a MHz-level shift, so it is appropriate to choose the heterodyne optical phase-locked loop.

The principle of heterodyne optical phase-locked loop is shown in Figure 1. After the two laser beams are mixed by a non-polarizing beam splitter (BS), the mixed light with beat signal will be output. After the mixed light passes through the photodetector, it is mixed with the heterodyne frequency source, and the output signal is sent to the loop filter. The filtered signal is used to control the PZT port of the laser resonator of the local laser (Laser2) to adjust the frequency of Laser2. And making it follow the frequency and phase changes of Laser1.

![Fig. 1 Schematic diagram of heterodyne optical phase lock](image)

2.2. PLL model.

The phase detector is realized through a multiplier. For the design of the loop filter, three parameters should be considered.

(1) Damping coefficient and natural frequency

The natural frequency and the damping coefficient have a decisive influence on the phase tracking loop. When the damping coefficient value is in the range of 0 to 1, the loop is under damped. And inputting a step excitation signal to the phase-locked loop, its response is more intense in the initial stage, and the phase-locked loop reacts more sensitively to the input signal. When the damping coefficient value is greater than 1, the phase-locked loop reacts slowly to the step-type excitation signal, and the oscillation in the initial stage is relatively small. The simulation analysis shows that with the continuous increase of the damping coefficient, the response of the phase-locked loop oscillates in the passband part, the gain is more stable, and the gain decline in the stopband part is slower, and filtering effect on out-of-band noise is worse. The design of the above two parameters involves the design of the loop bandwidth, so the specific setting of the damping coefficient and the natural frequency should be considered in conjunction with the setting of the loop bandwidth below.

(2) Loop bandwidth

The effect of the loop bandwidth on the phase-locked loop is mainly reflected in the fact that the phase-locked loop filters out noise signals outside the passband by setting the loop bandwidth, and allows useful signal components and part of the noise signal components in the passband to pass through
the loop. Therefore, the size of the loop bandwidth determines the size of the noise component entering
the phase-locked loop. The smaller the loop bandwidth, the greater the suppression of the noise
component, which means that the phase-locked loop can measure the useful carrier signal more
accurately. Conversely, the larger the loop bandwidth, the more noise components enter the phase-
locked loop, and the lower the phase measurement accuracy. However, in this case, the adaptability to
dynamic carriers is better. The loop bandwidth of the second-order phase-locked loop is:

$$B_L = \frac{\omega_n}{2} \left( \xi + \frac{1}{4\xi} \right)$$  \hspace{1cm} (1)

It can be seen from the above formula that the loop bandwidth is related to the damping coefficient
and the natural frequency. According to the influence of the loop bandwidth on the dynamic adaptability
and tracking accuracy of the phase-locked loop, when selecting the natural frequency and damping
coefficient, it is necessary to consider the balance between dynamic adaptability and tracking accuracy
to achieve better dynamics. The relationship between the carrier-to-noise ratio of the interference signal
received by the satellite-borne digital phase meter and the phase-locked loop's phase measurement
accuracy of the carrier is

$$\sigma_{PLL} = \frac{180^\circ}{\pi} \sqrt{\frac{B_L}{C/N_0} \left( 1 + \frac{1}{2\times T_{coh} \times C/N_0} \right)}$$  \hspace{1cm} (2)

(3) Loop update cycle
The loop update cycle refers to how often it controls and adjusts the output frequency of its
numerically controlled oscillator. The reciprocal of the update cycle is called the update rate.

2.3. Laser model.
The tunable laser is a key component in the optical phase-locked loop, and its performance parameters
determine the performance of the phase-locked loop and the entire coherent receiver. The main
parameters describing the performance of a tunable laser are as follows:

- Laser linewidth: reflecting the output frequency characteristics of the laser. It is related to the phase
  noise of the laser, and is directly related to the determination of the parameters of the phase-locked loop.
- Tunable range: It is related to the range that can be quickly locked.
- According to the product manual of the laser actually used, the adjustment coefficient of the PZT
  port of the laser is 2MHz/V, which means that every time the voltage applied at the PZT port increases
  by 1V, the frequency of the optical signal output by the laser will increase by 2MHz. The adjustment
  coefficient of the temperature port is -3.1GHz/V, which means that every time the voltage applied at the
  temperature end increases by 1V, the frequency of the optical signal output by the laser will drop by 3.1
  GHz. Since the frequency response speed of the temperature port of the optical phase-locked laser is
  slow, the temperature port mainly realizes the compensation of the large-scale frequency drift of the
  laser, and the real-time and fast phase-locked tracking is mainly completed by PZT, so the phase-locking
effect is also determined by the PZT port. The frequency control of the PZT port is mainly considered
in the simulation.

In the Matlab simulation, the local oscillator laser model adopts a linear model, and the oscillation
frequency changes linearly with the control voltage $u_c(t)$:

$$\omega_{LO}(t) = \omega_0 + K_0 u_c(t)$$  \hspace{1cm} (3)

$K_0$ is called the control sensitivity or gain coefficient, and the unit is rad-Hz/V. In the simulation,
$K_0$=2*pi*2e+6.

3. Simulation Verification
The heterodyne optical phase-locking technology is used to complete the optical frequency signal
coherent transmission of the inter-satellite laser interferometer. Figure 2 is a block diagram of the
simulation system.
First, consider that the output wavelength of the laser actually used is 1064nm, and its frequency is in the order of THz. It is not realistic to simulate this frequency in the simulation. Therefore, in the actual simulation process, the received signal frequency is selected as 20Mhz. The Doppler frequency shift caused by the relative motion between satellites is 2.8Mhz, and its calculation formula is as follows:

\[
f_d = \frac{v}{c} \cdot f = 2.8 \text{MHz}
\]  

\( f = 2.8e + 14 \text{Hz} \) is the laser frequency, \( c \) is the speed of light, and \( v = 3 \text{m/s} \) is the maximum relative motion speed between stars. When the sampling rate of the phase-locked loop is 58MHz and the heterodyne frequency source is \( f_{off} = 12 \text{MHz} \), the frequency ramp-up excitation input simulation system is selected to quickly verify the rationality of the parameters of the heterodyne optical phase-locked loop system. Figure 3 shows the output results of the phase detector and loop filter. It can be seen that in the initial 0.12s, the phase-locked loop is in a dynamic adjustment process, and the tracking result fluctuates greatly; after 0.25s, the loop enters a stable tracking state.

**Fig. 2** Simulation model based on Simulink

**Fig. 3** Frequency ramp-up signal tracking process
4. Summary
This article introduces the phase-locked coherent transmission interferometer system of the slave satellite. It simulates the optical frequency signal coherent transmission process of the inter-satellite laser interferometer through heterodyne optical phase-locked technology. In the case of the input signal frequency ramping up, the phase-locked loop can still better track the frequency and phase changes of the input signal. This simulation process simulates the frequency change of the laser signal received from the satellite due to the inter-satellite Doppler, and provides a theoretical reference for the engineering application of phase-locked coherent transmission from the satellite.

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