Research on Positioning Method in the Lunar Space

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Abstract. With the accomplish of Chang'e-5 mission, China's Chang'e mission has entered the next stage, that is, the development and utilization of the moon and the construction of the lunar station. However, in this stage of lunar surface exploration mission, the accuracy of positioning cannot meet the requirement. In the paper, we provide the telemetry, tracking, command (TT&C) and communication links in the lunar space at the lunar station. Then, the high accuracy positioning method is given. The method mainly positioning by ranging and angle measurement. The ranging completes the acquisition of radial parameters of transceiver nodes, and the angle measurement acquire the tangential parameters. In order to obtain high precision positioning results, BOC (5, 1) modulation system and dual one-way ranging (DOWR) are used to measure the distance, and L-type interferometer is used to measure the angle. Besides, we design the angle measurement algorithm to increase the number of transmitter that can be measured by the interferometer. Under the condition of carrier to noise ratio of 60 dBHz, the ranging accuracy is 0.947 ns, and the angle measurement accuracy is higher than 0.02 rad.

Keywords: Lunar base · TT&C · Positioning · Ranging · Angle measurement

1 Introduction

As the nearest celestial body to the earth, the moon will be used as a relay station for deep space exploration in the future. Since the 1970s, the United States, the Soviet Union and other countries have been carrying out exploration of the moon to show the strength of nation. With the end of the cold war, the exploration of the moon has gradually changed from a political mission to a scientific mission [1]. Since the launch of Chang'e-1 on October 24, 2007, China's Lunar Exploration Mission has been carried out step by step. As of December 18, 2020, the five Chang'e exploration missions have been successful.

In the future, manned landing on the moon and the construction of lunar sur-face stations will also be carried out. After completing the first phase of Chang'e exploration missions, China will gradually start the construction of lunar station.

However, the lunar polar resource exploration, manned lunar landing and the construction of lunar station put forward higher requirements for navigation and positioning tasks. And the high-precision lunar navigation and positioning function is a vital part of

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manned lunar exploration. Although very long baseline interferometry (VLBI) observation can achieve high precision positioning of 10 m magnitude, there are many nodes on the moon surface during the construction of the moon base which will lead to the lack of the spectrum resources and VLBI resources. Besides, the combination of inertial navigation system (INS) and image navigation are used in most missions. However, the error of INS will drift with time, it is impossible to achieve high-precision navigation and positioning [2].

This paper analyzes the high-precision positioning methods in the construction of the lunar station. Firstly, the scene of this stage is designed, including the distribution of each node on the lunar surface and the allocation of related links. Then, the BOC & single carrier mode is used to position the lunar surface unit. BOC signal is used for ranging, and single carrier signal is carried at the central frequency of integrated signal for angle measurement. If the results of angle measurement and range measurement are obtained, the lander or rover on the lunar surface can be located. After obtaining its body coordinate system, it is converted to the moon fixed coordinate system through the lunar stations or lander at a fixed position on the lunar surface.

2 The Scene and Link Design of Lunar Station

There are two methods to position the lunar unit. One is to locate the lunar surface unit through the TT & C links between earth and moon. The method has a large number of TT & C units on the ground which has complete functions and strong controllability. However, the control unit far away from the moon, with prolonged time and large signal attenuation. The second method is to position the lunar surface unit through the near moon unit or the lunar surface unit (including the lunar relay satellite, rover, etc.), which has the advantages of strong autonomy, short distance from the unit and high measurement accuracy, but the disadvantage is that it needs strong autonomy. In this paper, the positioning of the near moon unit is carried out through the earth moon TT & C link and the orbit information of the near moon unit. And the unit on the moon surface can be positioned by near moon unit. The link designs in the two scenarios are as follows [3].

The earth and nearby nodes are mainly as follows .

1) Mission Center: it provides command of the whole task;
2) Deep space TT & C network: it provides ground TT & C support and completes high-speed data receiving and sending on the ground.
3) VLBI measurement station: it mainly finish the TT & C of spacecraft;
4) Earth relay satellite system: it is the system in earth orbit that provides relay services for spacecraft data transmission;
5) Beidou navigation satellite system: to a certain extent, it is the communication relay for the space units near the moon (Fig. 1).

The moon and its nearby nodes are as follows:

1) Lunar station: it is the main node of the lunar surface and serves as the center of the whole trunk communication;

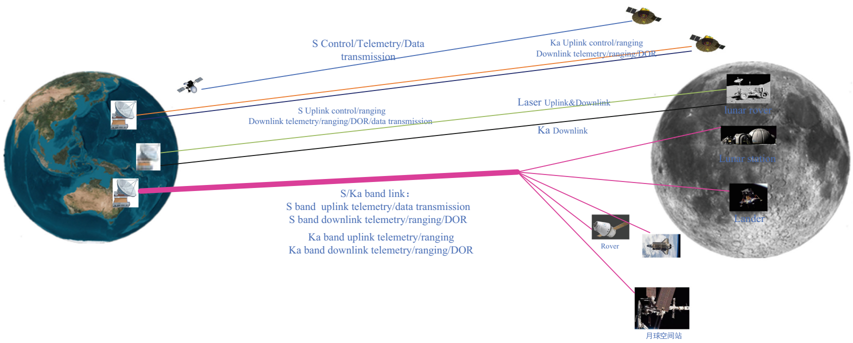

Fig. 1. Design of links between earth and moon

2) Relay satellite system: it is located in the orbit around the moon, providing data relay services for lunar orbiting spacecraft and landing facilities;
3) Lunar orbiting space station: it is the smallest platform in lunar orbit. Its main purpose is to improve the capability of deep space exploration as a test site;
4) Lunar Rover: it provides large-scale exploration vehicle within the scope of the moon, it is necessary to establish links on the ground to ensure the security of the mission.
5) Lunar surface lander/ascender: it is a spacecraft used to land and rise on the lunar surface and rendezvous with the lunar orbiting space station;
6) Astronaut: the executor of space science exploration activities (Fig. 2).

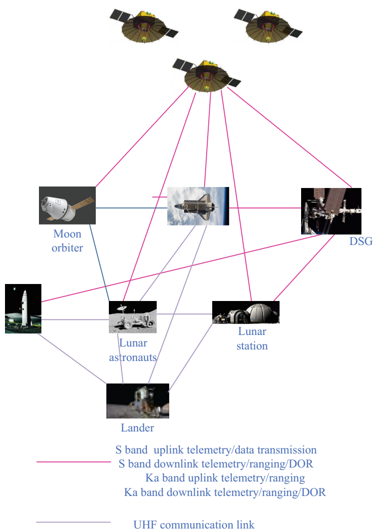

Fig. 2. Design of links near moon

The functions of lunar station can be generally divided into the following parts:

1) Scientific exploration and the related experimental functions.

2) Ensuring the basic survival of relevant personnel.

The above units need to carry out data links with the lunar relay satellite, the ground, the astronauts and each other at the same time, so they need to be equipped with standard S band TT & C, navigation system, Ka band TT & C, navigation system, Ka/laser high-speed data transmission system and UHF local communication system.

Considering there are many lunar surface units and the bandwidth resource is scarce, S/Ka band is used for TT & C data transmission. For example, the relay satellite needs to establish TT & C data transmission links with large instruments on the lunar surface. In addition, data transmission is needed between large lunar units (such as manned spacecraft, lunar orbital space station and lunar base).

3 Design of Lunar Positioning Signal

The lunar surface communication unit should equip standard S band TT & C system, navigation system and UHF communication system. Besides, it must have sufficient redundant communication capability and emergency communication capability. The lunar rover and the lander use the lunar surface UHF communication link to realize data exchange. When the lunar unit cannot observe more than three navigation units at the same time, the system uses single point ranging and angle measurement are used for positioning. Here, the lunar rover and lander are taken as examples to illustrate. First, we can achieve data exchange between lunar rover and lander by lunar UHF communication link. Then, UHF duplex communication terminals with BOC modulation and single carrier modulation are configured on lunar rover and lander respectively. The DOWR is used to eliminate the clock error and pseudo range to further improve the positioning accuracy. The angle is measured by carrier phase differential interferometry [4].

3.1 Signal Model

In the paper, the binary offset carrier (BOC) signal and single carrier signal transmit at the same frequency. Due to the BOC signal can free the bandwidth of the center frequency, the single carrier can transmit at the same time for angle measurement.

The BOC signal can be expressed as (3.1):

$$s(t) = d(t) \cdot g(t) \cdot c(t) \tag{3.1}$$

Here, $d(t)$ is navigation data. $g(t)$ represents the PN sequence which the frequency can be expressed as f_c. $c(t)$ is the subcarrier sequence which the frequency can be expressed as f_s. And the f_c and f_s are multiple of 1.023 MHz. (3.2) is the relationship between them.

$$\begin{cases} f_s = m \times 1.023\ \text{MHz} \\ f_c = n \times 1.023\ \text{MHz} \end{cases} \tag{3.2}$$

In the paper, the BOC signal adopts BOC (5, 1) signal. The main lobe range is 4.092 MHz–6.138 MHz. In addition, BOC (5, 1) has excellent anti-multipath ability.

The bandwidth of integrated signal is less than 15 MHz, and the signal transmission and reception can be realized by digital signal processing. Besides, the RF channel is easy to realize and miniaturize.

The integrated signal can be expressed as (3.3)

$$s_{IF}(t) = s(t)\cos(2\pi f_{IF} t) + \cos(2\pi f_{IF} t) \quad (3.3)$$

Here, $s_{IF}(t)$ is intermediate frequency (IF) signal. f_{IF} is the frequency of IF signal. $\cos(2\pi f_{IF} t)$ is the single carrier signal which used to angle measurement. In the paper, we adopt 14.96 MHz as IF.

The power spectrum of the transmitted signal are shown in Fig. 3.

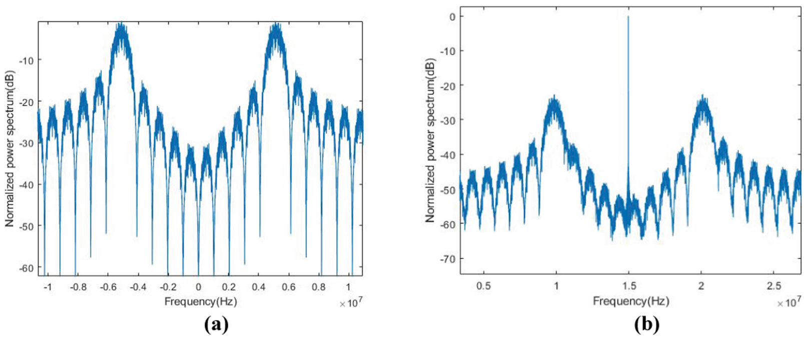

Fig. 3. Normalized power spectrum of transmitted signal. (a) Normalized power spectrum of base-band BOC (5, 1) signal; (b) Normalized power spectrum of intermediate frequency signal

3.2 Angle Measurement Signal Receiving Algorithm

The position of antenna array elements is shown in Fig. 4.

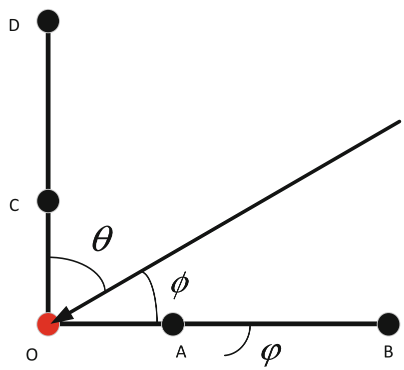

Fig. 4. Diagram of orthogonal baseline phase interferometer

In the lunar surface positioning system, the two-dimensional linear interferometer is used to measure the angle. The distance between the baseline OA and OC are equal, and the distance between the baseline AB and CD are equal.

The UHF frequency is used for interference angle measurement on lunar surface. Considering that the ambiguity of carrier phase will exist when the length of the second baseline is larger than half wavelength of the signal, two groups of cross prime baselines are needed to solve the ambiguity. In this case, the traditional five antenna interferometer can only measure the angle of a single signal. Therefore, compared with the spatial spectrum algorithm, the interferometer system has a great disadvantage in measuring the arrival direction of multiple signals at the same time. The disadvantage means it cannot locate multiple targets on the lunar surface at the same time. Moreover, when the number of nodes near the moon is limited, it is impossible to ensure that the nodes can establish ranging links with more than four nodes at any time. Therefore, it is necessary to locate multiple nodes through a single interferometer antenna.

The receiver distinguishes the nodes by frequency division. The receiver receives signals of different frequency points at different times. The frequency switching modes are provided, such as Table 1.

Table 1. The frequency switching method of antenna

Time	Antenna				
	O	A	B	C	D
T1	f_1	f_2	f_3	f_4	f_5
T_2	f_5	f_1	f_2	f_3	f_4
T_3	f_4	f_5	f_1	f_2	f_3
T_4	f_3	f_4	f_5	f_1	f_2
T_5	f_2	f_3	f_4	f_5	f_1

Because the microwave switch will switch each antenna element, so each channel cannot track the signal stably. In this case, the receiver should recapture and track the signal frequently, which will eventually affect the accuracy of signal ranging and angle measurement. In this paper, when there is no corresponding frequency signal input, the external extrapolation method is used to keep the tracking loop stably. Thus, the tracking loop can ensure long-term ranging and interferometer measurement without losing lock.

The dual frequency point switching methods of antenna array element have their own advantages. The switching mode in Table 1 ensures each frequency point has corresponding signal reception at each time, and will not cause the loop locking due to the sudden change of Doppler frequency.

The tracking loop extrapolation algorithm is as follows:

1) At the end of the period when each antenna element has received signal, the carrier phase offset, and pseudo code phase offset in the carrier tracking loop and pseudo

code tracking loop are input into the simulate transmission signal module. And the analog transmission signal is offset according to the values;
2) When there is no signal input, the output of simulate transmitting signal module is imported into the tracking loop.

The angle measurement method is as follows:

1) Extract the carrier phase in the carrier tracking loop. If the baseline length is greater than half wavelength, the integer ambiguity should be solved according to the Chinese remainder theorem as (3.4).

$$\Delta e(N_1, N_2) = d_1 \cdot (N_2\lambda + \frac{\Delta\phi_2}{2\pi}\lambda) - d_2 \cdot (N_1\lambda + \frac{\Delta\phi_1}{2\pi}\lambda) \tag{3.4}$$

Here, d_1 is the length of OA. d_2 is the length of OB. N_1, N_2 are integer ambiguity. $\Delta\phi_1$ represents the carrier phase difference of OA. $\Delta\phi_2$ represents the carrier phase difference of OB. λ is the wavelength of signal.

2) Searching the integer N_1, N_2 when minimum Δe of baseline OAB and OCD. Through (3.5, 3.6), the angle measurement of baseline OAB and the angle measurement of baseline OCD can be calculated.

$$\phi = \arccos\left(\frac{N_{2\_OB}\lambda + \frac{\Delta\phi_{2\_OB}}{2\pi}\lambda}{d_2}\right) \tag{3.5}$$

$$\theta = \arccos\left(\frac{N_{2\_OD}\lambda + \frac{\Delta\phi_{2\_OD}}{2\pi}\lambda}{d_2}\right) \tag{3.6}$$

Here, N_{2_OB}, N_{2_OD} are the integer ambiguities of antenna OB and OD's carrier phase difference. ϕ_{2_OB}, ϕ_{2_OD} are the part which less than 2π in the antenna OB and OD's carrier phase difference.

3) The pitch angle is $\frac{\pi}{2} - \theta$, and the formula of azimuth angle is shown in (3.7)

$$\varphi = \arccos\left(\frac{\cos\phi}{\cos\theta}\right) \tag{3.7}$$

4 Simulation and Error Analysis

In order to realize the positioning of lunar spacecraft, the main measurement error comes from the process of ranging and angle measurement. Among them, BOC signal acquisition and tracking algorithm has been more mature in foreign and domestic, this paper mainly focuses on the simulation of multi-target interferometer measurement algorithm.

4.1 The Simulation of Angle Measurement Algorithm

The signal frequencies are set as $f_1 = 100$ MHz, $f_2 = 200$ MHz, $f_3 = 400$ MHz, $f_4 = 550$ MHz, $f_5 = 800$ MHz. For interferometer, the length of baseline OA and OC is 0.233 m, and the length of baseline OB and OD is 0.747 m. The carrier to noise ratio is 60 dBHz and the switching time of frequency is 0.15 s.

With the increase of time, the impact of frequency switching is gradually reduced. Finally, the angle measurement error obtained by different frequencies is shown in Fig. 5. With the increase of frequency, the angle measurement error decreases gradually.

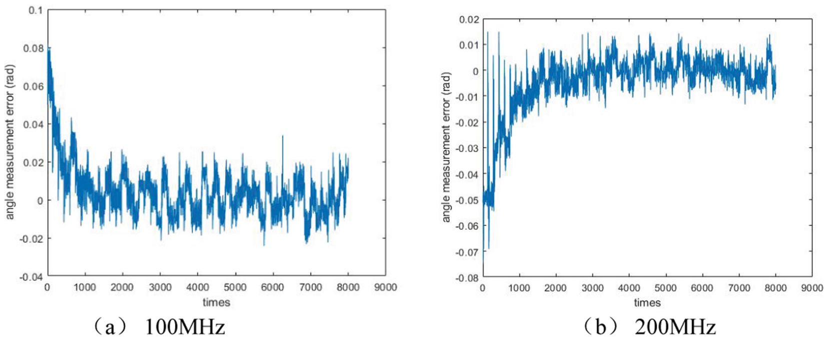

Fig. 5. The angle measurement error of different frequency (a) 100 MHz; (b) 200 MHz

4.2 Error Analysis

The main sources of receiver ranging error are thermal noise error and dynamic stress error. The dynamic stress error can be eliminated by carrier to pseudo code technique. Therefore, this paper only analyzes the ranging error caused by thermal noise. The theoretical calculation formula is as (4.1).

$$\sigma_{Ranging} = T_{chip}\sqrt{\frac{2F_1 d^2 B_{LD}}{CNR}\left[2(1-d) + \frac{4F_2 d}{T_{coh}\cdot CNR}\right]} \tag{4.1}$$

Here, T_{chip}(ns) is the code length of each chip. d is the code interval between leading/immediate/lagging of code tracking loop. B_{LD}(Hz) is bandwidth of the code tracking loop filter. T_{coh} is the integral and dump time. F_1 is the code loop correlator factor. F_2 is the code loop discriminator factor. CNR is the carrier to noise ratio.

In the system, due to we adopts the BOC (5, 1) to ranging, the parameters are as follows: $T_{chip} = 977$ ns, $d = 1/4$, $F_1 = 0.5$, $F_2 = 1$, $B_n = 10$ Hz, $T_{coh} = 1$ ms. And the thermal noise can be calculated as $\sigma_{Ranging} = 0.947$ ns.

The angle measurement process uses the carrier phase difference received by each antenna. And the phase noise of five receiving antennas has strong coherence. In the case of multi baseline carrier phase difference, the carrier phase jitter caused by the phase noise can cancel. Thus, the angle measurement accuracy is directly determined by the carrier phase measurement error (under the condition that the carrier integer ambiguity is ignored). If we adopt third-order PLL, the thermal noise error is as (4.2).

$$\sigma_{tPLL} = [\frac{B_{LF}}{C/N_0}(1 + \frac{1}{2T\cdot C/N_0})]^{0.5} \tag{4.2}$$

We choose $B_{LF} = 10$ Hz, $T = 1$ ms. And the carrier phase error is $\sigma_{tPLL} = 0.003$ rad when CNR = 60 dBHz. And the angle measurement error can be calculated as (4.3).

$$\sigma_\theta = \frac{\lambda}{d_2}\sigma_{tPLL} \tag{4.3}$$

5 Conclusion

This paper introduces the plan of lunar exploration in China, that is, the mission of building the lunar station initially. Then, the data transmission and TT & C links in the moon-earth space and near moon space are planned in the process of the mission. Aiming at the problem of insufficient lunar surface positioning accuracy, a high-precision positioning system for the future lunar station is proposed. We adopt DOWR to ranging and interferometer to angle measurement. And The integrated signal of ranging and side angle is designed.

For integrated signal, BOC (5, 1) signal is used for ranging. In this system, it can effectively reduce the multi-path interference of the lunar surface.

The angle measurement signal adopts single carrier and time division switching to realize multi-target high-precision angle measurement on interferometer.

At the end of the paper, the error in the process of ranging and angle measurement is analyzed and simulated.

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