Phase-based Radiometric System in Lunar Radio Measurements

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Abstract In December 2013, the Chang'E-3 lunar lander carrying an X-band beacon made a successful soft landing in the Rainbow Bay area, which fulfills a prerequisite for lunar radio measurement (LRM). A new LRM system had been built before the Chang'E-3 launch. And a stable phase transfer for multiple frequencies has been studied, and high-precision phase has been estimated for phase-based radiometric measurements. Finally, signal processing on the satellite DOR carrier has been conducted, and 10 mHz frequency estimation precision and 0.02 circle (7.2°) phase conjunction precision have been achieved.

Keywords Lunar radio measurement (LRM), lunar laser ranging (LLR), phase-based radiometric system, Chang'E-3 lander

1 Introduction

Precise lunar measurements form the basis for research into lunar motion and lunar geodesy. The temporal and spatial lunar reference frame is almost built based on high-precision lunar measurements. After the first lunar laser ranging (LLR) in the Apollo 11 mission, America and the former Soviet Union placed four other lunar laser mirrors. In more than 40 years, lunar laser ranging has developed, but has been limited to measuring efficiency, which needs at least eight minutes to obtain one result. Up to now, only about 20,000 standard point results have been obtained.

Compared with LLR, lunar radio measurement (LRM) can be conducted without effects caused by weather conditions and the lunar phase, which will cause a systematic error in measuring. (To avoid a strong background noise, laser lunar tracking is almost always done when the moon is halfway between new and full—rarely when the moon is full and never when the moon is new.) Moreover, once the radio transmitter of a lunar lander works, the target can be continuously tracked with a high temporal resolution. In the 1960s, radio measurements were used to obtain the lunar landing point for the American Apollo project. After 1977, due to funding limitations, LMR was interrupted for about 30 years. In December 2013, the Chang'E-3 lunar lander carrying an X-band beacon made a successful soft landing in the Rainbow Bay area, which provides a chance for us to conduct LRM again.

In contrast to traditional ranging measurements that use a pseudo code or a sidetone, the phase of a carrier is estimated and applied for precise orbit determination with a high accuracy range in the proposed LRM. Because the carrier phase in LRM can easily be polluted by phase shifts caused by environmental temperature changes, mechanical vibrations, and so on, a new LRM system in which a stable phase transfer is studied and applied to eliminate the phase error was built before the Chang'E-3 launch.

2 Signal Model

After receiving a satellite downlink signal, the radio signal should be downconverted outdoors, and then

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transmitted to a room via a cable. Suppose that the signal transmitted via the cable is presented as:

$$S(t) = A(t)\cos(2\pi f_c t + \phi)$$

With a link delay τ, the signal achieved indoors can be presented as:

$$S(t) = A(t)\cos[2\pi f_c(t-\tau) + \phi]$$

Due to changes in the environmental temperature and other influences, the link delay τ may fluctuate, which is defined as $\delta\tau$. In this case, the signal phase shift can be described as:

$$\delta\phi = 2\pi f_c \delta\tau$$

and $\delta\phi$ will cause a direct measurement error. To suppress the phase shift, we can compensate for the delay fluctuation $\delta\tau$ and apply a low frequency f_c. In the proposed system, we use an IF frequency f_c of about 70 MHz, which is far lower than the X-band and L-band frequencies.

To downconvert a radio signal to an IF signal, two levels of downconvertors are normally applied, where two local oscillator (LO) signals are required. In the proposed LRM system, we demonstrated a phase stabilization technique for multiple LO signals, where one of the LO signals is used as reference and round-trip transferred between the central station and remote end. Hence, the reference LO signal can carry the phase variation that arises from the fiber link. To stabilize the delay of the fiber link, the wavelength of the optical carrier is adjusted according to the phase variation of the reference LO signal. Obviously, the stability of the link delay will bring phase stabilities of other LO signals transferred through the same fiber link. Experimentally, LOs at frequencies of 1.21 GHz and two other values have been transferred through a fiber link; significant phase drift compression is observed. A recorded result is shown in Figures 1 and 2. The phase fluctuation of uncompensated delivery is 1.0 degree in a short time (the value will become much larger in hours). While the active compensation is on, the phase fluctuation is suppressed to about 0.05 degrees.

To obtain high-precision data products, the measurement accuracy of the system at X-band is required to be: frequency estimation accuracy better than 10 mHz and precision of relative range of about 1 mm.

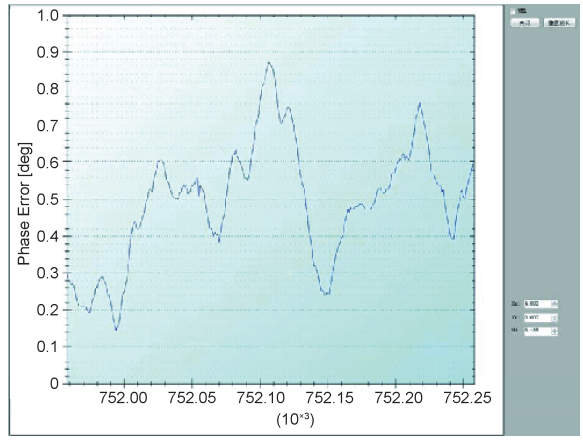

Fig. 1 Phase fluctuations of the reference signal without compensation.

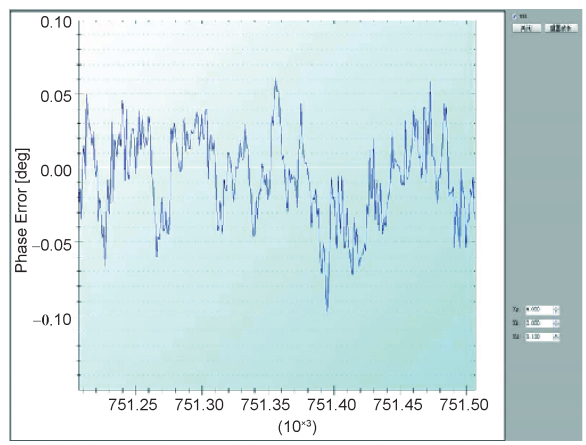

Fig. 2 Phase fluctuations of the reference signal with compensation.

The prerequisite for the overall accuracy is to eliminate each error source, including the phase drift of the RF signal.

3 Hardware System

3.1 Systematical Framework

The LRM system includes an S/X-band antenna, S-band and X-band radio links, a signal sampler, and a storage unit, as shown in Figure 3. Moreover, a phase-stable transmission sub-system for RF LO signals and a GNSS-based precise timing sub-system are built for phase-based range measuring.

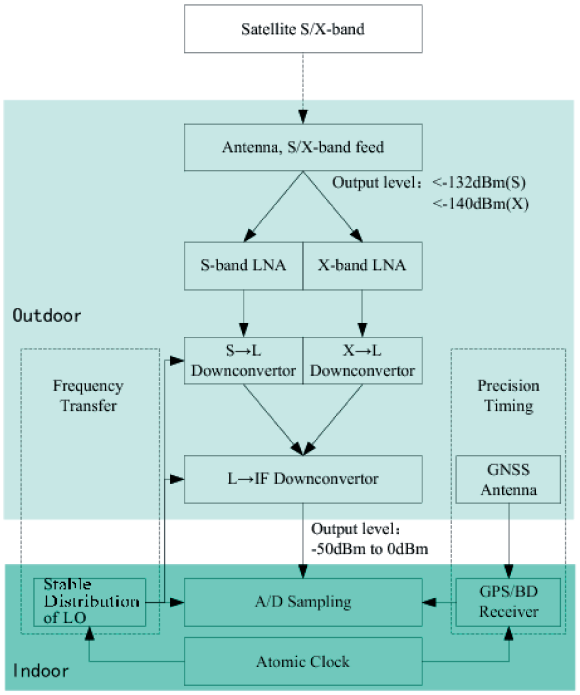

Fig. 3 Diagram of the LRM system.

Note that, to eliminate each measuring error, there are two innovations applied in the system: 1) RF LO signals, rather than an IF frequency reference signal, are transmitted to the down-converter directly, and a phase-stable transmission for RF LO signals is introduced, which has been discussed above, and 2) the down-converter is moved close to the low noise amplifier to shorten the RF cable.

3.2 Equipment

The LRM hardware system has been built completely and has received the downlink signal of the Chang'E-3 satellite. Part of the hardware equipment is presented in Figure 4.

4 Signal Processing

On 17 December 2013, the DOR signal transmitted from the Chang'E-3 lander was received. As a traditional signal processing, the received frequency has been estimated, as shown in Figure 5, where we can see that the precision of the estimation is about 10 mHz.

Fig. 4 Hardware equipment of the LRM system.

Moreover, the carrier phase of the DOR signal is also obtained for precise relative ranging, as shown in Figure 6. To avoid integer ambiguity, the phase skip between each processing conjunction is also given in Figure 6. Due to small phase skips during the observation, we believe there is no integer ambiguity.

Theoretically, the relative ranging between the lander (also the lunar) and the receiving antenna is smooth. Hence the phase of the carrier is also smooth. However, after a seventh order polynomial fitting, the residual is larger than the phase skip in Figure 6. And the fluctuation is clear, as shown in Figure 7. The reason is still unknown. If the fluctuation is caused by lunar motion with a high frequency, it will be very interesting.

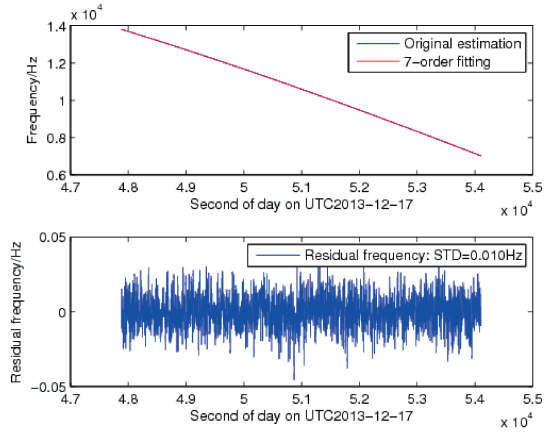

Fig. 5 Frequency estimation of the Chang'E-3 lander.

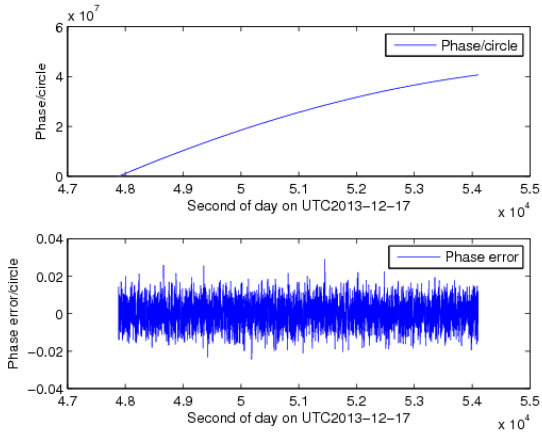

Fig. 6 Phase estimation and its conjunction error of the Chang'E-3 lander.

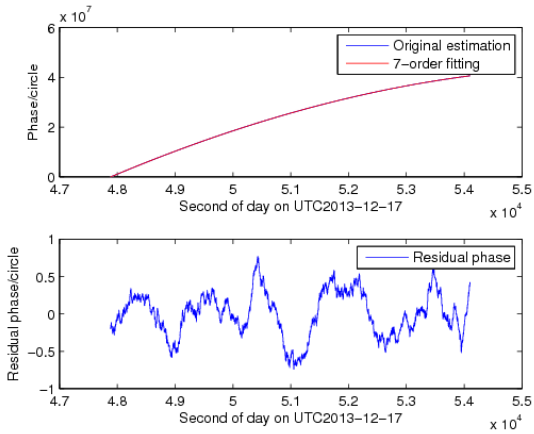

Fig. 7 Phase estimation and the residual with a seventh order polynomial fitting of the Chang'E-3 lander.

5 Conclusions

To obtain precise relative range data between the moon and the earth, a phase-based lunar radio measurement (LRM) system has been built to track the Chang'E-3 lunar lander. After proposing a stable phase transfer for multiple frequencies, the phase shift at the receiver is almost suppressed. Finally, the frequency and phase of a satellite DOR carrier are estimated with a frequency precision of 10 mHz and a phase conjunction precision of 0.02 circle (7.2°). Furthermore, after a seventh order polynomial fitting, there is an obvious fluctuation in the residual phase, which is very interesting and still needs to be explained.

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