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Obtaining the Chandrayaan-3 lander coordinates on the lunar surface by the Doppler measurements of the transmitted signal with an Earth-based receiving system

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Abstract. We determine the selenographic coordinates of the Chandrayaan-3 lander by Doppler measurements of its signal. The Chandrayaan-3 successfully landed in the south polar region of the Moon near the craters Manzinus and Simpelius on 23 August 2023 and had been transmitting scientific information and telemetry to Earth in the S and X-bands during 14 days. The accuracy of the obtained Doppler measurements do not allow unambiguous determination of the lander location on the lunar surface because the transmitter was degrading during the entire observing interval. For this reason, in our work we have evaluated the influence of the Doppler measurement characteristics on the accuracy of the transmitter location determination. It has been shown that for a signal with a relative frequency instability of the order of 10^{-13}, the achievable accuracy of coordinate determination is about 34 meters.

Keywords: ephemerides; Moon; space vehicles; techniques: radial velocities; telescopes

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1 Introduction

To obtain the position of a spacecraft in space, the optical and radio techniques are usually used. The ground-based optical observations of spacecraft have low accuracy because they are affected by the atmosphere, and the result of the measurements is the position of the object, not its distance. In addition, such observations are limited by weather conditions and daytime. The laser and radiolocation techniques allow one to measure the distance to a spacecraft directly. Both techniques have high accuracy (of the order of centimeters), but require the presence of retroreflectors (Murphy et al. 2011) or transponders (Marshalov et al. 2020) onboard. The conventional techniques for obtaining the position of a spacecraft which is transmitting a radio signal to Earth are the Doppler and radio interferometric measurements, which allow one to obtain the velocity and direction to the spacecraft, respectively (Duev et al. 2012).

Due to the increasing number of space programs for the exploration and development of the Moon, there is a need to quickly determine the coordinates of landers with acceptable accuracy. The modern numerical ephemerides of the Moon (Vasilyev et al. 2022) allow one to obtain the location of the lander using only Doppler measurements. The goal of our work is to evaluate the accuracy of the lunar lander location by the Doppler measurements of its signal for the case of the Indian Chandrayaan-3 [1] spacecraft.

2 Doppler measurements and processing of the Chandrayaan-3 signal

The receiving of the Chandrayaan-3 signals was carried out on August 28 and from September 1 to 4, 2023, using the 13.2-meter radio telescopes at the Zelenchukskaya and Svetloe observatories, which are part of the Quasar VLBI network (Shuygina et al. 2019). The signal was recorded in the S and X-bands in the right and left circular polarizations. Carrier frequencies of 2268 and 8460 MHz were measured using the digital phase-locked loop technique (Marshalov et al. 2020).

An analysis of the Doppler measurements showed a decrease in the signal-to-noise ratio and the degradation of carrier frequency stability. The standard deviation of the signal frequency was 0.1 Hz on August 28 and increased to about 10 Hz on September 1, which was most likely due to the degradation of the transmitter clock over time. On September 4, the signal was not distinguishable from the background noise, and on the same day the Indian Space Research Organization announced the completion of the Chandrayaan-3 mission.

[1] https://www.isro.gov.in/Chandrayaan3_Details.html

In order to obtain the location of the Chandrayaan-3 transmitter on the surface of the Moon, a numerical model of the variation in the frequency of the signal received by the corresponding antenna on Earth was developed. The model took into account the positions of the planets and the Moon according to the Planetary and Lunar Ephemerides DE440 (Park et al. 2021), corrections to the Earth's rotation parameters, and the signal propagation time (Brumberg et al. 2004).

We used the variation method, which does not depend on the accuracy of the initial data. For this purpose, the lander coordinates on the Moon's surface were varied with a given step in latitude and longitude, and for each such position the frequency of the received signal at the corresponding station on Earth was calculated and compared with the real measurements using the constructed model. As a result, we determined the probable area of the lander location with a size of approximately 200×1000 km, while Chandrayaan-3 was actually located on the border of the obtained area. Thus, the accuracy of the obtained Doppler measurements of the Chandrayaan-3 signal did not allow us to unambiguously determine its location on the surface of the Moon.

3 Influence of the Doppler measurement characteristics on the determination of the transmitter location

The main influence on the accuracy of the transmitter location on the lunar surface is exerted by such characteristics of the Doppler measurements as the signal frequency deviation, the duration of the measurements, and the relative position of the transmitting and receiving stations. The signal frequency deviation is composed of the transmitter clock deviation onboard the spacecraft and the deviation of the Earth-based receiving station clock, which are 10^{-13} and 10^{-15} units of relative instability, respectively. Hence, for the transmitted frequency of 8460 MHz, the deviation of the Doppler measurements is mainly determined by the onboard clock deviation of the order of 10^{-4} Hz.

Using the constructed model, series of 20-minute duration Doppler measurements at a frequency of 8460 MHz for the Zelenchukskaya observatory were generated. The deviation of the model Doppler measurements varied within 10^{-1}–10^{-6} Hz. Based on the contemporary level of technology, the deviation of the onboard clock should be considered in the range of 10^{-5}–10^{-3} Hz. The results show that the error of the lander coordinates should be in the range from 100 m to 10 km for a 20-minute measurement interval. The influence of measurement duration and selection of receiving stations on the transmitter position error was estimated for the Doppler measurements with a standard deviation of $\sim 10^{-4}$ Hz.

The duration of the model Doppler measurements varied from 20 to 90 minutes at a frequency of 8460 MHz for the Zelenchukskaya and Svetloe observatories in all configurations. The smallest error of 34 m in the lander location is achieved for the Zelenchukskaya observatory at a 90-minute measurement interval.

4 Summary

As a result of this work, we developed a model allowing one to obtain the transmitter location on the lunar surface using the Earth-based Doppler measurements of the transmitter signal. Using this model, we determined the main dependencies of the lander position error on the signal frequency deviation, the duration of the Doppler measurements, and the configuration of the Earth-based receiving stations. For a 90-minute X-band signal with a relative frequency instability of the order of 10^{-13}, the error of the lander position on the lunar surface is about 34 meters.

Receiving the Chandrayaan-3 transmitter signals was carried out using the 13.2-meter radio telescopes at the Zelenchukskaya and Svetloe observatories in the S and X-bands. An area of about 200×1000 km for the probable lander location was determined using the Doppler measurements of the received signals. Such a result is due to the transmitter signal instability, which increased from 10^{-11} to 10^{-8} over the observing interval.

The USA and China plan to deploy a network of beacons on the lunar surface in the coming decades. The clocks in the beacons with a relative signal frequency instability of 10^{-12}–10^{-13} will allow us to build and maintain a lunar coordinate system with meter accuracy. The method we have implemented is applicable both to individual spacecraft and to radio beacon networks.

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