Simulation of the radar signal reflection from the lunar surface

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Abstract. To determine the structure and mineralogical composition of lunar subsurface a radar complex RLK-L will be installed on the “Luna-26” spacecraft. The inverse problem solution of subsurface sounding will be more accurate if all factors affecting the shape of the reflected signal are taken into account. Topography is one such factor. The article deals with modelling the reflection of a radio signal from a rough surface. An analysis of a series of numerical experiments showed that destruction of high frequency part of the spectrum depends on the dispersion of the inhomogeneities’ heights in reflection spot. The simulation results are consistent with previously performed experimental measurements and well-known theoretical estimates. Therefore, in radar experiments, it makes sense to first analyze the signals reflected from smooth areas, then from the area in which a three-dimensional digital model of lunar surface reveals the presence of depressions, and then areas with mountain ranges.

1. Introduction

Radio sounding is one of the remote methods to study the structure and composition subsurface of Earth and other space bodies. For sounding a receiver and a transmitter are needed. For bistatic sounding they must be separated in space but combined for monostatic sounding. It is rational to use equipment placed on aerospace apparatus for large-scale studies in a short time. However, in this case the transmitter power is low, which is due to the requirements of electromagnetic compatibility with scientific and service equipment. It follows that the signals reflected from the subsurface will be very weak in comparison to the signals reflected from the surface. In order to be able to identify subsurface echoes complex signals or sounding technology are used. This introduces additional difficulties in interpretation of measurement results. The main purpose of radio experiments is to assess the dielectric characteristics of soils, to detect and identify internal heterogeneities, to map study area resources. The possibility of application of subsurface radars has been proved during Mars exploration. The first successful radar measurements were MARSIS radar from the ”Mars-Express” spacecraft (ESA) [1]. It used chirp signal in four modes with central frequencies of 1.8; 3; 4; 5 MHz.

When processing measurements, the reflected signals were recorded from the lower boundary of the ice layer. Ice thickness was approximately 3 km. The experiments confirmed the hypothesis that radio waves are poorly absorbed by soils without water. This fact allowed increasing the central frequency of the chirp signal of the next subsurface radar. Radar SHARAD was placed on the ”Mars
Reconnaissance Orbiter” (NASA) [2] and used 20 MHz frequency. By reducing the wavelengths of the signal, radarograms of this radar were much more informative than the ones of the MARSIS. MARSIS and SHARAD radar measurements were processed mainly over the Northern Polar Cap of Mars which surface is relatively smooth. It means that the signals from the side reflectors were absent [3]. Unfortunately, at the moment there is no method for separating the echo of side reflectors from the echo of internal boundary. There is an urgent need to develop such a methodology, since at present, within the framework of the Russian program of lunar and circumlunar space exploration, it is planned to carry out radar measurements along the flight paths of the orbital module “Luna-26” over the lunar surface. The module will be in a circular polar orbit at an altitude of 100 to 50 km.

2. Instruments and tasks to be performed
The radar complex RLC-L is installed on the spacecraft "Luna-26" [4]. RLC-L complex consists of two radars: low-frequency Radar-20 (figure 1) and high-frequency Radar-200 (figure 2). The aims of the complex's radar experiments are described in detail in [4], the technical parameters of radars (after 2018) are given in [5]. The instrument operation is provided both in monostatic and bistatic modes. Irkutsk Incoherent Scattering Radar of the Institute of Solar-Terrestrial Physics will be used for bistatic sounding [6].

![Figure 1. Radar-200.](image1.png)

![Figure 2. Radar-20.](image2.png)

By comparing the characteristics of the direct and reflected signals, the properties of the lunar soil will be predicted.

In addition to the reflected signals, echoes from rough surface enter the radar antenna. The questions arise: How can this fact be taken into account when processing measurements? How strong are the distortions? In which areas is it reasonable to carry out radar measurements? To answer these questions, it is advisable to carry out preliminary simulation experiments.

3. Reflected signals and their simulation
The first experiment of radar exploration of the lunar surface layer was conducted in 1972 from the "Apollo-17" spacecraft. As a result of measurements, signals reflected by subsurface boundaries of the ground partition at depths of 0.9 km, 1.6 km and 1.4 km were received [6]. The processing of the results lasted 2 years, as no methods were developed to separate signals reflected from the surface and signals scattered by side reflectors. We plan to simulate the reflected signal along the spacecraft path simultaneously with the measurements of the RLC-L. We hope to use the simulation results to correct the measurement results. For modelling a 3-D digital model of the Moon surface will be used. As an example, figure 3 shows a 3-D model of a portion of the Anaxagoras crater surface. This is the site of a possible landing of the "Luna-25" spacecraft. A 3-D surface model in the MOON ME coordinate system was provided to us by the Integrated Laboratory for Extraterrestrial Territory Research of
Moscow State University of Geodesy and Cartography. The reflection area of the signal is determined according to the method described in detail in [7].

Typically, statistical methods for describing surfaces are used to analyze the reflection of radio signals. But the theory is developed for a wide range of surfaces, and not for a specific one. Since in our case we are interested in the signal reflection from a certain region, we have chosen the modified facet surface model [8]. The surface is considered as a set of reflective elements. The element is a triangular part of the surface constructed between the nodes of the map grid (figure 4) and the points between the middle of the segments connecting the non-adjacent nodes. For each element the Lambert's law was implemented in combination with the law of mirror reflection for the vertical incidence of radio waves. If the direction of the beam connecting the radar location and the centre of the reflecting area coincides with its normal, the reflection is determined by the value of the Fresnel coefficient \( r_{01} = \), where \( \varepsilon \) is the dielectric permittivity of the soil. Otherwise, the coefficient changes accordingly to coefficient \( r_{01} \cos^2(\theta) \), where \( \theta \) is the angle of wave incidence on the surface. Such approximation of the reflecting surface is quite acceptable for evaluating reflection from many types of surfaces at average angles of radio waves incidence [9]. Information on the dielectric properties of lunar soil samples is discussed, for example, in [10-12]. The reflected signal was calculated as the sum of the partial signals, each of which is shifted by the time necessary for the signal to propagate from the spacecraft to the centre of the corresponding reflective element and back in accordance with figure 5. Each partial signal was set by a function:  
\[
U_i(t) = \begin{cases} 
AS_i r_{01} \cos^2(\theta) \cos(2\pi(f_{min} + t\Delta t / T)t), & t \in [t_i, t_i + T] \\
0 & \text{otherwise}
\end{cases}
\]

Here \( S_i \) is the square of the i-th reflecting item, \( t_i = \frac{2d_i}{c} \), \( d_i \) is the distance between the spacecraft and the i-th element.
4. Results and discussion
The delay time between the vertically reflected signal and the signals coming from the side reflectors is small compared to the duration of the emitted signal; it is practically impossible to separate the start and the end of these rapidly oscillating signals in the time domain. The solution of subsurface sounding inverse problem is most informative in the frequency domain, i.e. is reduced to the analysis of the reflected signal spectrum. The simulation results show that the spectrum shape really depends on surface topology: reflected signal spectrum from flat surface is smoothly destroyed in the high-frequency part. According to [13], the spectrum amplitude of the signal reflected from a statistically inhomogeneous surface decreased in the high-frequency region as $\exp(-\delta / \lambda^2)$, where $\delta$ is the dispersion of the heights of the inhomogeneities in the signal reflection zone, $\lambda$ is the radio wave length. Despite the fact that the amplitude of the spectrum does decrease exponentially, we were unable to relate the factor in the exponent with the relief. When a signal is reflected from an area with a mountain range, oscillations are observed in the echo spectrum module. They look like an echo of a ground signal with an inner layer. So, without modelling it is difficult to separate one from the other.

The presence of depressions destroys the modulus of the spectrum of the reflected signal less than the presence of mountain ranges.

For example, figure 6 (a) shows the spectrum of the Radar-20 signal. The spectrum of the initial signal is shown in gray, and the signal reflected from the terrain with the mountain range is shown in blue.

Figure 6 (b) shows the amplitude of the spectrum of the signal reflected from the terrain with a cavity. For modelling, topological objects with commensurate linear dimensions and a similar orientation with respect to the flight path of the spacecraft were selected.
Figure 5. Constructing of a reflective map grid element.

Figure 6. Amplitude of spectrum of the Radar-20: initial signal (gray) and reflected signal (blue). (a) - reflection from a mountain range, (b) – from a cavity.

5. Conclusion
The paper describes the scheme for modelling of the RLK-L signals reflected from the lunar surface. For simulation, a three-dimensional model of the Moon surface was used. The simulation results are analyzed in the frequency domain, that is, a change in the shape of the spectrum depending on the topography in the reflection area is considered. It is shown that the high-frequency part of the spectrum is destroyed, which is consistent with theoretical estimates and experimental observations. From the simulation results it follows that the interpretation of the results of radio measurements should begin with experiments over flat areas, then over domain with single depressions, and only then over the mountains.

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