Determination of Lunar Surface Characteristics with Ground Penetrating Radar (GPR) using Mathematical Modelling. I. O. Dubrovin[1] and S. S. Bricheva[2], Lomonosov Moscow State University, Faculty of Geology, Seismics and Geoacoustics Department, Moscow, Russian Federation, [1]dubrovin.io@icloud.com, [2]svebrich@gmail.com.

Introduction: The exploration of the Moon and Lunar resources combines a wide range of fundamental scientific and applied tasks, for each of which an individual approach to select landing sites for both manned and unmanned Lunar missions and location areas for potential Lunar bases is required. The characteristics of the surface such as content of stones and craters are of great importance to the said selection. Building and maintaining bases also requires information about subsurface structure.

Our goal is to find the best possible way of determining these surface characteristics and explore the possibility of learning about subsurface structure using Ground Penetrating Radar. The first step in any research of that kind is to solve the direct problem – calculate the expected radar responses from a variety of theoretical models to later compare the results with actual radar data.

We will model the responses of a theoretical orbital radar and compare the results to the Lunar Reconnaissance Orbiter Miniature Radio-Frequency (LRO Mini-RF) radar data. We will also examine how the results would improve using not only orbital radars, but also radars potentially carried by drones at much lower heights and even surface radars. The main advantage of using lower positioned radar is higher horizontal resolution. This means, that with lowering the vertical position of the radar, the minimum distance to resolve two objects as separate objects decreases.

Thus, by analyzing all the available data on electrical properties of Lunar soils and rocks we are going to create a model of Lunar surface and subsurface, mathematically calculate the direct problem for orbital, drone-mounted and surface radars in conditions of the Moon, compare the results with existing radar data and try to extract information about the subsurface structure in all three cases.

Methods: Ground Penetrating Radar (GPR) is a geophysical technique that uses electromagnetic waves to probe the subsurface. The waves radiated into the medium reflect from the subsurface heterogeneities and structures with different electrical properties and are detected by the receiver. By analyzing the intensities and the arrival times of the reflected waves a model of the subsurface is created. On Earth, the main applications of GPR are geological, archeological and hydrogeological, (e.g. mapping ground water levels or determining the thickness of the seasonal freezing zone) and also include searching for local objects like cables, pipelines and other engineering structures.

For modelling radar responses from the Lunar surface we are using gprMax: open source software that simulates electromagnetic wave propagation by solving Maxwell's equations using Finite-Difference Time-Domain (FDTD) method. [1] To simulate the behavior of electromagnetic field in a given medium we need to know 4 properties of that medium: its relative dielectric permittivity, electrical conductivity, magnetic permeability and dielectric loss tangent. A model thereby is a combination of different mediums, each defined by these 4 key properties.

Simple models of Lunar surface: The first models we ran were very simple – a round rock on a flat surface. They were intended to estimate a possible change of the waveform, since this change may significantly complicate both processing and interpretation of gathered data. In these models we were only interested in the first detected reflections – from the top of the rock and from the soil. The main factor that may affect the waveform is the electrical conductivity. During literature review (e.g. [2], [3], [4]), we found out that conductivity is also the only electrical property of the soil that changes on the surface, since it is highly dependent on temperature, which can increase about 280 K from Lunar dawn to Lunar noon. [2] We used the suggested in [2] dependency for conductivity vs. temperature and calculated a set of conductivities for both soil and rock, then ran a simulation for each pair leaving all the remaining parameters (permittivity, permeability and loss tangent) constant.

Fig. 1 illustrates the geometry of these models. Tx and Rx are transmitter and receiver respectively. For a simulation like that it is not important how high we locate them since it will only affect the amplitudes of the reflected waves which can be modified while processing anyway. In both cases the rock (red) is of the same shape: it is round and has radius of 0.28 meters. In the first case it is located on the flat surface of the soil (grey), in the second – under it.

The dielectric properties we used for rock are: relative permittivity is constant, $\varepsilon_r = 5.91$; magnetic permeability is constant, $\mu_r = 1$; dielectric losses are absent; conductivity varies from 7×10^{-14} to 8×10^{-10} S/m. For soil: $\varepsilon_r = 2.95$; $\mu_r = 1$; dielectric losses are absent; conductivity varies from 1.5×10^{-17} to 2×10^{-13} S/m.

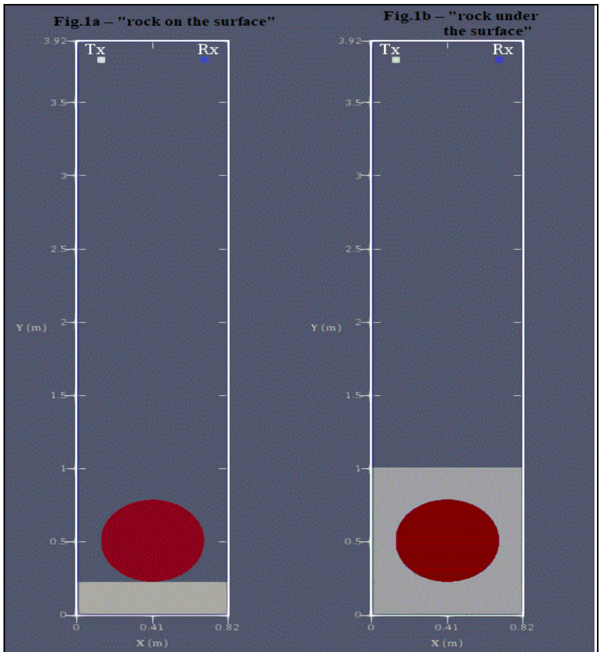

Fig.1. The geometry of the first models designed to estimate a possible change in the form of the pulse. Gray area is the soil, red – stone, dark gray – vacuum.

Chosen ranges for conductivity cover the temperature changes during the Lunar day. We ran each model for each waveform (Gaussian/Ricker/single Sine) for 12 defferent conductivities and received a total of 72 theoretical traces to carefully check for waveform changes.

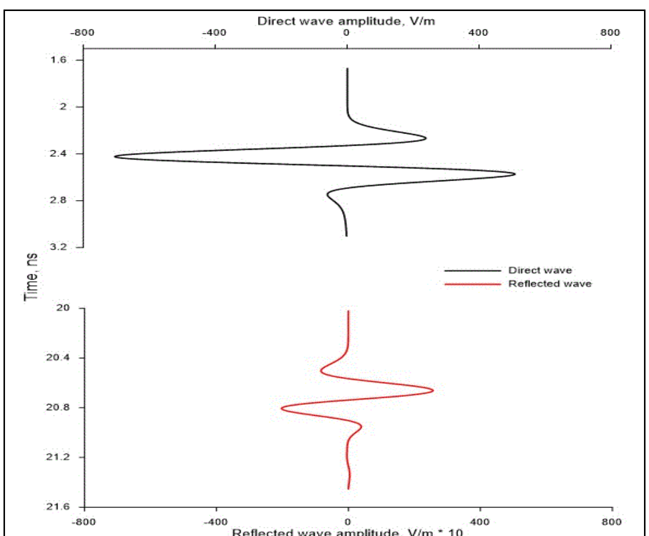

Fig.2 Comparison of transmitted and reflected waveforms (the amplitude of the reflected wave is multiplied by 10)

Discussion: Fig.2 illustrates the result of a simulation of a "rock on the surface" model using the Ricker waveform. Amplitudes are shown along the horizontal axis, time – along the vertical one. The amplitude of the reflected wave was multiplied by 10 for easier comparison. Despite the change of the phase and a drop in amplitude, which are explained by the reflection coefficient and spherical divergence, it is obvious, that the waveform did not change.

Conclusion: After a close look at all the results we conclude that the waveform is not affected by conductivity changes we considered on the surface. That means that a waveform change observed in future (i.e. more complicated) models implies some distinctive characteristics of the medium. It also allows us in our future research to rely on some processing and interpretation techniques based on knowing the radiated waveform.

These results allow us to move forward to more complex models containing multiple rocks in different configurations, start working on modelling craters and complicated soils.

Of course, modelling has limitations. For example, the Mini-RF instrument, which will be used, is working with a circular polarized signal, and we are not yet sure whether it will be possible to model that using gprMax software. In addition, the allowed complexity of a model is limited by the accessible computational power.

Nevertheless we achieve an idea of what to expect from lunar GPR research and how to adress specific tasks in future.

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References: [1] Warren, C., Giannopoulos, A., and Giannakis I. (2016) *gprMax: Open source software to simulate electromagnetic wave propagation for Ground Penetrating Radar, Computer Physics Communications*. [2] Grant H. Heiken, David T. Vaniman, Bevan M. French (1991) *Lunar Sourcebook. A user's guide to the Moon, Cambridge University Press.* [3] D.W. Strangway, W.B. Chapman (1972) *Electrical properties of lunar soil dependence on frequency, temperature and moisture*, Earth and Planetary Sience Letters, 16, 275-281. [4] G.R. Olhoeft, D.W. Strangway (1974) *Dielectric properties of first 100 meters of the Moon*, Earth and Planetary Science Letters, 24, 394-404.