ESTIMATION OF BEARING CAPACITY OF LUNAR SOIL FROM THE DEPTH OF TRACKS OF THE LUNOKHOD WHEELS.

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Introduction: Here we describe measurements of depth of the Lunokhod-1 and 2 wheel tracks in TV panoramic images and from them estimate bearing capacity of the upper layer of lunar soil (Fig. 1). These results were compared with measurements of depth of the wheel tracks of Chinese Yutu-1 and Yutu-2 rovers [1]. A correlation was determined between the results of assessing the strength of the soil by the depth of the track and by the results taken by penetrometer on board the Soviet lunar rovers [2].
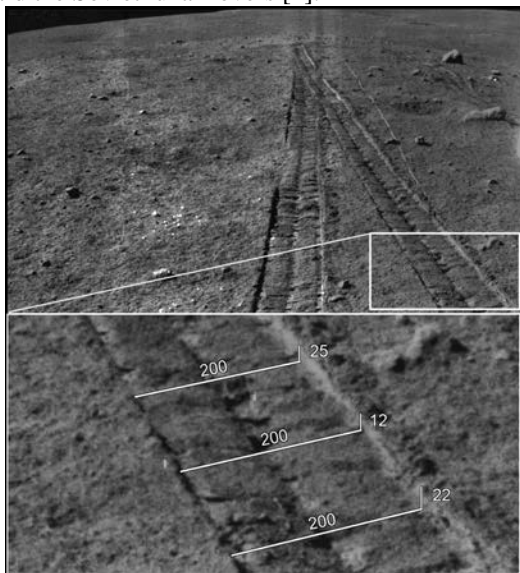

Fig. 1. An example of image of Lunokhod-1 wheel track using which the track depth was measured.

The depth measured in 13 places along the Lunokhod-1 route (Fig. 2) and in 13 places along the Lunokhod-2 route (Fig. 3). For that we applied the special photogrammetric analysis using parameters of the Lunokhod panoramic images [3].
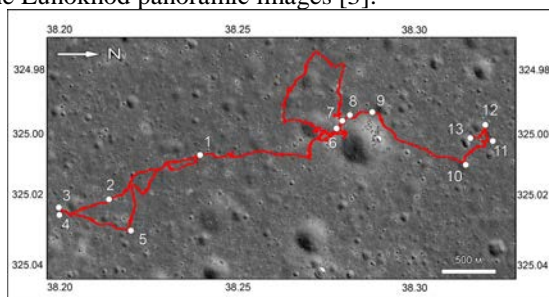

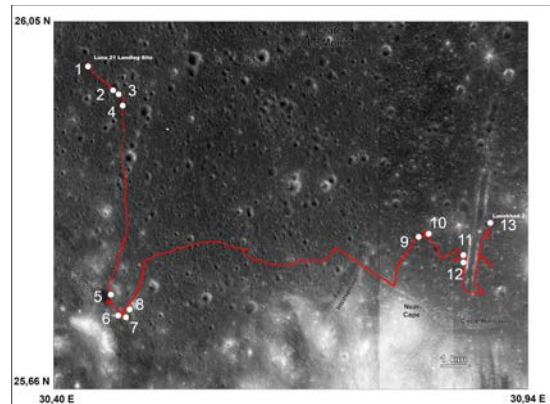*Fig. 2. Route of Lunokhod 1 (red line) and places where the here used TV images were taken (numbers).*

Fig. 3. Route of Lunokhod 2 (red line) and places where the here used TV images were taken (numbers).

The track depth measurements: For the measurements we used the software for PROViDE project [4] modified for the current task. Measurements of the depth or height of any object on the surface using only one panoramic image is not exact, because the distance from camera to the object on surface is not available (not possible to measure). That is why track depth was determined with three assumptions: 1) The lunar surface near the Lunokhod (in distance ≤10 m) is equal to the spherical surface with the Moon radius. 2) The camera orientation was determined using the skyline curve on the image. 3) The starting lower point for the measurements is always placed on the selected surface (the Moon sphere).

Before the track depth measuring, we had to find the camera orientation angles (yaw, pitch, roll) and height above surface in the survey point. Our software allows matching the skyline calculated using input orientation angles and height of the camera with the skyline on panoramic image in semiautomatic mode. Camera orientation parameters detected by this software help us to improve precision of the track depth measurements. Uncertainty of camera orientation parameters affects the accuracy of surface normal vector determination and leads to increasing the measured value of depth. To decrease this error, 80% of measured wheel tracks were selected closer than 3.5 m from Lunokhod (max distance 7.5 m). The measurements results are: for Lunokhod-1 range 9-49 mm, mean 24 mm, standard deviation 2,1 mm, for Lunokghod-2 range 12-32 mm, mean 21 mm, standard deviation 2,0 mm.

Calculation of bearing capacity: To calculate the strength of the lunar soil based on the track depth (or *sinkage* of the wheel) the design of the metal mesh rim of the hard wheels of the Soviet lunar rovers and the Chinese lunar rovers Yutu were considered. The use of a mesh reduces the mass of the contact surface of the rim. At the same time, the mesh allows to increase the traction force of the wheel due to the cohesion of the soil in each cell, integrated over the entire contact area. At a low speed of movement of lunar rovers with remote and autonomous control on a relatively flat surface, the sector of the rigid rim immersed in the soil can be regarded as a kind of stamp (Fig. 4). The area of the contact patch of this stamp must be calculated taking into account the depth of the track, and the actual dimensions of the contact surface of hoops and wire.
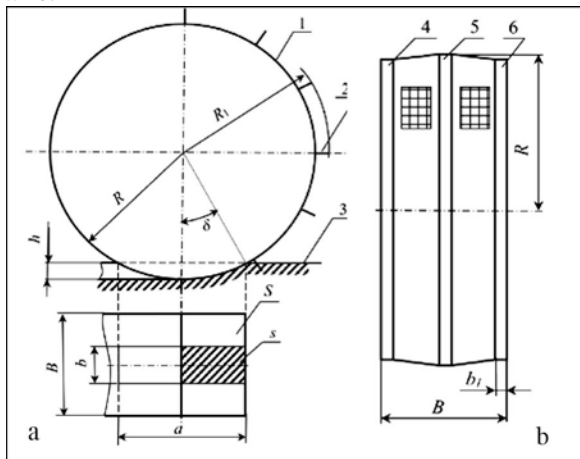

Fig. 4 Calculation scheme of the interaction of the front wheel with the lunar regolith (a) and the scheme of the rim (b): 1- rim, 2-traction amplifiers, 3-soil, 4,6-extreme hoops, 5-middle hoop, S-projection of the contact area, s - estimated area of the wheel stamp

Other design simplifications allowed for small (no more than 5°-7°) slopes of the bearing surface: the redistribution of normal reactions caused by reactive torques is not taken into account; soil subsidence is considered the result of the first deformation, skidding or slipping of wheels on the regolith is absent.

Taking into account the analogy of the design of the rims of the Soviet and Chinese lunar rovers, the calculation of the bearing capacity of the lunar soil along the routes of movement of low-speed, unmanned mobile spacecraft can be carried out according to a single method. The difference in the orientation of the traction amplifiers on the wheel rims, due to the use of different turning methods, does not affect the calculation results when driving on the regolith. Both "oblique" (at an angle to the wheel axis, Lunokhod-1 and 2) and "straight" (parallel to the wheel axis, Yutu and Yutu-2) traction amplifiers cut into the ground to the full height, and the subsidence of the wheels into

the ground is limited by the rims. Their geometry determines the area of the contact patch. The results of calculating the bearing capacity, which are numerically equal to the specific pressure of the soil wheels, are shown in Fig. 5.
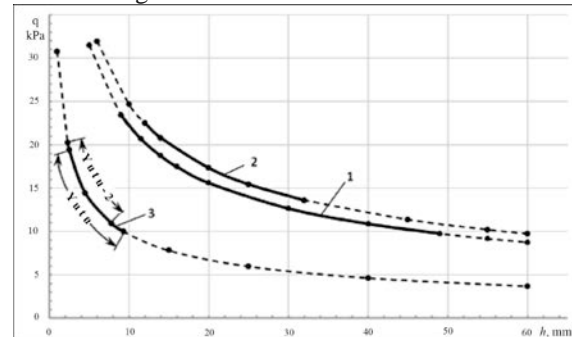

Fig. 5 Specific wheel pressure q depending on the track dept: 1, 2-Lunokhod1and 2; 3-Yutu and Yutu-2.

The dashed line shows the calculated characteristics. The solid line shows the sections of the calculated characteristics corresponding to the range between the minimum and maximum value of the track depth [1] on the investigated section of the route. On the investigated sections of the route for Lunokhod-1, a range of soil bearing capacity was obtained from 9.8 to 23.4 kPa, an average value of 15.4 kPa, and a standard deviation of 4.1 kPa. For Lunokhod-2 - from 13.6 to 22.5 kPa, the average value is 16.4 kPa, the standard deviation is 2.8 kPa.

The report analyzes the possibility of correlating the results of assessing the bearing capacity of the lunar soil by the depth of the track and by the readings of the device for assessing the traverse ability (PRoP) [2]. It was shown that the relationship between the pressure of the wheel q and the stamp of the PRoP q_s in the considered range of the depth of the surface layer of the soil can be represented by a linear function.

Conclusions: The above consideration showed that estimation of bearing capacity of lunar soil using depth of the wheel tracks of lunar rovers is achievable and can be applied to the results of future lunar and planetary missions. The work continues.

References: [1] Tang Z, et al. (2020) *Geophys. Res. Lett.* V. 47. e2020GL089499. [2] Leonovich A K, et al. In: Vinogradov A P (ed.). Mobile Laboratory on the Moon: Lunokhod-1. V. 1. Nauka Press. 1971, 78–88 (in Russian). [3] Mobile laboratory on the Moon – Lunokhod-1. V L Barsukov (ed.). Nauka Press. V. 2. 1978 (in Russian). [4] Kozlova N et al., (2014) *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences.* V. XL-4, 121-126.