The multiparametric method of analyzing the lunar dynamic processes

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Abstract: The present paper focuses on studying the lunar dynamic processes. As selenophysics is a complex system and moonquakes are complex multi-parametric systems too, the analysis of moonquakes and the development of an analytical theory of such processes require the application of robust methods and using multiparametric calculations. Moreover, selenophysics is a more complex system than geophysics. In this connection, the study of lunar processes and determination of moonquakes parameters require reliable estimates of the results obtained and application of the methods of complex system physics. The observations from “Apollo” space mission were used in the study, and the multiparametric correlation method was developed for their processing. Currently, one uses various methods, similar to the ones for the Earth’s seismic process investigation, such as seismic interferometry for deep moonquakes, time scales analysis, seismic phenomena magnitude gradient change, solution of the inverse problem of signals reflection on “Apollo” stations. Now, on the basis of moonquakes data, the internal structure of the Moon is being studied. Using the moonquakes data, a model of the lunar tidal parameters had been developed and was later refined by “GRAIL” (gravitation), “LRO” (shape), and “LLR” (rotation) space missions’ data. As a result, in the areas where deep moonquakes occurred, the inner layer of the Moon with low viscosity was found. In the present work, the author’s method of analyzing moonquakes allowing to conduct multiparametric analysis of seismic time series observations was applied. The method was developed for the investigation of seismic processes occurring on the Earth using the space observations. In order to provide qualitative description of moonquakes dynamical parameters, the special software was developed.

1. Introduction
Analysis of "Apollo" mission's moonquakes data (1971-1974) showed the lunar seismic activity was very similar to the processes taking place on the Earth [1]. The lunar activity was also less at the Poles and polar ice cap of the Moon, achieved maximum value in middle latitudes of both hemispheres, and had a stable minimum near the equator. Shallow moonquakes have their epicenters at depths of 100-300 km and usually take place in latitudes of 30°-40° of both lunar hemispheres. Deep moonquakes (at depths of 800-1100 km) have their epicenters near the equator in lunar latitudes of 10°-30°. On the other hand, analysis of data on more than 200000 earthquakes by International Seismological Catalog showed:
1) Seismic activity at the Poles and polar ice caps was almost absent;
2) In the middle latitudes of both hemispheres there was maximum activity;
3) Near the equator there was a stable minimum of seismic activity.
Epicenters of earthquakes in most cases for large geographical latitudes are located at depths less than 20 km. As they come to middle latitudes, epicenters are gradually achieving depths from 20 up to 60 km. Near the equator earthquakes epicenters are located at depths 100-240 km or deeper than 500 km. Thus, distribution of seismic processes for both celestial bodies is equal for latitudes and very similar for depths. Therefore, there is a fundamental connection between seismic processes and certain physical phenomena which are equal for both the Earth and Moon. In the work [1] it is assumed that seismic events on the Earth and Moon depend on tidal impacts from the Sun. That theory enables to explain the similarity of earthquakes and moonquakes quantity distribution for latitudes. The main cause of earthquakes is considered to be tectonic processes [2]. The main cause of moonquakes is
considered to be the Earth's gravity. However, those theories cannot explain the same for the Earth and Moon distribution of seismic activity for latitudes.

In the work [3] based on the analysis of 1000 tidal moonquakes with energies up to 109 Erg, magnitudes 0.3-1.3, periodicity of 13, 27 (lunar month), 206 days, and 6 years, it was found that periodicity of moonquakes correlate with dynamic parameters of the Moon's orbital motion around the Earth and Sun. 60 tidal moonquakes epicenters were studied and it was found that forms of signals for all the tidal moonquakes repeated during the entire observation period. Tidal moonquakes epicenters are usually located in territories of lunar basaltic seas and fall into 4 global seismic belts. Lengths of those belts are 1000-2500 km, widths are 100-300 km, and depths are 800-1000 km.

2. Seismic lunar observations data
Seismic lunar observations include all the seismic data recorded by 5 out of 6 ALSEP (The Apollo Lunar Surface Experiments Package) stations. Those stations were adjusted by the American astronauts during the "Apollo" space missions in 1969-1972 and kept operating until 1977. The least number of moonquakes are located in the territory of Southwestern area on the Moon, where a lot of meteorite craters are situated. In the West the line of moonquakes crosses Mare Serenitatis and goes slightly north of Mare Crisium. In the North, the line of moonquakes passes through the middle of Mare Imbrium and almost reaches the Northern Pole. In the South, the line of moonquakes goes through the middle of Mare Cognitum and Mare Humorum and almost approaches the Southern Pole of the Moon.

3. Analysis of the lunar internal structure based on moonquakes
Density of the Moon is 3340 kg/m³, which is similar to the Earth's mantle. The seismographs of the "Apollo" space mission have shown that moonquakes occur permanently, however, they are significantly different compared with earthquakes. Four seismometers were installed on the surface of the Moon [4]. The data from the "Apollo" space mission was used to simulate the lunar internal structure for its depth areas up to 400 km. The structure near the center of the Moon was not determined. In some studies there were attempts to identify seismic waves reflected on the borders between liquid and solid layers of the Moon by the analysis of noise signals [5], but significant differences between the models of deep moonquake areas were found.

In the work [2] it was found that numerous inhomogeneous moonquakes occurred repeatedly in special source-areas located at depths 700-1200 km [6]. A small amount of minor earthquakes caused by meteoroids and artificial moonquakes were found, though.

In the work [7] it was concluded there was partially molten layer inside the lunar sphere. It was determined that low viscosity of about 106 Pa at the bottom part of the lunar mantle could be the result of significant amount of molten substance and even certain critical state. In the paper [8] it was found that high content of water could explain the lunar dissipation without considering partial melting of the mantle. Nevertheless, the existence of partially molten layer is not yet proven.

4. The method of the moonquakes time series polyharmonic model construction
The aim of the research is improving the lunar "seismic weather" forecasting accuracy by identifying the polyharmonic components for seismic time series modeling of moonquakes. The method of the model constructing, including systematic and random components, was developed. This method of the moonquakes time series analysis assumes the selection of statistically significant and the most stable in time harmonics in the non-stationary process for the conditions of mild systematic component is defined. In this case preliminary estimation of the stability of a polyharmonic structure of the time series model, the search of the statistically significant harmonics, the analysis of their amplitudes stationarity require the special attention. To solve these problems, we used the MDR (Modeling of Dynamical Regressions) approach. MDR-approach allows to select statistically significant polyharmonic components of the seismic activity in moonquakes time series. The moonquakes time
series have the mild regular components. The proposing adaptation of the MDR-approach to the lunar seismic activity time series includes several interrelated procedures:
- the multi-window spectral analysis approach for averaging;
- the fractal analysis of time series for detection the trends of their behavior;
- wavelet analysis for studying the harmonics stability in time;
- the method of robust search (with adaptation) for significant harmonics;
- the cross-spectral analysis for the joint analysis of the time series;
- the use of Kalman filter to describe the random components of the time series model.

The use of these procedures allows selecting significant components in the time series polyharmonic models [9].

For this purpose the software package "Automated system of selenoseismic regression modeling” (AS SRM) has been developed. AS SRM software package include all the components listed above. Along with the interactive time series processing, AS SRM can automatically analyze data and build the combined time series dynamics models [10, 11].

During the analysis, we used the moonquakes time series described in [12].

As results of "exploratory" analysis, which included the use of the stationarity test and fractal analysis, we revealed:
- moonquakes time series are non-stationary;
- moonquakes time series are trendstable (Hurst index h = 0.592) and has a long memory;
- trendstability is relatively low;
- there is a low predictability of the moonquakes time series model.

According to the developed method of identification of polyharmonic components of the moonquakes time series, the following procedures were carried out.

1) The averaging of the original moonquakes time series was carried out. As a result, σ = 1.005 and σΔ = 0.904, where σ - mean square deviation (MSD) of approximation over the whole studied interval, σΔ - MSD of forecasting on the time interval accounting for 10% of the original data duration. Through a random search including adaptation 8 significant harmonics were selected. The harmonic amplitudes are uncorrelated with each other (σ = 0.985, σΔ = 0.867). Wavelet analysis of the selected harmonics revealed their instability over time. Application of the Kalman filter and the model based on it of the first-order autoregressive reduced MSD of approximation to the σ = 0.600, and MSD of forecasting to σΔ = 0.537, i.e. errors decreased 2 times.

2) The combined mathematical model of the dynamics of the moonquakes time series has been created and has the form as follows:

\[ y(t) = 12,14 + 0,03 \sin(2 \pi t / 3 - 17,14) + 0,054 \sin(2 \pi t / 13 - 4,301) + \\
+ 0,048 \sin(2 \pi t / 15 + 114,3) + 0,067 \sin(2 \pi t / 33 + 174,14) + 0,076 \sin(2 \pi t / 76 + \\
+ 89,545) + 0,080 \sin(2 \pi t / 96 + 229,38) + 0,073 \sin(2 \pi t / 133 \\
- 30,873) + 0,118 \sin(2 \pi t / 599 + 91,623) + 0,501 y_1(t-1) + y_2(t), \]

where \(y_1(t)\) is a residual after removal of the harmonic component, \(y_2(t)\) is the residual for the combined model.

3) The model for the averaged by weeks background moonquakes time series has a similar structure:

\[ y(t) = 12,105 + 0,02 \sin(2 \pi t / 14 - 7,101) + 0,03 \sin(2 \pi t / 18 + 40,302) + \\
+ 0,017 \sin(2 \pi t / 28 + 133,85) + 0,0041 \sin(2 \pi t / 120 + \\
+ 200,75) + 0,2 \sin(2 \pi t / 599 + 91,628) + 0,5011 y_1(t-1) + y_2(t). \]

4) Similarly, the models for background-2 seismicity and the data averaged over days are constructed.

5) The moonquakes time series models were studied for the ability to carry out the forecasting estimations. The correlation coefficients between observations and forecast have the prediction error of 11% for samples at the end of the time series.

For correlation coefficients the week is the most perspective unit of measurement for the prediction and identification of its “horizon".
Among the known methods of analyzing seismic activity there is a narrow class of approaches aimed at "seismic weather" predicting, i.e. at the detection of maximum and minimum seismic activity. These approaches are not suitable for the prediction of single moonquakes. The first of these methods implies using the spectral-time diagram, the second one is developed in [13].

Comparative analysis of these two approaches showed that both methods can obtain:
- periodic components of the investigated seismic process;
- instability of selected harmonics.

Method of selection of statistically significant harmonic components allowed to significantly expand the practically important information on the lunar seismic process studied and to produce properties of the mathematical model:
- the fractal properties were found in the moonquakes activity,
- the most common lunar seismic periods were revealed,
- trendstable polyharmonic model allowing to determine the non-zero "horizon of moonquakes weather prediction" in a mild systematic components of moonquakes time series was created.

The developed technique allowed to reveal the stable regular components in the description of the seismic activity dynamics, which indicates that the seismic processes has deterministic components.

The comparative analysis between our approach and ARIMA method was conducted. The methodology of ARIMA (Auto Regressive Integrated Moving Average) or Box-Jenkins [14] approach is used for the analysis of time series. Firstly, ARIMA evaluates the stationarity of the series [15]. Various tests revealed the presence of unit roots and allowed obtaining the order of integration of the time series (usually limited to the first or second order). When comparing the MSD σ and σΔ for the models based on the method implemented within AS SRM with the accuracy of modern ARIMA models it was revealed that the developed technique provides 2 times more accurate approximation and prediction.

Application of the method of forming a statistically significant polyharmonic components of moonquakes time series for the description of nonstationary seismic process, unlike the approach used at Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS) and the one based on the frequency-time diagram [16], allows revealing the degree of process trendstability constructing and investigating the statistical model as a systematic and random components, and predicting the "seismic weather" and determining the maximum and minimum activity over a two-month interval.

5. Summary and conclusions

The models of the dynamics of lunar seismic activity are obtained; they have the same structure consisting of the polyharmonic component and autoregressive component of the first order. For moonquakes, time series could not detect stable amplitudes of periodic components in the analysis of the released energy of the general and background seismicity. The "flickering" structure in which the periodic components of lunar seismic activity time series repeatedly amplify and reduce in amplitude is found. Nevertheless, this structure reflects the weak but certain stability of the seismic process indicated by exponents of fractal analysis.

During the "Apollo" space mission, more than 8000 moonquakes were recorded including tidal moonquakes, tectonic tremors, fall of meteorites, and impacts by spent spacecrafts' stages. Based on the analysis of lunar seismic waves, the lunar internal structure was studied. At depth of a half the lunar radius there is the lunar lithosphere in which seismic waves do not weaken. Deeper than the lithosphere is the asthenosphere (lunar liquid core) through which transverse seismic waves cannot go. In the area of lithosphere-asthenosphere transition there are tidal moonquakes epicenters. Based on the analysis of moonquakes in the lithosphere one may distinguish basalt-anorthosite crust and peridotite mantle. The border between the crust and the mantle at depth of 60 km is sharp.

Along with tidal moonquakes the lunar seismic stations recorded tectonic pushes. They were observed at depths up to 300 km. 25 tectonic pushes, which had been much more intensive than tidal ones (value of magnitude: 4-5), were noted. There was no periodicity found in the tectonic pushes, but they
coincided in time with the strongest tidal moonquakes. Epicenters of tectonic pushes are located near the borders of global seismic belts. Convection velocity in the bowels of the Moon is much less than on the Earth, that is why moonquakes energy (1018 Erg) is million times less than the Earth's one. However, the discovered general regularities between earthquakes and moonquakes are based on small number of observations. Nevertheless, the existing theories, according to which the main cause of moonquakes is tidal forces, while in case of earthquakes the main cause is tectonic processes, cannot explain the results of space observations. Currently, there is a project of installing 10-12 seismometers for collecting data for 3 to 5 years. According to the researchers, this work is essential in terms of finding the safest areas for spacecraft landing. In the future, the results of the present project are going to be applied to other celestial bodies [17]. It will be taken into account that there is very few information on the Poles of the Moon [18], while this is especially important, since it is planned to place manned lunar bases at the lunar Poles.

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