Stratification of Lunar Regolith Based on Attribute Analysis

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Abstract. On December 14, 2013, China's Chang'e-3 missions landed on the lunar surface, providing valuable information for better study of the moon. LPR (Lunar penetrating radar) is a very important and effective detection method. The lunar surface shallow radar data we obtained through the lunar exploration radar can be used to understand the geological structure of the lunar surface and the thickness of the lunar regolith. This paper analyzes the processed LPR data of "Chang'e-3" by using instantaneous attributes, and obtains the instantaneous amplitude attributes, instantaneous phase attributes, and instantaneous frequency attributes of the radar profile. According to the results of the instantaneous attribute analysis, the lunar regolith structure of the radar profile is divided, and it is found that it can be well matched with the previous research results.

1. Introduction
The moon is the closest celestial body to the earth, and the exploration of the moon is the beginning of human exploration of the universe. Lunar exploration is mainly divided into two phases: during the period 1950-1980s, human exploration of the moon was mainly conducted by the United States and the former Soviet Union, mainly to understand and understand the moon [8,12,13]; after the 1990s, lunar exploration has become a research hotspot in many countries, and a new stage aimed at utilizing resources and establishing bases [18]. China has also proposed and implemented three five-year lunar exploration programs marked by "circling", "falling" and "returning" in 2005-2020s [1,4,5,10,11,17,18]. Due to the unique advantages and functions of radar detection, it has become a very important method of lunar detection.

On December 2, 2013, China successfully launched the "Chang'e-3" mission, and successfully landed in the northwest of Yuhai on December 14, 2013. The "Chang'e-3" probe consists of a lander and a patrol (named "Yutu"). Among them, the Yutu cruiser is equipped with a two-frequency LPR system (60Mhz, 500MHz). It conducted radar detection at a distance of about 100m in the Yuhai Hongwan Lunar Landing Area, and obtained a wealth of data [3]. On January 3, 2019, China's "Chang'e-4" mission successfully landed on the back of the moon at the south pole Aitken Basin, and the "Yutu-2" patrol vehicle also carried the same LPR system [6,18].

At present, many researchers have analyzed and interpreted the LPR data obtained by "Chang'e-3", and have obtained many results. Xiao et al. [14] identified 9 underground layers based on the results of the LPR and the comprehensive interpretation of the regional geology of the landing site, indicating that the area has experienced complex geological processes since the Yuhai Era and is different in composition from the Apollo and Luna landing sites. Zhang et al. [19] based on spectral reflection and elemental analysis of the lunar regolith at the landing site revealed that the young basalts may be from a mantle reservoir rich in ilmenite. Yuan et al. [16] explained the sequence of lava flows deposited on the lunar surface at different periods, and inferred the most probable directions of these flows. The
interpretation of the cross-section imaging results showed that the Chang'e 3 landing site and the Apollo landing site had similar underground structures.

This paper uses the method of instantaneous attributes analysis to obtain the instantaneous amplitude attribute, instantaneous frequency attribute and instantaneous phase attribute of "Chang'e-3" data. We divided the lunar regolith layer based on these three attributes and compared them with previous results. The results show that the three attributes can better distinguish the interface between lunar regolith and bedrock, and the amplitude attribute can divide the inner layer of lunar regolith.

2. Principle of Instantaneous Attribute Analysis
The instantaneous attribute includes instantaneous amplitude attribute, instantaneous phase attribute, and instantaneous frequency attribute. They are calculated by the method of constructing complex signal by real signal through Hilbert transformation [20].

Assuming the time function of the radar pulse wavelet is \( s(t) \), then

\[
s(t) = t^2 e^{-\beta t} \sin \omega_0 t
\]

Where \( \omega_0 \) is the center frequency and \( \beta \) is the attenuation rate coefficient of the pulse wavelet.

If the Hilbert transform of \( s(t) \) is \( \hat{s}(t) \), Instantaneous amplitude, phase and frequency are:

\[
A(t) = \sqrt{\hat{s}^2(t) + s^2(t)},
\]

\[
\phi(t) = \arctan \frac{\hat{s}(t)}{s(t)}
\]

\[
\omega_c(t) = \frac{d\phi(t)}{dt}
\]

3. Attribute Analysis Results of Chang'e-3 Radar Data and Lunar Regolith Stratification
In this chapter, we use CH-2B data of the Chang'e-3 lunar exploration radar to conduct attribute analysis, and obtain the conventional three instantaneous attribute profiles, and layer the lunar soil according to the profiles.

The CH-2B data of the LPR was collected by the channel 2 antenna (500Mhz) of "Chang'e-3". Before we use it for instantaneous attribute analysis, we perform some pre-processing on the CH-2B data. The pre-processing steps are mainly based on Zhang Ling's article [18], and the processing flow is shown in Table 1.
Table 1. CH-2 data processing flow of LPR.

| Processing Flow | Explanation |
|-----------------|-------------|
| i Data input    | The data is divided into 9 segments. According to their storage format (*.psd, a format widely used for astronomical data storage), data and location information are read one by one. |
| ii Data splicing| Because it is divided into 9 segments, we need to stitch them together. Different data segments and errors in the acquisition start time will cause vertical misalignment of the image. Adjust the gather according to the same strong reflection coincidence axis. |
| iii Trace adjustment | "Yutu" walking is not continuous, and it will stop at some waypoints to collect other scientific data. At this time, the LPR is still collecting data, which leads to the repeated collection of many repeated traces at the same location. These duplicate collections need to be removed. There are also collections with extremely low signal-to-noise ratios that need to be deleted. |
| iv Trace selection | "Yutu" walking is not continuous, and it will stop at some waypoints to collect other scientific data. At this time, the LPR is still collecting data, which leads to the repeated collection of many repeated traces at the same location. These duplicate collections need to be removed. There are also collections with extremely low signal-to-noise ratios that need to be deleted. |
| v Time difference adjustment | The receiver turns on 28.203 ns earlier than the transmitter. This time difference needs to be adjusted. |
| vi Useless data removal | Only the first 150ns of data is of research value, and the remaining data has a low signal-to-noise ratio and needs to be cut. |
| vii Bandpass filtering | Bandpass filtering is used to remove noise. |
| viii Background removal | In order to highlight the reflection of the anomalous body, the interference of the direct wave and the ground reflection is removed, and the averaging channel processing is performed. |
| ix Gain | In order to highlight the lower information, automatic gain processing is performed. |
| x Re-locate | Add location information to the data. |

After processing the CH-2B data through the above preprocessing steps, the radar profile shown in Figure 1 was obtained. From Figure 1, we can only vaguely see the existence of the interface between lunar soil and bedrock, which is difficult to distinguish. It is also difficult for us to obtain other relevant information about lunar regolith.

Next, we use the instantaneous attribute to analyze the pre-processed CH-2B data, and obtain the instantaneous amplitude property profile (Figure 2 (a)), instantaneous phase property profile (Figure 2 (b)), and instantaneous frequency property profile (Figure 2 (c)). Based on these three profiles, we can easily find that the instantaneous phase attribute profile and instantaneous frequency attribute profile can clearly see the interface between the lunar soil and the bedrock, and the instantaneous amplitude attribute profile can obtain information about the inner layer of the lunar regolith. Therefore, we used these three profiles to perform lunar regolith stratification.

4. Conclusions

In this paper, the instantaneous attribute analysis is applied to the LPR data analysis of the Chang'e-3 to help divide the interface between lunar regolith and bedrock, and at the same time divide the inner layer of the lunar regolith. According to Figure 2., it can be seen that the instantaneous attribute analysis method can make the layer interface more intuitively and easily distinguishable, which is beneficial to the characterization of the layer interface. Therefore, two lunar regolith internal layer interfaces, as well as the interface between the layer interface and bedrock, were drawn. According to the formation mechanism of lunar regolith and the geological structure of the study area, it can be divided into the impact crater sputter layer, the strongly weathered ancient lunar regolith layer, the weakly weathered ancient lunar regolith layer and the lunar basalt layer from top to bottom (See ①-④ in Figure 3). In order to judge the effectiveness of the method in dividing the layers, we labeled all the interface depicted in Figure 2 to Figure 1, and compared with the results of previous [14,18], and got Figure 3. According to Figure 3, it can be found that the layers we obtained are roughly consistent.
with the previous results, and it also shows that this method is very effective for the analysis of LPR data.

![Figure 2](image-url)

**Figure 2.** Three instantaneous attribute analysis results: (a) Instantaneous amplitude attribute profile; (b) Instantaneous phase attribute profile; (c) Instantaneous frequency attribute profile.

The interface marked with red 2 represents the interface between the lunar regolith and the bedrock according to the instantaneous phase attribute in Figure 2; The interface marked with red 3 represents the interface between the lunar soil and the bedrock according to the instantaneous frequency attribute in Figure 3. The black solid line is the interface divided by Zhang et al. And the yellow dotted line is
the interface divided by Xiao et al; Red ①-④ represents impact crater sputter layer, the strongly weathered ancient lunar regolith layer, the weakly weathered ancient lunar regolith layer and the lunar basalt layer respectively.

Figure 3. Comparison of layers division results. The interface marked with red 1 represents the inner layer interface of the lunar soil according to the instantaneous amplitude attribute in Figure 2.

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