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Supporting Information for

Properties of Lunar Regolith on the Moon's Farside unveiled by Chang'E-4 Lunar Penetrating Radar

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Text S1. Signal processing methods for LPR data

The transmitter of Chang'E-4 (CE-4) lunar penetrating radar (LPR) produces ultra-wide band (UWB) carrier-free nanoseconds pulse and radiates UWB signals downward by transmitting antenna. The signals would reflect and scatter when meeting buried objects during propagation, such as interfaces between different medium, subsurface voids and subsurface boulders. The time window and the sampling point of CE-4 LPR Channel-II are 640 ns and 2048, respectively.

Considering the radar system noise and the out-of-band environment noise, the raw LPR data are with low signal-to-noise ratio (SNR) (Fig. S1). Therefore, some processing methods should be performed to improve the SNR of LPR data before further analysis. Here, we employed direct-current (DC) removing, background removing, filtering and amplitude compensation and so on, as usually used for ground penetrating radar data on the earth applications (Jol, 2009; Dong et al., 2016).

1. Direct-current (DC) Removing

Direct-current (DC) component comes from the oscillation of low frequency during the saturation recovery procedure of receiver. It should be removed before subsequent processing because it doesn't indicate any useful information. The process of DC removing is to slide a window from the beginning to the end of one trace, and then compute the average within the window and subtract the mean value from center value of the window, as shown in equation (S1).

$$Y(n) = y_c - \frac{1}{N}\sum_1^N y(n) \quad \text{(S1)}$$

Where, y_c and $Y(n)$ represent the values of amplitude before and after processing, respectively. $y(n)$ represents raw LPR data, *N* is the window length.

2. Background Removing

Background removing aims to eliminate the repetitive and successive interference at the same time delay in every trace. Here we used it to remove the direct wave that coupled from transmitting antenna to receiving antenna, so only the part before surface echoes was processed. The processed amplitude could be derived as equation (S2).

$$x'(m,n) = x(m,n) - \frac{1}{N}\sum_{n=0}^{N-1} x(m,n) \quad \text{(S2)}$$

Where $x(m,n)$ is raw LPR data, $x'(m,n)$ is processed data, N is the trace number. The LPR data after DC removing and background removing are shown in Fig. S2.

3. Amplitude Compensation

The LPR antenna could be approximated to an oscillating dipole that radiates spherical waves. The amplitude of electromagnetic wave that propagates under the ground suffers, therefore, a geometric attenuation due to the distribution of the energy on the front of spherical wave. The amplitude $A(r)$ at the distance r is given as follows:

$$A(r) = G(r)A_0 e^{-\alpha r} \quad \text{(S3)}$$

Where A_0 is the value of the initial amplitude transmitted from LPR antenna, α is attenuation constant, $G(r)$ is the factor of geometrical spreading which can be derived by equation (S4):

$$G(r) = \frac{1}{r} \quad \text{(S4)}$$

Therefore, the amplitude can be compensated by multiplying the LPR signals by$1/G(r)$. The compensated data show more subsurface information because the deeper signals are amplified, as shown in Fig. S3.

4. Filtering Processing

A filter in line with the characteristics of LPR data is an effective method to improve the signal-to-noise ratio (SNR). The designed central frequency and bandwidth of CE-4 LPR Channel-II are 450MHz and 500MHz, respectively. Therefore, we chose a band-pass filter with a pass band of 200-700MHz (Fig.S4).

From the above methods and procedures, the processed LPR data have improved signal-to-noise ratio compared to the raw data (Fig.S5), which contributes to analyze the subsurface geological structures and estimate the properties of lunar regolith.

Text S2. Layer localization method for LPR data

Because of the high pulse repetition frequency (PRF) of LPR and the low speed of Yutu-2 roving, the LPR echoes of two adjacent traces from the same interface have

similar time delay and amplitude, namely, good correlation. Thus, we can take advantage of the good correlation of two adjacent traces to localize the interface of subsurface layers. However, the buried objects or other underground interference would influence the effect of localization. As a result, we put forward a modified trace correlation method in order to suppress interference and accurately extract subsurface layers, which includes the following steps:

(1) Determination of initial values

Regard the first trace as reference trace and determine appropriate values for length of reference window and search window, correlation threshold (T_C) and time threshold (T_L) (T_C and T_L are empirical values), and then determine initial search point (P_1) by visual inspection.

(2) Calculation of correlation

Take the next trace as target trace and calculate correlation between the signal in reference window of reference trace and the signal in search window of target trace, and then determine the maximum value of correlation (M_C) and corresponding point (P_2) (Fig.S6).

(3) Determination of layer position

If $M_C > T_C$ and $|P_2 - P_1| < T_L$, then consider P_2 as the layer position of target trace, also as the new search point, regard the target trace as new reference trace. If $M_C < T_C$, or $M_C > T_C$ but $|P_2 - P_1| > T_L$, then consider the nearest extreme point from P_1 as the layer position of target trace, but keep the preceding reference trace and search point.

(4) Implement step (2) and (3) to all the traces in order.

Text S3. Estimation for dielectric properties of lunar regolith materials

For LPR data interpretation purposes, the lunar subsurface geological structure at CE-4 landing region could be modeled as a set of three planar layers (i.e., vacuum, surface layer and subsurface layer) (Fig. 3). Each layer is assumed to be semi-infinite that has a magnetic permeability equals to that of free space.

The reflection and transmission coefficients at each layer interface i can be described as follows:

$$\gamma_i = \frac{\sqrt{\varepsilon_{r,i}}-\sqrt{\varepsilon_{r,i+1}}}{\sqrt{\varepsilon_{r,i}}+\sqrt{\varepsilon_{r,i+1}}} \quad \text{(S5)}$$

$$\tau_i = \frac{2\sqrt{\varepsilon_{r,i}}}{\sqrt{\varepsilon_{r,i}}+\sqrt{\varepsilon_{r,i+1}}} = 1 + \gamma_i \quad \text{(S6)}$$

The dielectric constant of the surface layer ($\varepsilon_{r,1}$) can be derived from equation (S5):

$$\varepsilon_{r,1} = \varepsilon_{r,0}\left(\frac{1-A_0}{1+A_0}\right)^2 \quad \text{(S7)}$$

Where $\varepsilon_{r,0}$ is dielectric constant in vacuum. A_0 is signed relative reflection amplitudes which represents the ratio between the amplitudes of the surface reflection and the amplitude of the incident signal.

The relative amplitude of the reflected pulse at the interface between surface and subsurface A_1 can be given by:

$$A_1 = (1-\gamma_0^2)\gamma_1 e^{-\alpha d} \quad \text{(S8)}$$

where α is attenuation constant, d is thickness of surface layer. Approximate expression for α can be derived as:

$$\alpha = \sigma_1\eta_0/2\sqrt{\varepsilon_{r,1}} \quad \text{(S9)}$$

Where $\eta_0 = 120\pi$ is wave-impedance in free space. Replacing the reflection coefficient and the attenuation constant with their respective expressions yields the following equation:

$$A_1 = (1-A_0^2)\frac{\sqrt{\varepsilon_{r,1}}-\sqrt{\varepsilon_{r,2}}}{\sqrt{\varepsilon_{r,1}}+\sqrt{\varepsilon_{r,2}}} e^{-\eta_0\frac{\sigma_1}{\sqrt{\varepsilon_{r,1}}}d_1} \quad \text{(S10)}$$

The conductivity σ_1 can be found by transforming this equation, as given by equation (S11):

$$\sigma_1 = \frac{\sqrt{\varepsilon_{r,1}}}{d_1}\frac{1}{\eta_0} log\left[\frac{1-A_0^2}{-A_1}\frac{\sqrt{\varepsilon_{r,1}}-\sqrt{\varepsilon_{r,2}}}{\sqrt{\varepsilon_{r,1}}+\sqrt{\varepsilon_{r,2}}}\right] \quad \text{(S11)}$$

As a result, the loss tangent and TiO_2+FeO content of lunar regolith can be derived subsequently.

Li *et al.* (2020) found that the bulk density is ρ_{bulk} = 1.9 g/cm^3 (or 1.67 g/cm^3 depending on their model) for a layer that is 6m thick. Hence, Li *et al.*'s dielectric constant of ε' = 3.5 corresponds to the average ε'$_r$ of the upper 6-m-thickregolith

material, as shown in Fig. S7. In this study, considering that the permittivity of lunar regolith increases rapidly at shallow depth, but increases more slowly at deeper depths, we assumed the average permittivity ($\varepsilon_{r,1,average}$) of regolith materials as ~3.6.

Text S4. Estimation for permittivity of lunar subsurface materials

LPR observes subsurface structures (such as boulders and interfaces) by detecting dielectric discontinuities. As the distance between the antenna and the subsurface object changes with the moving of Yutu-2 rover, single target buried in the subsurface produces parabolic-shaped diffraction (PSD) in the radar cross section.

Considering that rocks in the regolith mostly have irregular shapes and the effect of a rock's diameter will be reduced as the depth increases, we approximate the object as a point reflector in order to simplify the model. Fig. S8 demonstrates the mechanism of target detection for LPR. The propagating distance of electromagnetic (EM) wave from LPR to the subsurface object (L_1) and the minimum propagating distance when LPR is over the subsurface object (L) conform to Eq. (S12) based on the geometric relationship:

$$L_1^2 - \mathrm{L}^2 = \mathrm{D}^2 \tag{S12}$$

Where D is the horizontal distance from LPR to the subsurface object, which can be derived according to the location of Yutu-2 rover. Moreover, L_1 and L could be described as Eq. (S13), respectively:

$$\mathrm{L}_1 = \frac{\mathrm{vt}_1}{2},\ \mathrm{L} = \frac{\mathrm{vt}}{2} \tag{S13}$$

Where t_1 and t are the two-way propagating time corresponding to L_1 and L, v is the propagating velocity of EM wave.

The velocity of EM wave (v) is determined by the relative dielectric permittivity (ε_r) as:

$$v = \frac{c}{\sqrt{\varepsilon_r}} \tag{S14}$$

Where c is the speed of light in vacuum. Replacing the propagating distance in Eq. (S12) and the propagating velocity in Eq. (S13) with their respective expressions yields the following equation:

$$\varepsilon_r = \left(\left(c\sqrt{t_1^2 - t^2}\right)/2D\right)^2 \tag{S15}$$

As a result, the relative dielectric permittivity of lunar subsurface materials can be calculated with LPR data.

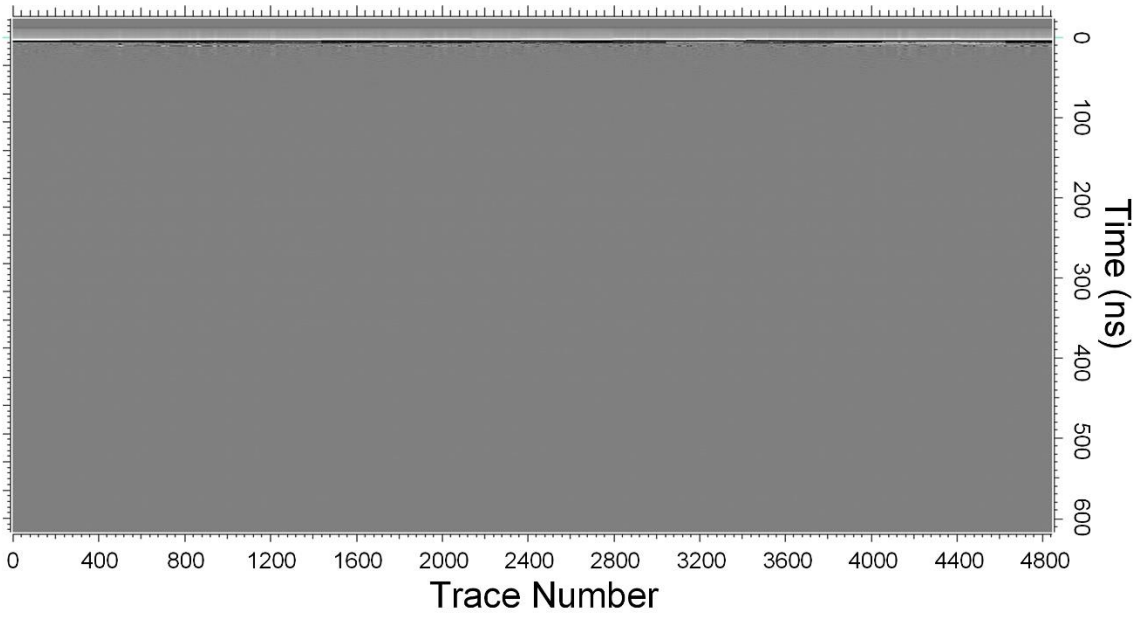

Figure S1. The raw LPR Channel-II data.

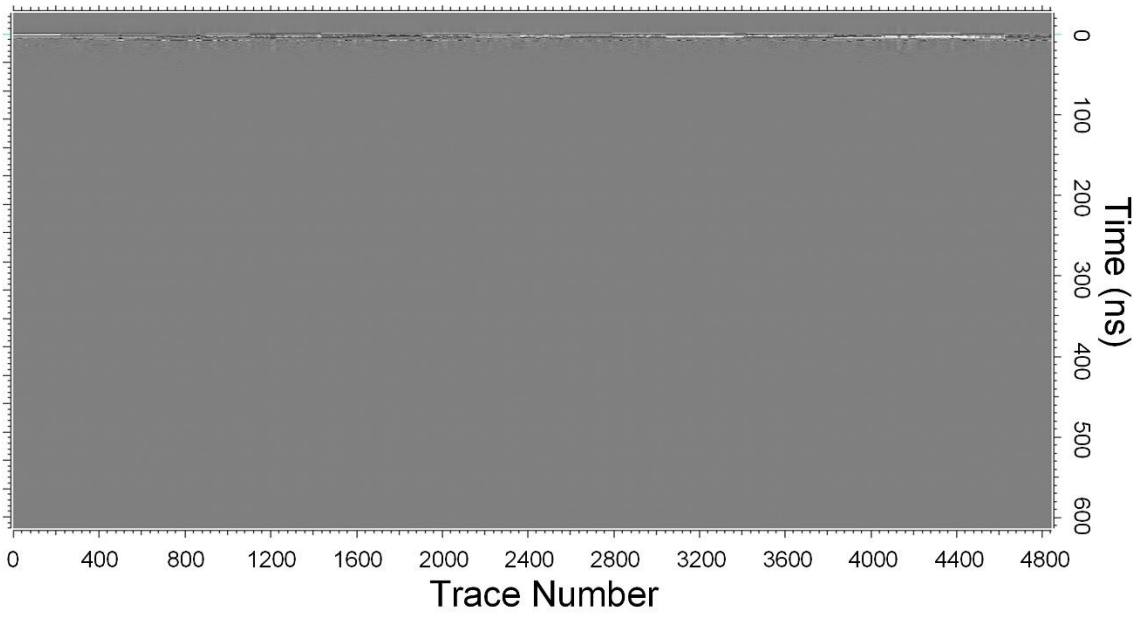

Figure S2. The LPR Channel-II data after DC removing and background removing.

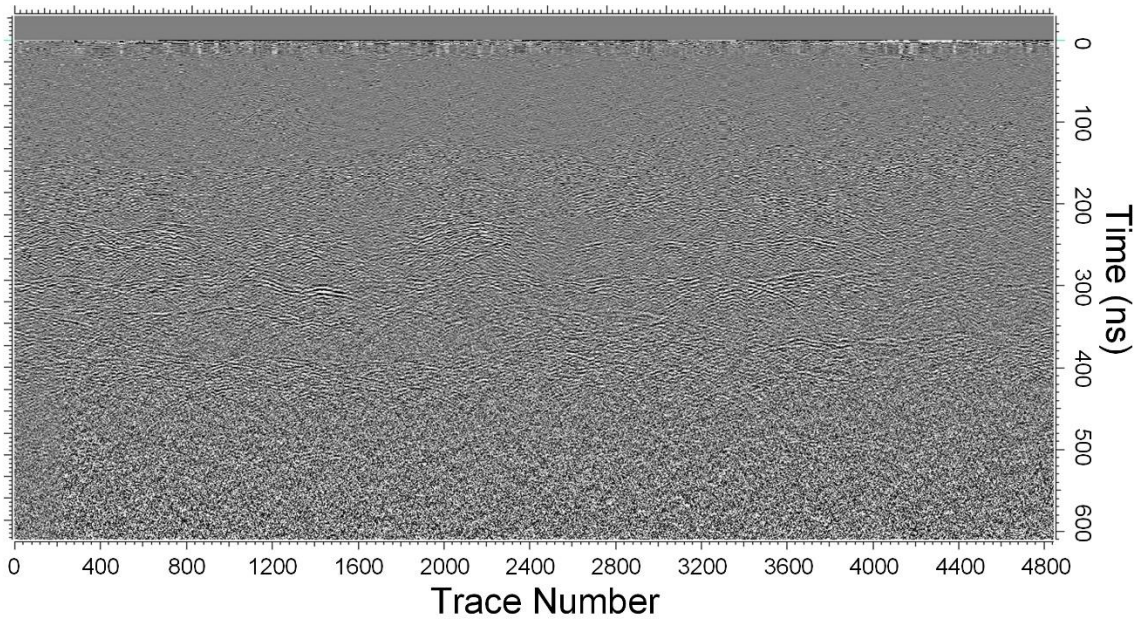

Figure S3. The LPR Channel-II data after Amplitude Compensation.

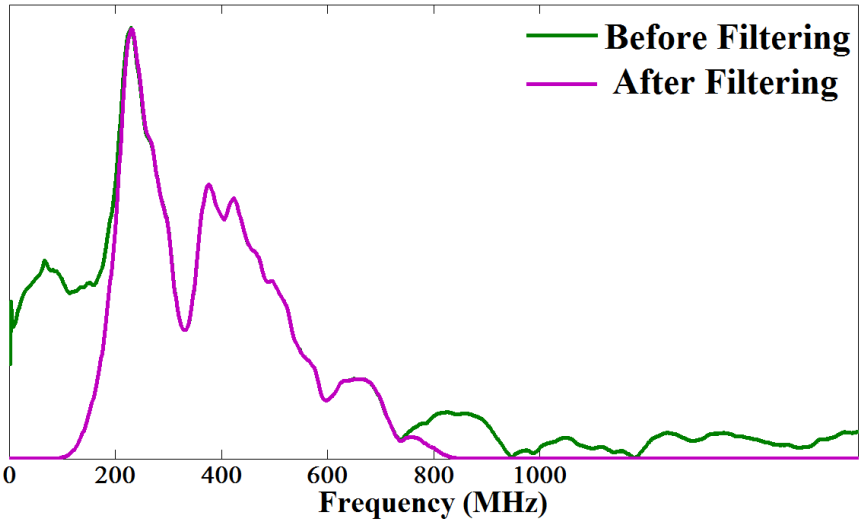

Figure S4. The frequency spectrum of LPR signal before (the green line) and after (the purple line) band-pass filtering.

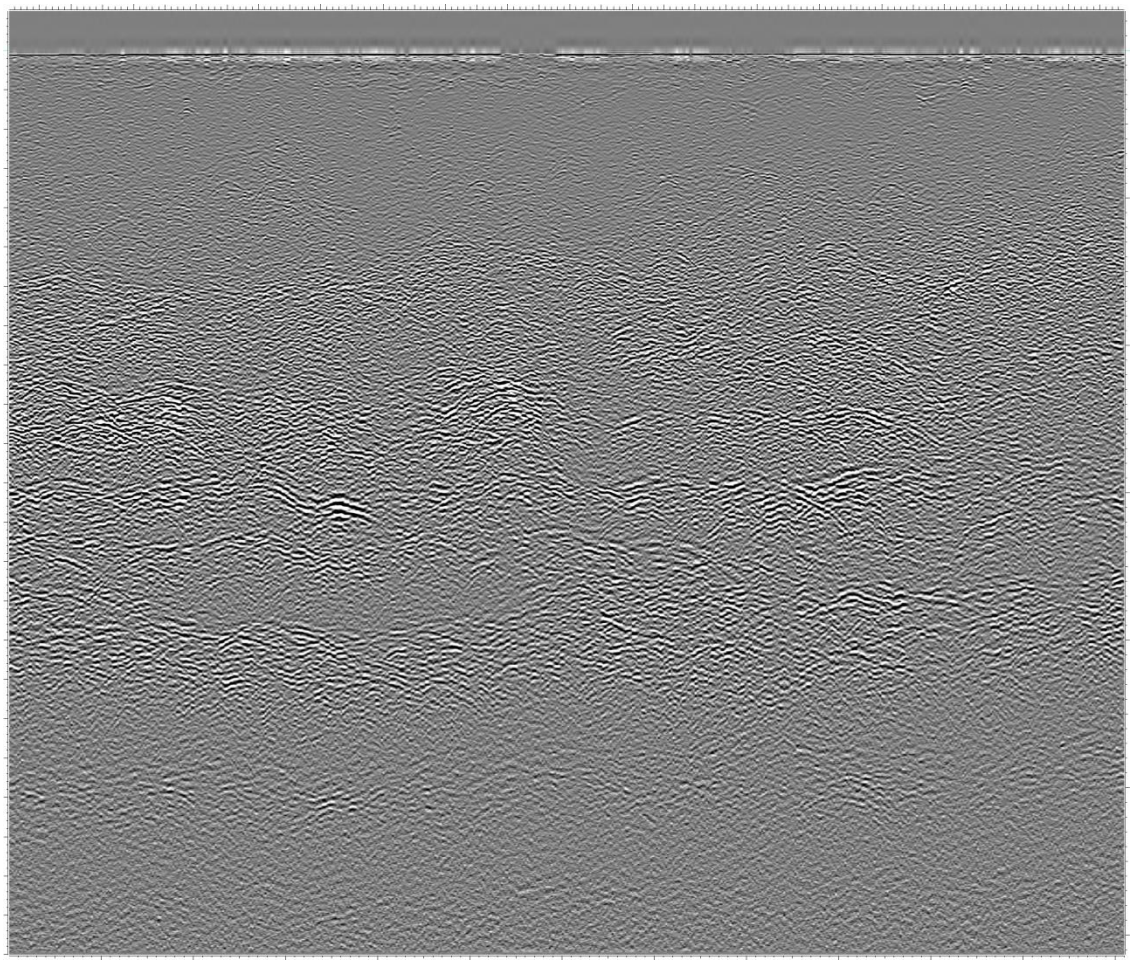

Figure S5. The radargram of processed LPR data after filtering.

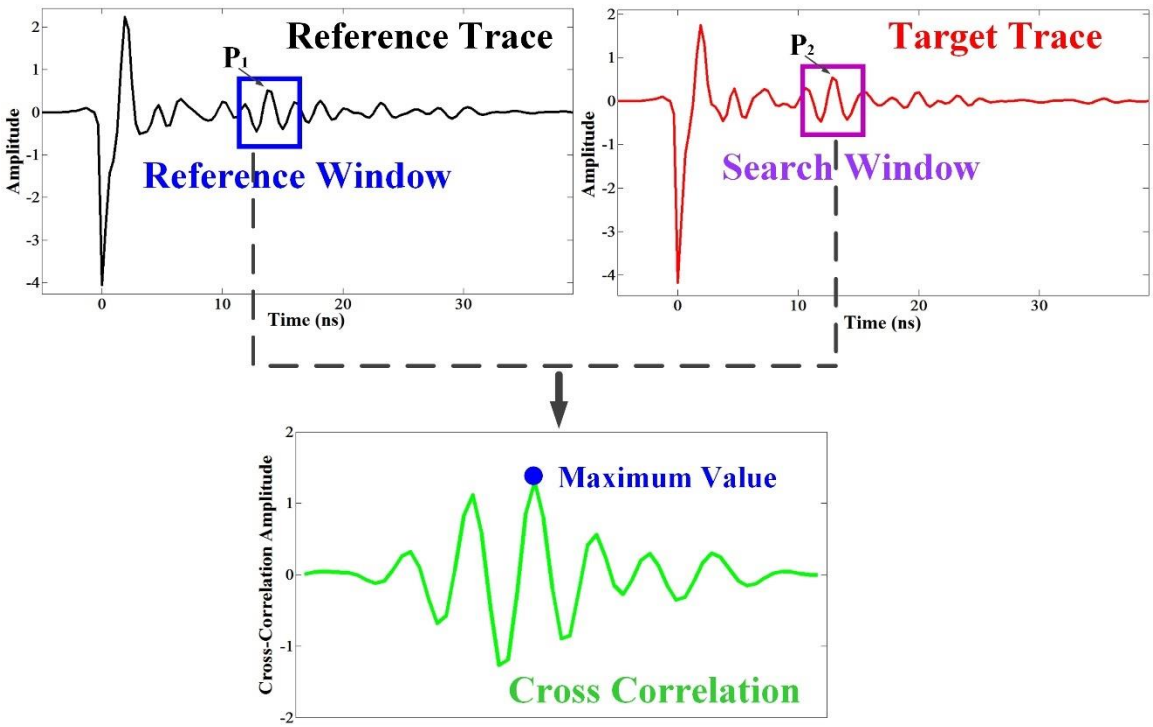

Figure S6. The schematic for the layer localization method. The black signal and red signal indicate reference trace and target trace respectively. The blue and purple rectangles indicate reference window and search window respectively. The search point is the center of both reference window and search window. The green line indicates the cross correlation between signals within reference window and search window. The blue point is maximum value of correlation.

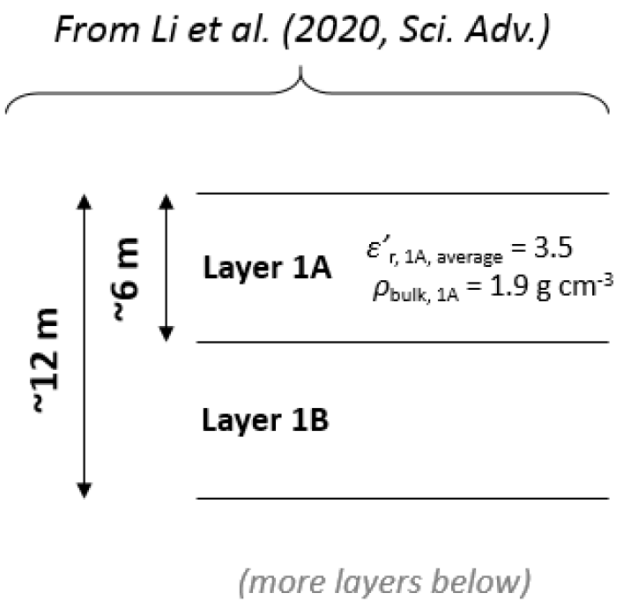

Figure S7. The model of subsurface layers in Li *et al.* (2020, *Sci. Adv.*)

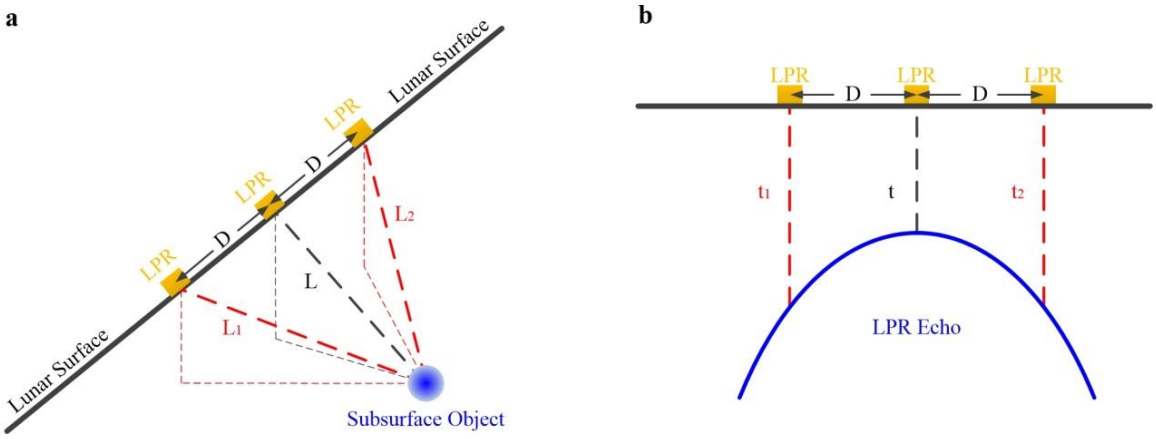

Figure S8. Mechanism of the hyperbolic fitting method.

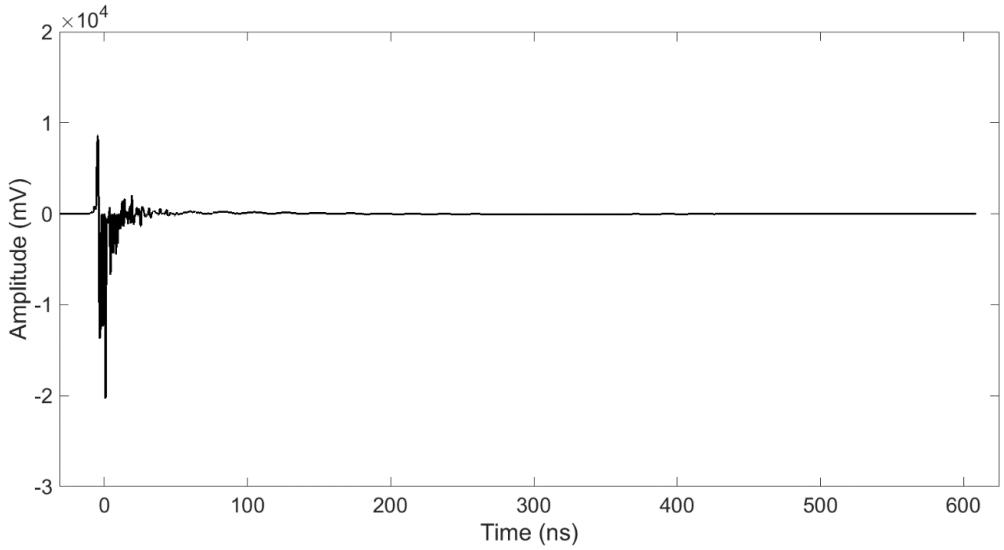

Figure S9. One trace of calibration signals of LPR Channel-II.