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Recognition of salt crust types by means of PolSAR to reflect the fluctuation processes of an ancient lake in Lop Nur

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ABSTRACT

Lop Nur once was a huge lake located in northwestern China. Its environmental evolution is significant for understanding historical global climate change. At present, there is no surface water in Lop Nur Lake Basin, and on SAR images it looks like an "Ear". The objective of this article is to recognize different types of salt crust by surface roughness parameters and interpret their environmental meanings in Lop Nur. Surface roughness parameter estimation, by means of microwave remote sensing technology, is a topic which is intensively studied yet not solved satisfactorily. In this article, the potential of using Polarimetric Synthetic Aperture Radar (PolSAR) acquisitions for the estimation of surface roughness parameter in Lop Nur Lake Basin is investigated. A new parameter S_l is proposed to characterize surface roughness and to discriminate salt crust types. Through the analysis of scattering mechanisms, the physical meaning of the PolSAR parameter Single Bounce Eigenvalue Relative Difference (SERD) is reinterpreted and it is used to retrieve parameterS_l. A good linear correlation between the measured surface roughness parameter S_l and SERD with an R^2 value of 0.72 was obtained. Furthermore, the distributions of different salt crusts in the certain lake area were analyzed. Based on hypotheses of the evolution of surface salt crust and the drying-up cycle of lakes, the fluctuation processes of an ancient lake in Lop Nur were discussed theoretically. These can help to have a better understanding of environmental changes in arid and semi-arid regions.

1. Introduction

Lop Nur in northwestern China is a typical extreme arid region. It is a representative of global arid regions and highly sensitive to regional climate changes, making it an ideal area for global climate change research. It is located at the lowest point of Tarim Basin with an average elevation of 780 m (Xia, 2007), and is the destination of almost all the rivers running through the Tarim Basin. Lop Nur is a microcosm of the evolution for the entire Tarim Basin and the mountains surrounding it. It is renowned in ancient Chinese history and located in the throat area of the ancient "Silk Road", the link of East and West cultural exchange. So the research of Lop Nur has important scientific and cultural values. Its environmental evolution in the recent ten thousand years, particularly the relationship between human activities and ecological evolution is of great significance (Li et al., 2008).

Since 1972, Lop Nur has been found to have a ring texture — the "Big Ear" feature on Landsat-1 images, and it has aroused widespread discussion by scientists. The ring texture is generally considered to be a faithful record of the historical shorelines which contains a wealth of geological and paleoclimate information. Due to the penetrating capability of microwave signals in arid regions, Synthetic Aperture Radar (SAR) images can portray the "Big Ear" feature more clearly, especially in the edge area of the basin. A very broad distribution of various types of salt crust is found in Lop Nur, which is associated with specific geological, geomorphological, and hydrogeological climatic conditions (Ma et al., 2011). Remote sensing is capable of studying the geological phenomena at a large spatial extent. It can be used to complement the traditional field work and other means of reconnaissance. It is conducive to the overall recognition of Lop Nur "Big Ear" patterns and can effectively assess the lake surface and subsurface material composition, morphology, structural features, and other significant information (Gong, 2010). Combined with field investigations and laboratory measurements, the climate and environmental information inherent in the rings can be extracted effectively. This article focuses on studying the distribution of different salt crust patterns in the Lop Nur Lake Basin using PolSAR data.

SAR remote sensing has great potential for monitoring and mapping of soil surface parameters. And electromagnetic scattering models can help to better understand the scattering features of natural targets. Surface electromagnetic scattering problems are hot issues in recent years. In established models, a large number of assumptions are made to obtain relevant equations, corresponding to high or low frequencies. At

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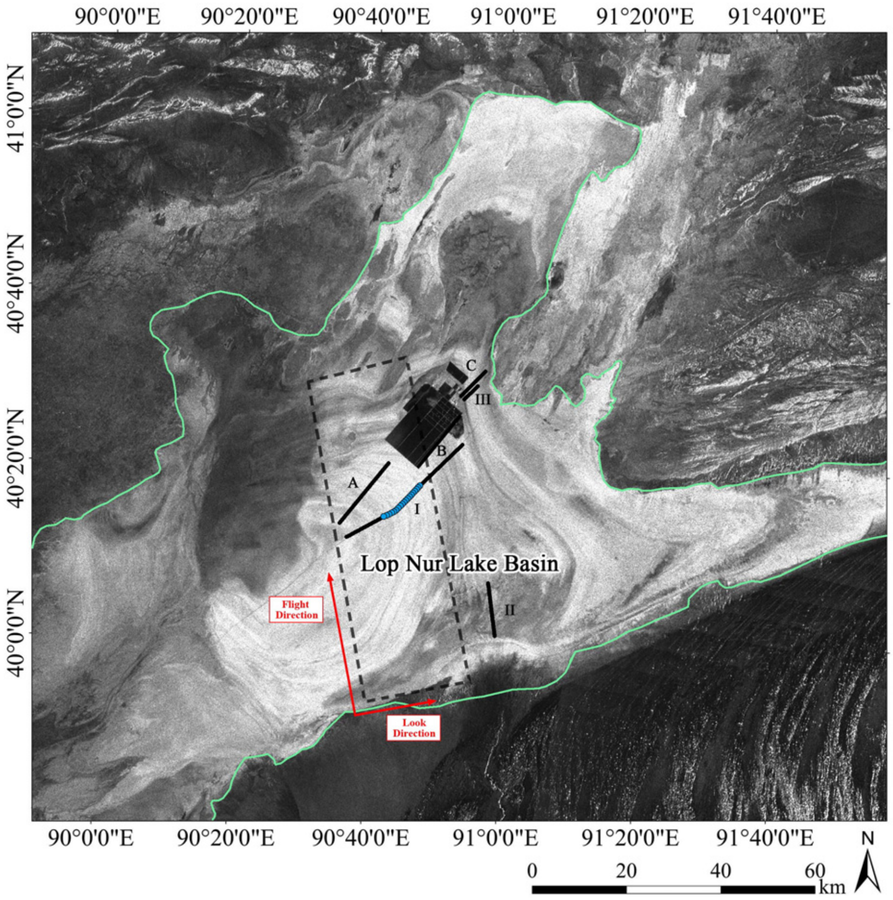

Fig. 1. Field investigation routes and sampling site locations. A, B and C are field routes in 2006, and I, II and III are field routes in 2008. The blue dots are positions of sampling sites of 2013. The dashed rectangle is the coverage of ALOS full-polarimetric SAR data used in the last part of this article. The flight and look directions of this data were marked out with red arrows. There is a large salt pond in the middle of the image as a black square. The green lines mean the scope of Lop Nur Lake Basin area. ALOS-PALSAR image (HH polarization, ScanSAR mode) obtained on 15 January 2011 was used as the basemap.

high frequencies and small incident angles, Kirchhoff approximation formulas are commonly used, and for low frequency and large incident angles, Small Perturbation Method (SPM) is mainly applied (Fung & Chen, 2010; Saepuloh, Koike, Urai, & Sumantyo, 2015). In 1992, Fung established the Integrated Equation Model (IEM), which can accurately reflect backscattering under a certain surface roughness range (Fung, 1994; Fung, Li, & Chen, 1992). It has been widely used in microwave surface scattering simulation and the analysis of radiation. In 2003, Chen et al. proposed the Advanced IEM (AIEM) concept and proved that the AIEM could describe surface scattering and radiation processes very well through the Monte Carlo numerical simulation (Chen et al., 2003; Fung & Chen, 2004). In the late 1980s, it was found through experiments and computer simulations, that the backscattering enhanced phenomenon occur more obviously on the rough soil surface. Based on this, Hsieh developed Modified Integral Equation Model (MIEM), which particularly considers the multiple scattering term (Hsieh, 1996; Hsieh, Fung, Nesti, Sieber, & Coppo, 1997). In the case of rough surfaces or interfaces, multiple scattering contributions are no longer small and should not be ignored. And the multiple scattering contribution appears more significant when surface roughness is more pronounced (Gong, Shao, Zhang, Liu, & Gao, 2014).

All the models approach the scattering behavior under the controlled conditions. However due to the over-parameterized modeling processes, the direct inversion remains difficult. Nevertheless, scattering models are still useful tools for analyzing physical propagating mechanisms, which is an important basis for inversion algorithm development.

A promising approach for surface parameter extraction begins with the investigation of second-order scattering statistics of surface scatterers (Hajnsek, 2001; Schuler, Lee, Kasilingam, & Nesti, 2002). Many recent studies have investigated the potential of the correlation coefficient between two polarization channels. At the beginning, linear or circular polarization correlation coefficients were used to extract roughness parameters. Later on, Schuler et al. (2002) found that the real part of the circular polarization correlation coefficient is more efficient in surface roughness measurements and can use polarization data to extract topographical information. More recently, the relationship between the surface roughness parameter and the eigenvalues of the polarimetric coherency matrix, which have a physical significance in terms of scattering amplitudes, has been demonstrated using laboratory data (Hajnsek, Pottier, & Cloude, 2003). Cloude (1999), studied extracting surface roughness parameters from the eigenvalue and eigenvector parameters calculated from polarimetric coherent decomposition, finding a good linear relationship between polarization scattering anisotropy 'A' and surface Root Mean Square (RMS) height. With the increase of surface roughness, the surface depolarization effect increases, so the polarization scattering entropy will increase (Cloude, 1999). Hajnsek et al. (2003) studied the surface parameter extraction problem from polarimetric SAR images. They studied on how to use the H, A, and α parameters obtained from the Cloude decomposition to separate surface roughness parameters from soil moisture parameters. They also proposed an improved model, called the X-Bragg model, as the SPM model can't describe the cross-polarization and depolarization features very well (Fung & Chen, 2010; Hajnsek et al., 2003; Saepuloh et al.,

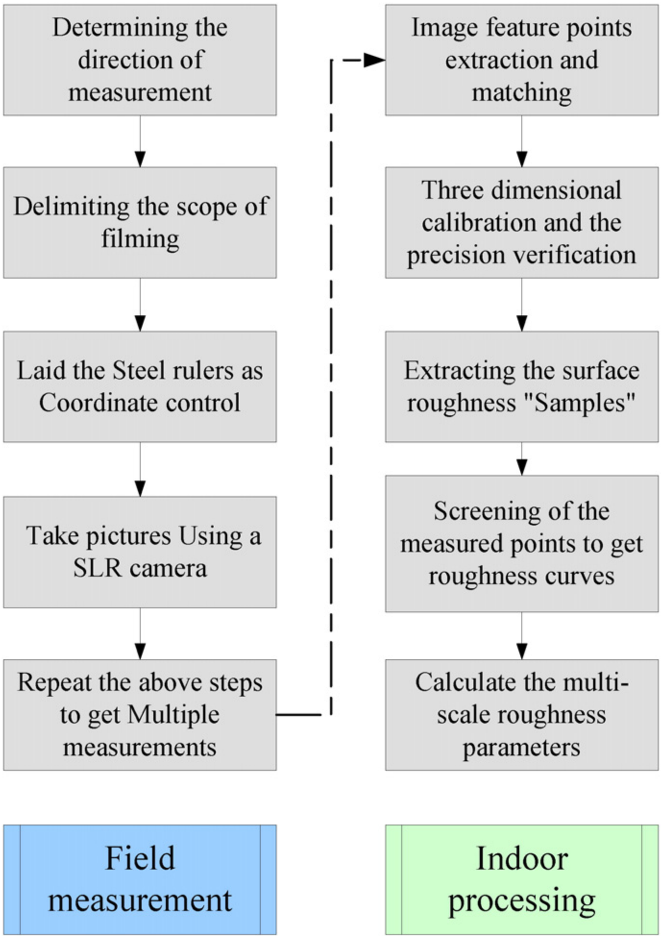

Fig. 2. The flow chart of the proposed digital three-dimensional micro-topography reconstruction method. It can measure surface roughness parameters in a multi-scale way with high accuracy.

2015). In 2003, Allain combined the polarization eigenvalue decomposition method with physics-based IEM and AIEM surface scattering models and used a look-up table method to conduct surface roughness inversion (Allain, 2003; Allain, Ferro-Famil, & Pottier, 2004). This method applies to a relatively wider range of surface roughness. As for Lop Nur Lake Basin, with extremely rough surfaces, such inversion methods can't be executed precisely. Allain et al. also proposed a parameter called Single Bounce Eigenvalue Relative Difference (SERD). It is important for media with large entropy values and can effectively determine the importance of the different scattering mechanisms (Allain, Ferro-Famil, & Pottier, 2006; Allain, Lopez, Ferro-Famil, & Pottier, 2005). In this article we will try to use the SERD parameter to recognize different types of salt crust.

The objective of this article is to recognize different types of salt crust from surface roughness parameters and interpret their environmental meanings in the Lop Nur area. The inversion of surface roughness in areas with very rough surfaces is a challenging work and is the precondition of salt crust discrimination. So the problem of rough surface parameter inversion by polarimetric parameters is first presented in this article. The ALOS-PALSAR L-band polarimetric data are used to obtain the polarimetric characteristics. In Section 2.1, the study area and description of the acquired data sets used for this article are discussed. In Section 2.2.1, the basic scattering mechanisms in Lop Nur are introduced. In Section 2.2.2, the SERD parameter derived from the eigendecomposition of the coherency matrix considering the reflection symmetry hypothesis is described in detail and the physical meaning of it is reinterpreted. The roughness estimation results of Lop Nur lake area and their environmental implications are discussed in Section 3. Finally, summary and concluding remarks are presented at the end of this article.

2. Materials and methods

2.1. Test site and field investigations

2.1.1. Test site description and image data

Lop Nur is located in the eastern Tarim Basin in the Xinjiang Uygur Autonomous Region, northwest China. Its environmental history reflects the processes of climate and environment evolution in arid areas, containing information of quaternary geology, paleoclimate, and other disciplines. It also has some response relationships on global environmental changes (Liu et al., 2014; Luo et al., 2006; Luo et al., 2009). The former lake bed displays features of extreme salinification and severe wind erosion. A large number of rimous salt crusts are found in the lake basin, resulting in an extremely coarse surface and fairly complex scattering mechanisms that developed during soil formation (Gao et al., 2014).

Lop Nur formed the modern salt crust topography during the final drying process. The basic types of salt crust are: early cracking salt crust, crack-like salt crust, very rough honeycomb salt crust and hummocky salt crust. The crack-like salt crust can be separated into polygonal structure, double polygon and honeycomb structure. Different salt crust patterns reflect different evolving stages. Under the combined influence of environmental factors, salt crusts experience the evolutionary

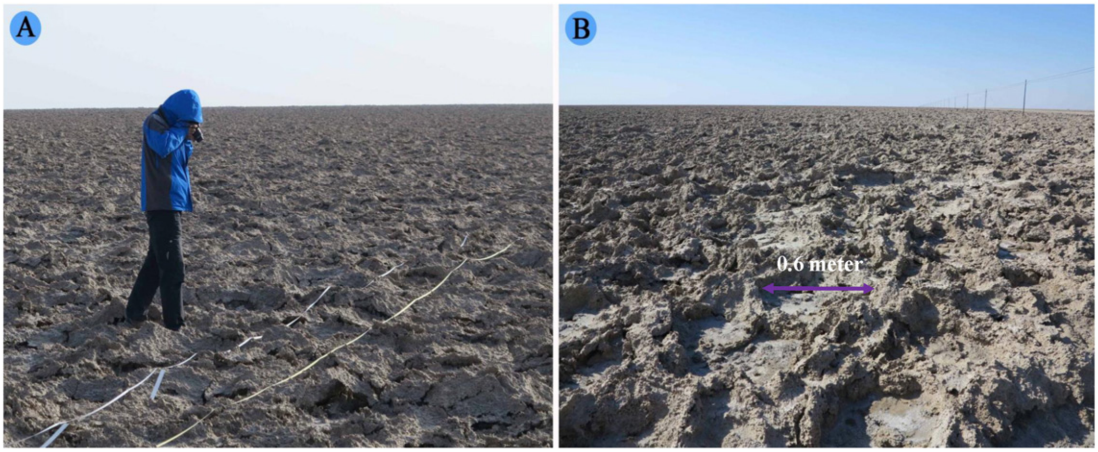

Fig. 3. Photos of surface roughness measurement and surface conditions. The linear objects in the Photo A are two tapes which are used to calibrate the measurement range. The scale mark is also shown on Photo B.

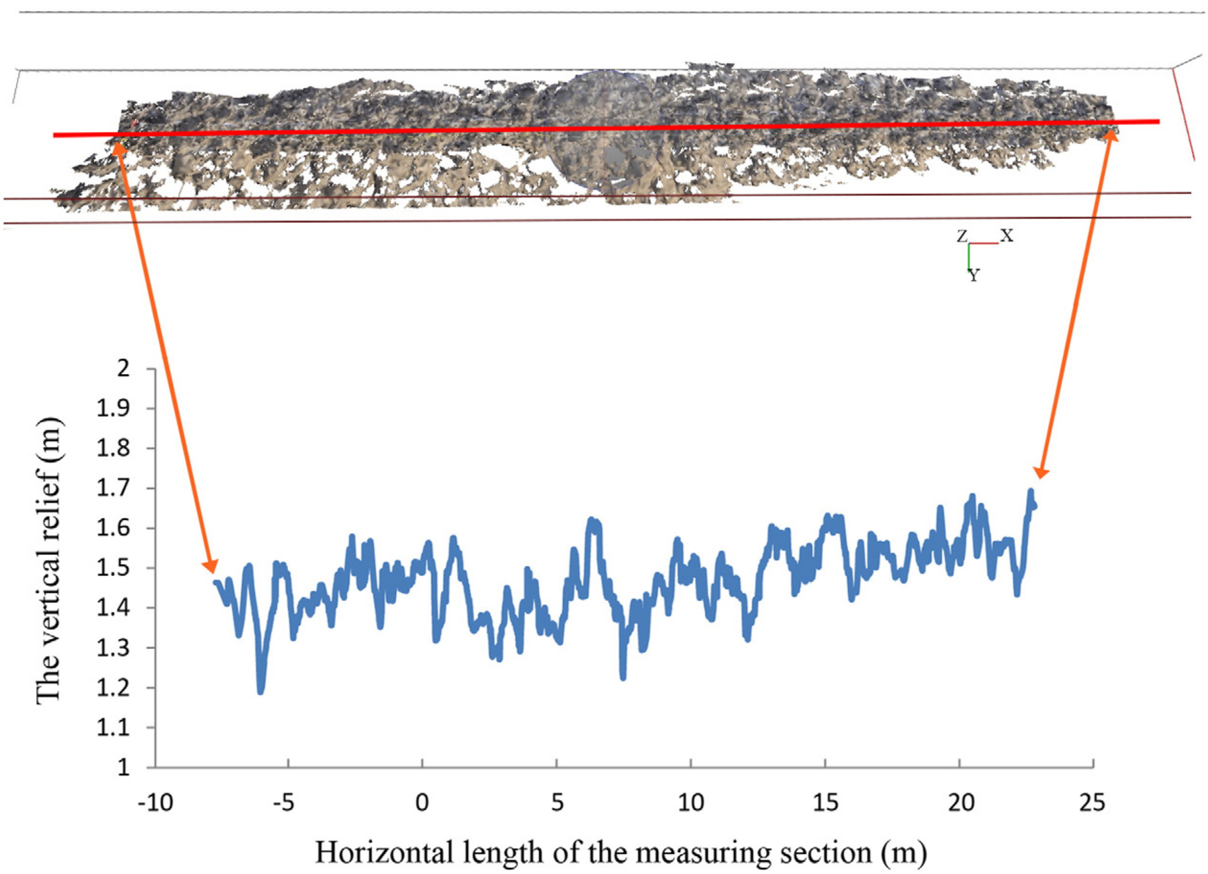

Fig. 4. The reconstructed three-dimensional micro-topography and the extracted roughness curve. The upper picture is the reconstructed three-dimensional micro-topography and the red line in the middle is the sampling line. The lower picture is the roughness curve composed by the sampling points extracted from the micro-topography.

sequence of flat, crack-like, micro shell-like and flat patterns (Li et al., 2008; Zhao, Xia, Wang, Cao, & Lu, 2005). It is pointed out that different types of salt crust are shown as significant zonal distributions. Many scholars believe the ring-like texture of Lop Nur is a true record of the shrinking of the lake, with implications of climate change from wet to dry. Remote sensing technology facilitates the spatial analysis of the surface micro-topography distributions in Lop Nur, which can help to analyze environmental evolution processes in arid regions. Fig. 1 shows the investigated routes and the distribution of the sampling site. Fig. 2 is the flow chart of the proposed field measurement method and Fig. 3 shows the surface condition and outdoor samples collection. One scene of ALOS-PALSAR data (HH polarization, ScanSAR mode) obtained on January 15, 2011 is used as the basemap in Fig. 1.

Table 1
Roughness measurement results in Lop Nur Lake Basin.

Test site no.	RMS height s (m)	Correlation length l (m)	$S_l = s/l$
1	0.0657	0.5002	0.1313
2	0.0863	0.5949	0.1451
3	0.0605	0.5712	0.1059
4	0.0806	0.5342	0.1509
5	0.0847	0.5627	0.1505
6	0.0903	0.9644	0.0936
7	0.0703	1.1349	0.0619
8	0.0857	1.1297	0.0759
9	0.0681	1.1979	0.0568
10	0.0876	1.2023	0.0729
11	0.0870	1.0888	0.0799
12	0.0650	0.9579	0.0679
13	0.0664	1.2497	0.0531
14	0.0717	0.6524	0.1099
15	0.0742	1.1184	0.0663
16	0.0683	0.5138	0.1329
17	0.0935	0.6496	0.1439
18	0.0836	1.0359	0.0807
19	0.0872	0.8388	0.1040

The ALOS-PALSAR imagery used in this article is the full polarimetric mode obtained on May 6 2009, and the off-nadir angle is 23.1°. Images were reprojected on to the UTM/WGS84 coordinate system after basic radiometric, geometric correction using PolSARpro and MapReady softwares. The fine geometric correction was conducted by ENVI software using ground control points.

2.1.2. Field investigation and roughness measurement technique

Our research group performed six field investigations in Lop Nur. The field investigations and measurements provided data, which can support the subsequent quantitative analysis. In November 2006, the authors visited the ruins of the Lou Lan Kingdom and the Lop Nur Lake Basin, where lacustrine deposits were sampled along a 41 km profile at intervals of 2 km to the northeast of Lop Nur. The second field investigation was conducted in November 2008, which included three routes, and four study areas. 78 sampling sites were selected along a profile length of 62 km. Lacustrine samples from the surface and subsurface were collected at every sampling site.

The 2013 field experiments spanned from October 14 to November 3, and our article is mainly based on this field investigation. The field work included dielectric constant measurement, Optical Stimulated Luminescence Dating (OSL) sampling, and surface roughness measurement. Note that the expedition route was the same as the route I of 2008.

Precise estimation of surface roughness parameters from field-measured ground truth data is a challenging work and has not been

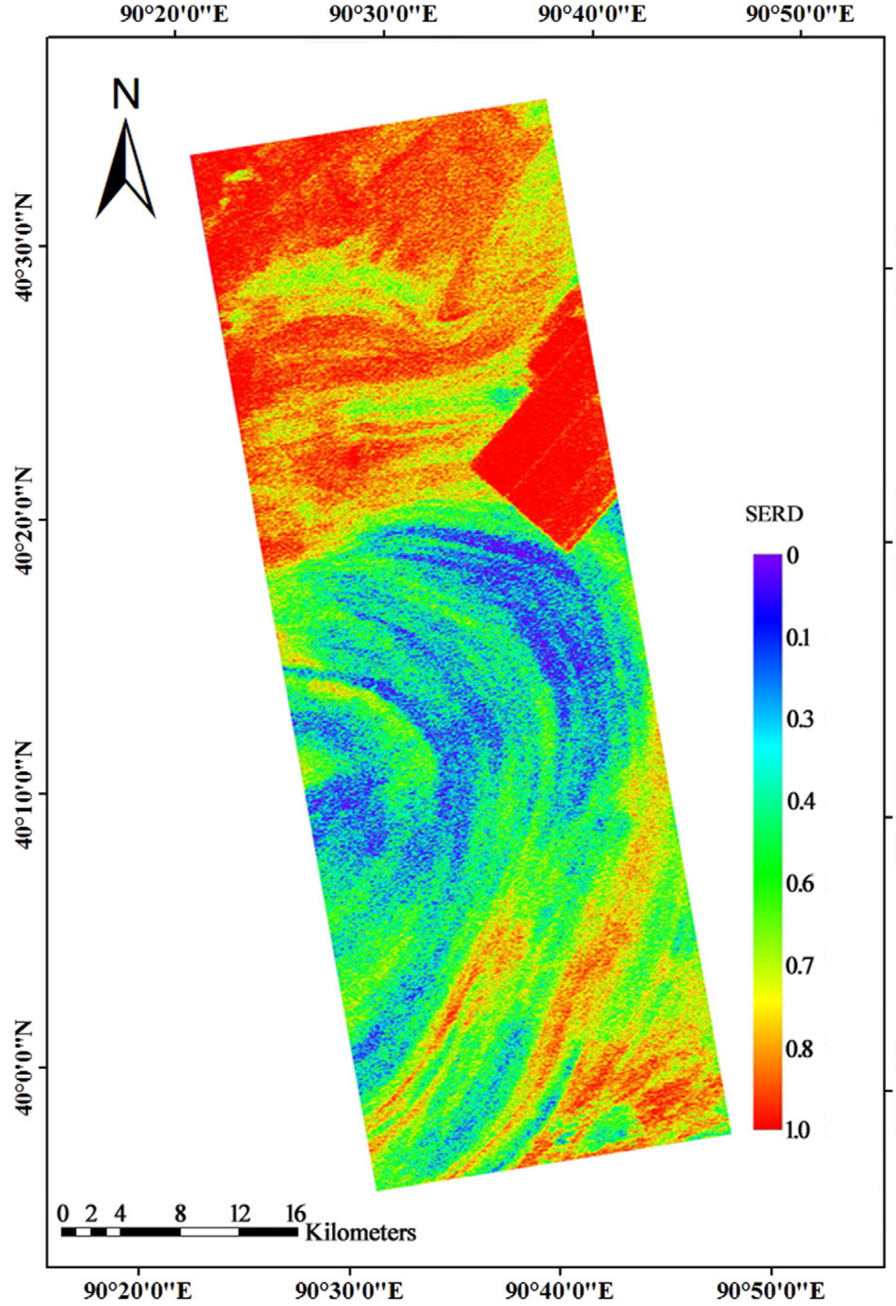

Fig. 5. The distribution of the SERD throughout the Lop Nur lake area got from eigenvalue-based decomposition method. In the lake area the significant changes in SERD parameter can be found, which is similar to the ring-like stripes to a certain extent.

fully resolved. Oh et al. found that in order to measure the surface parameter with a precision of ± 10%, the surface segment should be at least $40\bar{l}$ long, where $\bar{l}$ is the mean or true value of the surface correlation length (Oh & Hong, 2007; Oh & Kay, 1998). In our study area the general needle plate measuring is very difficult to reach this requirement and is easily influenced by artificial operation. Based on digital close-range photogrammetry theory, we proposed a three dimensional (3D) micro-topography reconstruction method to measure surface roughness in a multi-scale way. Using this method, a 3D model of the micro-topography can be constructed by automatically splicing many scenes of overlapping photos, from which the profile of the micro-topography can be extracted, and the RMS height and correlation length can then be calculated. The examples of the reconstructed three-dimensional micro-topography and the extracted roughness curve are expressed in Fig. 4. This method could measure a wide range of surface roughness values and the roughness parameters can be obtained at different wavelength scales. The proposed method is very practical and can measure the surface roughness parameters with high accuracy. The roughness measurement results from the Lop Nur Lake Basin are presented in Table 1.

Most radar data based roughness inversion studies are only aimed at the parameter of RMS height *s*. The effect of the correlation length *l* on backscattering coefficient σ^0 is usually neglected (Zribi & Dechambre, 2003). It is maintained that using only the RMS height *s* as a roughness parameter is not sufficient to portray the real surface. In fact, taking two different values for *s* and *l* in the IEM simulations may lead to the same

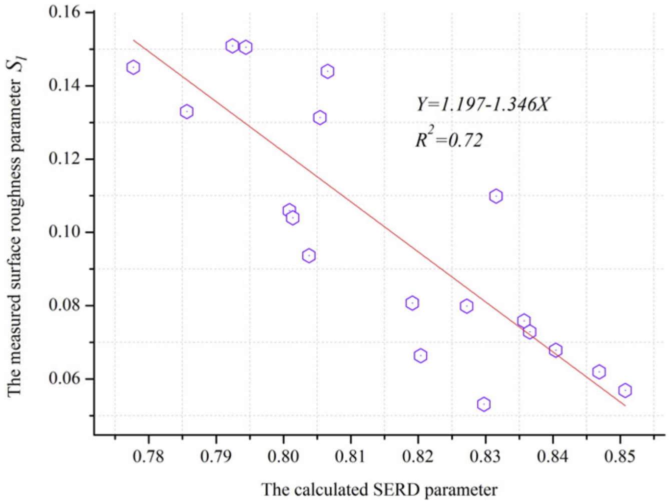

Fig. 6. Comparison between the SERD calculated from eigenvalue-based decomposition and the measured S_l from the field investigation. One scene of ALOS-PALSAR polarimetric data was used, with R square and linear fitting formula shown. The solid line in diagram accounts for the linear fitting line.

σ^0 under the certain condition. For these reasons, a new roughness parameter S_l is proposed to describe the surface roughness in this study, with the objective to mix the effects of s and l. The proposed parameter S_l is defined as:

$$S_l = s/l. \tag{1}$$

2.2. Principles and methods

2.2.1. Scattering mechanisms analysis in Lop Nur lake basin

At present, the bed of Lop Nur lake is extremely rough and uniform, with endless dry salt crusts in all directions. In this area the average RMS height(s) is 5.9 cm and the normalized RMS height (ks) for the L-band (1.25 GHz) is 1.54 and for the C-band (5.25 GHz) is 6.6. The upper salt crust layer is extremely dry with zero water content, resulting in a very low complex dielectric constant. However, with further digging into the lacustrine deposits, a moist/brine layer was found widely distributed at the depths of 50–60 cm (Shao et al., 2012). Then the subsurface structure of Lop Nur can be regarded as consisting of two layers with different dielectric properties: an upper dry layer and a moist saline subsurface layer (Gong et al., 2014; Liu, Gong, Shao, & Li, 2015).

From the perspective of scattering mechanisms, in Lop Nur lake SAR signals can penetrate the rough surface to detect subsurface targets because the dielectric properties of the top layer are very low (Shao et al., 2012), which means that the attenuation effect on the signals is weak. When the signals arrive at the top interface, strong surface scattering will happen because of the rough micro-topography. Note that there exists single scattering and multiple scattering simultaneously, and it has been indicated that the multiple scattering contribution appears more important when surface roughness is more pronounced (Gong, 2010; Gong et al., 2014; Hsieh, 2001). Then, the transmission effect will allow a partial of signals to propagate sequentially into subsurface layer, where absorption and volume scattering may attenuate the signal intensity furtherly.

In this study, depolarization effect is discussed in detail. Depolarization mainly results from multiple scattering behavior, and as for Lop Nur Lake Basin, there are two parts. Specifically one is from surface scattering at rough air-surface interface, and the other is from volume scattering at subsurface layer. In addition, according to the salt crust geomorphology dynamics, the subsurface properties (constitution, particle size, salinity etc.) drives the surface patterns development, which means volume scattering at subsurface and surface scattering are correlated. And both of them are related to surface configuration, acting as depolarization effect. In order to recognize the salt crust types in Lop Nur Lake Basin, certain remote-sensing parameter representing depolarization is anticipated.

2.2.2. Polarimetric target decomposition based inversion algorithm

In recent years, many scholars try to extract soil parameters by polarimetric decomposition. Polarimetric decomposition can be classified into two categories, which are the physical model based and the matrix eigenvalue based. Considering the special surface condition and the scattering mechanisms introduced in 2.2.1, the matrix eigenvalue based decomposition method is adopted to retrieve the surface roughness parameter in Lop Nur.

Two eigenvalue-based parameters, the SERD and the double bounce eigenvalue relative difference (DERD) were introduced by Allain et al. in 2005 to characterize natural media. These two parameters are derived from the averaged coherency T_3 matrix considering the "reflection symmetry" hypothesis (Allain et al., 2005). The corresponding averaged coherency T_3 matrix is given by:

$$T = \frac{1}{2}\begin{pmatrix} \left\langle |S_{hh}|^2 \right\rangle + 2\mathrm{Re}(\langle S_{hh}S_{vv}^* \rangle) + \left\langle |S_{vv}|^2 \right\rangle & \left\langle |S_{hh}|^2 \right\rangle - 2jIm(\langle S_{hh}S_{vv}^* \rangle) - \left\langle |S_{vv}|^2 \right\rangle & 0 \\ \left\langle |S_{hh}|^2 \right\rangle + 2jIm(\langle S_{hh}S_{vv}^* \rangle) - \left\langle |S_{vv}|^2 \right\rangle & \left\langle |S_{hh}|^2 \right\rangle - 2\mathrm{Re}(\langle S_{hh}S_{vv}^* \rangle) + \left\langle |S_{vv}|^2 \right\rangle & 0 \\ 0 & 0 & 4\left\langle |S_{hv}|^2 \right\rangle \end{pmatrix}. \tag{2}$$

In such a case, it is possible to derive the analytical expressions of the corresponding Non-Ordered in Size ("NOS") eigenvalues (VanZyl, 1992):

$$\lambda_{1NOS} = \frac{1}{2}\left(\left\langle |S_{hh}|^2 \right\rangle + \left\langle |S_{vv}|^2 \right\rangle + \sqrt{\left(\left\langle |S_{hh}|^2 \right\rangle - \left\langle |S_{vv}|^2 \right\rangle \right)^2 + 4\left\langle |S_{hh}S_{vv}^*|^2 \right\rangle} \right) \tag{3}$$

$$\lambda_{2NOS} = \frac{1}{2}\left(\left\langle |S_{hh}|^2 \right\rangle + \left\langle |S_{vv}|^2 \right\rangle - \sqrt{\left(\left\langle |S_{hh}|^2 \right\rangle - \left\langle |S_{vv}|^2 \right\rangle \right)^2 + 4\left\langle |S_{hh}S_{vv}^*|^2 \right\rangle} \right) \tag{4}$$

$$\lambda_{3NOS} = 2\left\langle |S_{hv}|^2 \right\rangle. \tag{5}$$

The first and second eigenvalues depend on the copolarized backscattering coefficients and on the correlation between the vertical and horizontal channels (ρ_{HHVV}). In this case, the relation $\lambda_{1NOS} \geq \lambda_{2NOS}$ always holds. The third eigenvalue corresponds to cross-polarized channel. It is the characterization of depolarization effect and is mainly related to multiple scattering effect. Because in general the single scattering is the major contribution to the like-polarized scattering, but the multiple scattering is the only contribution to the cross-polarized scattering (Hsieh, 2001; Hsieh & Fung, 2005).

In order to determine the scattering mechanisms, an analysis is led on the α_i angles extracted from the first two eigenvectors $\underline{u}_1$ and $\underline{u}_2$ associated to the first two eigenvalues λ_{1NOS} and λ_{2NOS} with:

$$\alpha_i = \arccos(|u_{i1}|) = \arctan\left(\frac{\sqrt{|u_{i2}|^2 + |u_{i3}|^2}}{|u_{i1}|} \right) \text{ with } 0 \leq \alpha_i \leq \frac{\pi}{2} \tag{6}$$

where u_{i1}, u_{i2}, and u_{i3} correspond to the components of the unitary eigenvector $\underline{u}_i$. The nature of the scattering mechanism is thus determined according to (Lee & Pottier, 2009):

$$\alpha_i \leq \frac{\pi}{4} \Leftrightarrow \text{Single reflection} \quad \alpha_i \geq \frac{\pi}{4} \Leftrightarrow \text{Double reflection} \tag{7}$$

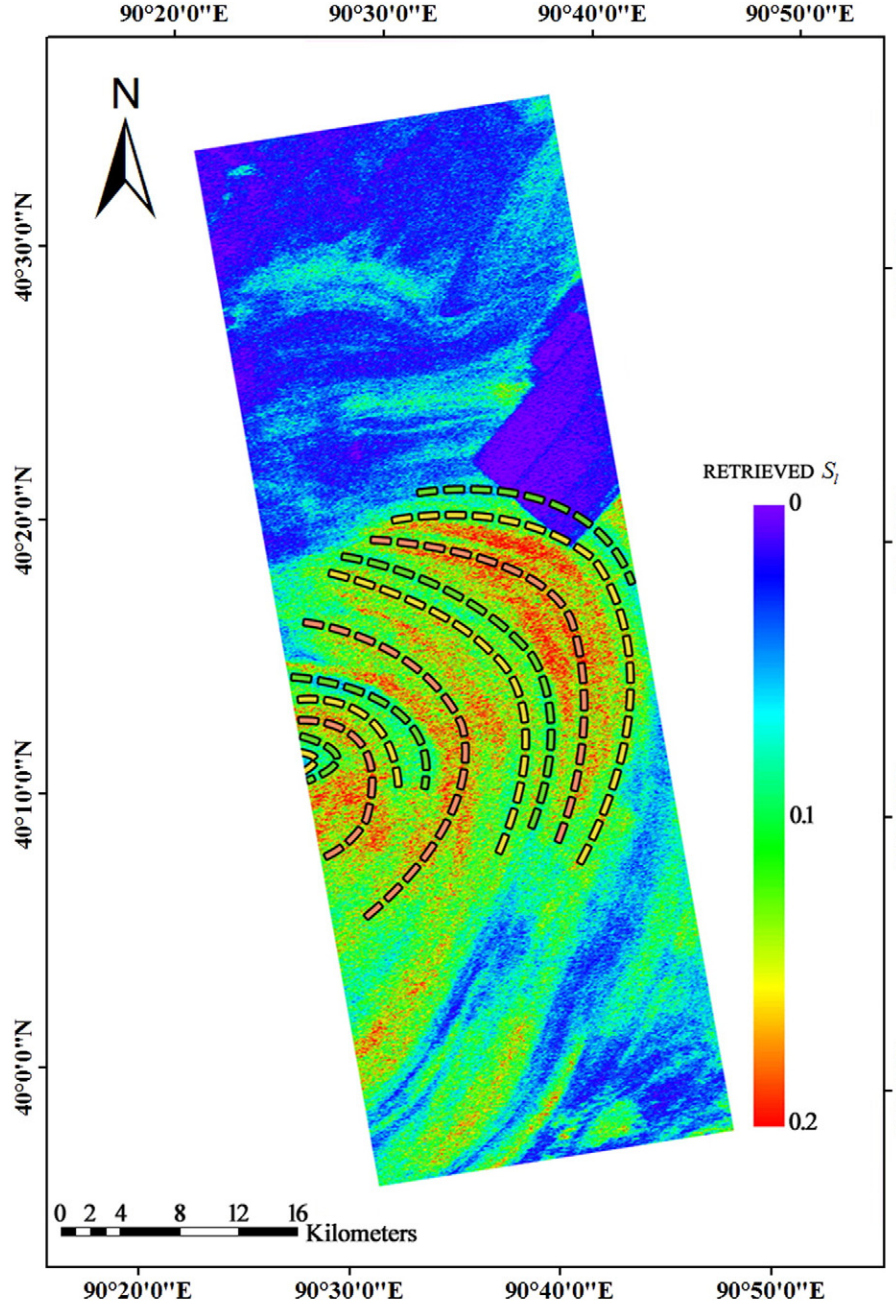

Fig. 7. The distribution of S_l throughout the Lop Nur lake area retrieved by SERD. According to the different surface roughness, the salt crusts in Lop Nur lake area can be divided into three main types: early cracking, crack-like and very rough honeycomb salt crusts. These three types were expressed by dotted lines with green, yellow and red colors, respectively. Note that the repeated sequence of this triplet implies the repeated cycles of flooding and drying of the lake.

moreover, the orthogonality condition between the eigenvectors leads to:

$$\alpha_1 + \alpha_2 = \frac{\pi}{2}. \tag{8}$$

The two eigenvalue-based parameters called the SERD and the DERD are defined as:

$$SERD = \frac{\lambda_S - \lambda_{3NOS}}{\lambda_S + \lambda_{3NOS}} \tag{9}$$

$$DERD = \frac{\lambda_D - \lambda_{3NOS}}{\lambda_D + \lambda_{3NOS}} \tag{10}$$

where λ_S and λ_D are the two eigenvalues respectively associated to the single bounce and to the double bounce scattering mechanisms, and are fixed according to:

$$if\alpha_1 \le \frac{\pi}{4} \Leftrightarrow or\alpha_2 \ge \frac{\pi}{4} \Rightarrow \begin{cases} \lambda_S = \lambda_{1NOS} \\ \lambda_D = \lambda_{2NOS} \end{cases} \text{ and } if\alpha_1 \ge \frac{\pi}{4} \Leftrightarrow or\alpha_2 \le \frac{\pi}{4} \Rightarrow \begin{cases} \lambda_S = \lambda_{2NOS} \\ \lambda_D = \lambda_{1NOS} \end{cases} \tag{11}$$

The two parameters (SERD and DERD) permit to cover the entire NOS eigenvalues spectrum and to compare the importance of the various scattering mechanisms. The DERD parameter can be compared with the anisotropy$A$derived from the second and the third eigenvalues of the averaged coherency T_3 matrix. The SERD parameter usefulness becomes important for media with large entropy H values, in order to determine the nature and the importance of the different scattering mechanisms (Lee & Pottier, 2009).

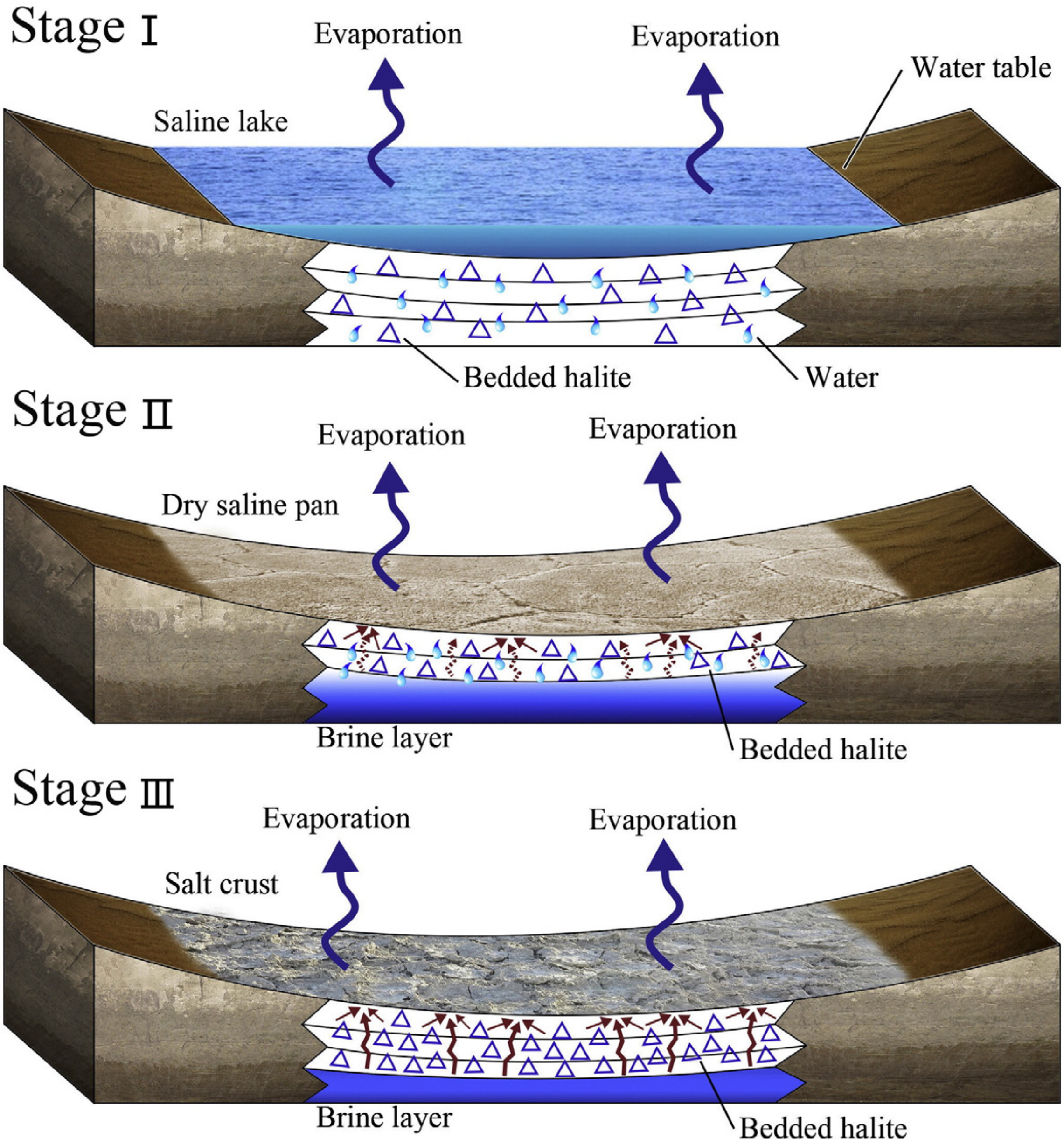

Fig. 8. The process from lake retreat to salt crust formation. It is divided into three stages. Stage I is the salt lake evaporative and concentration stage. Under the strong evaporation, the concentration of salts in water is rising and salts will begin to separate out during this process. Stage II is the saline pan desiccation stage. The evaporation is continuing, under the effect of soil capillarity the dry saline pan on surface will begin to crack into polygons. At this stage the effect of soil capillarity is relatively weak and it is expressed with dotted line. Stage III is the formation process of surface rock shell. The effect of soil capillarity is very intense and it is expressed with solid line. At this stage the location of the brine layer will gradually decline and the amount of the precipitated salts (the triangles) in subsurface will increase.

In the case of rough bare soil surfaces, single scattering dominates the mean scattering mechanism, even on very rough surfaces. Thus, the SERD parameter values are very high. It is very sensitive to surface roughness parameters and can be employed for quantitative inversion of bio- and geophysical parameters (Lee & Pottier, 2009).

In definition, SERD determines the relative size between single and multiple scattering (the depolarization effect). It is built up to compare the relative importance of the different scattering mechanisms. As for Lop Nur, the surface is very rough and single scattering is still the major scattering mechanism. As previously discussed, it is known that there exists single scattering and multiple scattering simultaneously in Lop Nur Lake Basin, and rougher surface could produce more notable multiple scattering effect. The λ_{3NOS} value of SERD is characterized by the depolarization effect, and through the Section 2.2.1 it can be concluded that the multiple scattering effect from both the rough surface and subsurface layer contribute to the λ_{3NOS} value. Furthermore combined with salt crust formation process it is proposed that the surface pattern also has close correlation with the subsurface multiple scattering effect. Thus it can be strongly supposed that with surface roughness increasing, the value of multiple scattering parameter λ_{3NOS} will increase accordingly, and the value of SERD will decrease.

By analyzing the scattering mechanisms it can be considered SERD is suited for the extraction of roughness parameters in Lop Nur. In this article surface roughness is mainly expressed by parameter S_l and we tried to use SERD to retrieve it.

3. Results and discussion

After basic radiometric and geometric correction processing, one scene of ALOS-PALSAR fully polarimetric data of Lop Nur is adopted for the following analysis. Based on the theory described in Section 2.2.2, the SERD parameter can be calculated from eigenvalue-

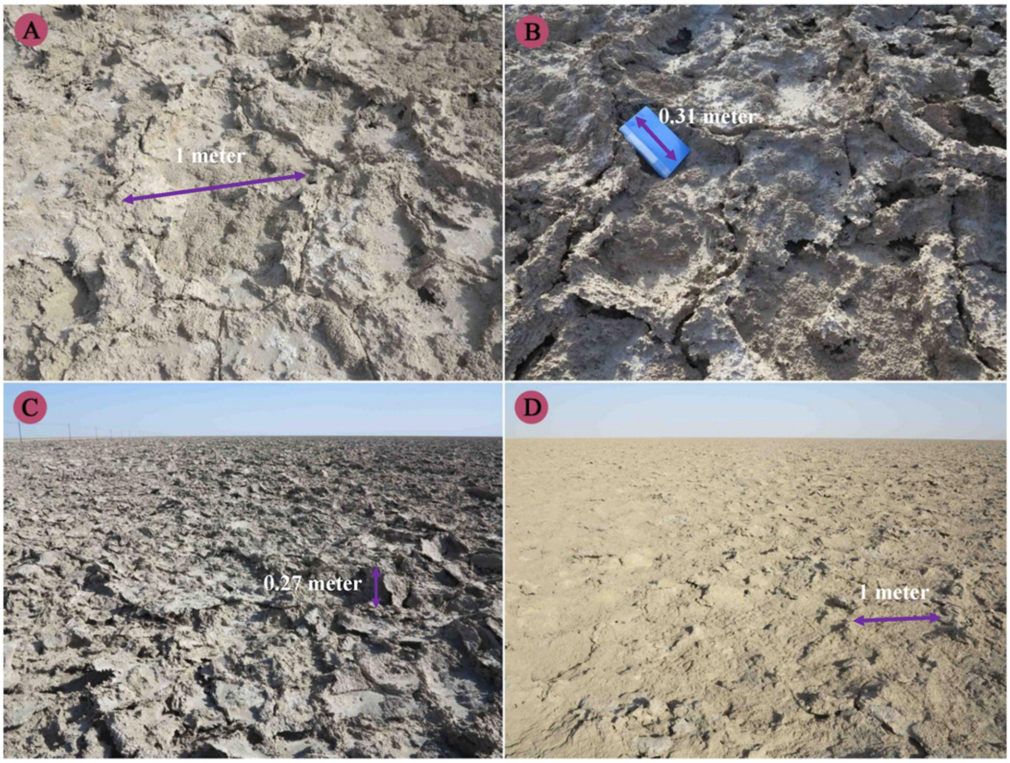

Fig. 9. Different stages of the growth and evolution of salt crusts. Four main stages are described. All the photos were taken from Lop Nur Lake Basin. (A) The early stage of polygonal cracks formation. Halite crusts break into polygons soon after desiccation. After polygonal cracks are formed, groundwater evaporation takes place preferentially at crack edges leading to the formation of efflorescent halite. (B) Later on, this process causes the polygonal halite crusts to become honeycomb-shaped halite crusts. (C) Over time, this process causes the polygonal halite crusts to be buckled into high relief surfaces and they are called as very rough honeycomb salt crusts. (D) If the groundwater table becomes too deep to form new halite, the buckled crusts will become flatter due to wind erosion and rain dissolution. This process causes the polygonal halite crust to form mound-shaped pattern.

based polarimetric decomposition method. Fig. 5 shows the distribution of the calculated SERD in Lop Nur Lake Basin. It can be seen that this parameter has good distinction of the different ring-like stripes.

In order to retrieve the surface roughness parameter, a total of 19 sampling sites were obtained from the lake region. The positions of the sampling sites are marked with blue dots in Fig. 1. Fig. 6 shows the linear fit of the results between the SERD and the measured surface roughness parameter S_l. It is found that the SERD has a good correlation with the measured S_l parameter, with an R^2 value of 0.72. Overall, the accuracy suggests eigenvalue parameters derived from the polarimetric coherency matrix have great potential in terms of surface parameter inversion.

By the functional relationship established in Fig. 6, the roughness parameter S_l is retrieved from the SERD image and the results are presented in Fig. 7.

In Lop Nur Lake Basin, cracked surface rock shell structures, sedimentary characteristics, mineral salts, and geochemical characteristics have obvious zonal features. On remote sensing images, these features are shown as clear concentric depositional patterns. The “Big Ear” composed by the ring textures, is the most striking feature of Lop Nur on satellite images. Different interpretations have been proposed for the ring-like stripes. Although the arguments differ, it is clear that each ring texture is the mark of one Lop Nur lake border during a certain climate period. The presence of concentric zones of salt deposits provides an excellent case for the study of the salt crust development and evolution. From Fig. 7, significant changes of the surface roughness parameter S_l in the lake area can be obtained, which also distribute in a ring-like shape around the Lop Nur Lake Basin. That means S_l is a good indicator of the salt crust structure in Lop Nur. Through the map of S_l the distributions of different salt crust types can be known. It is maintained that different types of salt crust stand for different paleoclimate conditions. In order to reconstruct the environmental evolution process of the Lop Nur lake, the knowledge on the salt crust growth process should be involved, and it will help to reveal the environmental meanings before.

In this article the salt crust formation and evolution theory developed by Bobst et al. (2001), is accepted as the theoretical basis for the salt crust growth process in Lop Nur. The process from lake retreat to salt crust formation is illustrated in Fig. 8.

In arid areas, as evaporation continues, salt lakes will gradually dry up when water supply reduces at the same time. Due to the capillary action of the underground brine layer, salts from the subsurface layer continue to be risen upward. This process is accompanied by the crystallization and precipitation of a large number of salt crystals. Later, due to the surface tension, surface rock shells will crack and gradually broken into polygonal shapes. Since then, the evaporation and migration effect will become more intensely. After that the salt shells will experience many stages of growth and evolution. The different stages of salt crust in our study area can be shown in Fig. 9.

In the Lop Nur Lake Basin, the main salt crust growth process occurs from A to D, where D is the last process of the rock shell evolution process, mainly located in the edge region of the lake basin. The sample sites of this article are located in the interior of the basin. And most of the salt crusts are still at the growth stage, because the subsurface brine layer is fairly shallow (Liu et al., 2015). Thus Stages A to C is mainly considered in this study. Salts at different growing period have different roughness conditions, and in Fig. 9 with the continuous growth and development of salt crusts, the surface roughness of Stage A to Stage C is gradually increasing. With the increase of surface roughness, the value of S_l will also increase. This is the relationship of salt crust growth and the surface roughness. According to the value of S_l the salt crusts can be divided into three main types as early cracking salt crusts ($0 \le S_l \le 0.07$), crack-like salt crusts ($0.07 < S_l < 0.13$), and very rough honeycomb salt crusts ($0.13 \le S_l$). In Fig. 7 it is clear that the three types of salt crust appear repeatedly along the direction of lake body shrinking. Combined with the process from lake retreat to salt crust formation, if the water is continuously shrinking, the evolution of the salt shell should have a continuous trend. The recurrence of different salt crust types means that during the long-term evolution the Lop Nur lake experienced many cycles of filling and drying (in the middle of a large lake retreat cycle, due to a certain temporary abrupt climate change, several cycles occur). This result is consistent with the conclusions of our previous research (Liu et al., 2015). The "Big Ear" is the record of the drying sequence of the Lop Nur lake in the lateral direction. Different types of surface salt crust reflected the growth, decline, and withdrawal of the lake water and recorded the shoreline succession process (Ma et al., 2011). By means of remote sensing technology, the distribution of salt crusts and corresponding climate significance can be obtained quantitatively. These works are very helpful for better understanding the environmental changes in arid and semi-arid regions.

4. Conclusions

Lop Nur is a well-known salt lake, whose drying up process is the record of climate evolution history in arid zones. It is of great significance to the research of global climate change. The continuous development of remote sensing technology allows us to study geological phenomena on a large spatial scale using different data sources. Surface roughness is a valid characterization of surface micro-topography and fully polarimetric radar is a promising way for the inversion of surface roughness. Different surface roughnesses represent different forms of surface salt crust, and the morphology of the surface salt crust also represents its evolution stage. In the near future, we will combine our results with the recorded climate data, to give a more systematic and detailed analysis of the connection between salt crust type distributions and regional environmental changes in arid areas. This will provide supplementary reference information for the study of environmental evolution progresses of salt lakes and climate changes in arid zones. Checking for local environmental changes and looking for the research that could explain how much they stem from local and/or global causes are also the interesting topics for future research.

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