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Abstract. The quantitative study of the arid Lop Nur lake basin is significant to investigate the environmental changes in the arid area of northwestern China and extremely arid areas of Eurasia in general. Synthetic aperture radar (SAR) imagery, with its penetration capability and advantages for studying geological phenomena on a large spatial scale, is very suitable for analyzing the subsurface of the Lop Nur area. Based on the full polarimetric ALOS PALSAR data and field investigation, it was found that the two-layer scattering mechanism of the dry sediments is very special and complex. The scattering mechanism in the bright strips is more complex than that in the gray strips according to the co-polarization correlation analysis. The experimental results show that the Cloude–Pottier decomposition method is more appropriate for this area. Moreover, the polarimetric characteristics and Cloude-Pottier decomposition results are very important for the study of the past climatic change in Lop Nur area. In conclusion, full polarimetric SAR data and target decomposition theory provide a new technique for obtaining information and quantitatively studying the subsurface characteristics of arid areas. [DOI: 10.1117/1.JRS.8.083681]

Keywords: Lop Nur; full polarimetric synthetic aperture radar; scattering mechanism; incoherent target decomposition; information extraction.

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1 Introduction

Lop Nur, a lake located at a strategic point along the Silk Road, was once a corridor for trade, travel, and communication between Chinese and Western cultures in ancient times. Lop Nur is located in Xinjiang Province and was once a famous lake in the arid area of western China with a longstanding reputation for a high level of civilization throughout the history of ancient China.[1–3] Due to the evolution of the natural environment and human activities, Lop Nur has gradually and completely dried up, leaving only a vast dry lake bed, an extremely undulant salt crust, eolian sediments, and few evident signs of life; this dry lake basin is locally called the "Dead Sea" or "Drought Pole."[4–7] Moreover, Lop Nur is the drought center of China and the Asian Continent and is a salt and water-accumulating region in the Tarim Basin; thus, its environmental evolution is significant with respect to global climatic change.[8–10]

The Lop Nur area is vast and subjected to harsh natural conditions; thus, field work is difficult to perform, and remote sensing technology is especially useful.[11] Remote sensing imagery has advantages for studying geological phenomena on a large spatial scale and may be used to supplement traditional field surveys and reconnaissance work.[12,13] In general, optical remote sensing is used to analyze and study the spectral features of surface ground objects. Synthetic aperture radar (SAR) can also detect subsurface objects and their concealed characteristics, due to its ability to penetrate the dry, shallow subsurface.[14–17] Thus, SAR provides a theoretical and technical basis for gathering information and quantitatively studying the subsurface characteristics of arid areas.[18,19] Although the dry lake basin of Lop Nur is not covered by surface vegetation, its distinctive surface morphology and subsurface structures enable SAR to incorporate the complicated scattering mechanisms in this area.[20,21] Polarimetric analysis and polarimetric target decomposition are mathematical methods used for the analysis of full polarimetric SAR data according to different scattering mechanisms. Particularly, polarimetric decomposition is able to separate different components of the scattering mechanisms based on certain conditions, thus making it suitable for studying the scattering mechanisms of the dry subsurface sediments in Lop Nur.[22,23]

For the extremely dry, coarse, and irregular surface conditions of the Lop Nur basin, it is necessary to use the incoherent target decomposition method.[21] Common incoherent polarimetric target decomposition methods include Huynen decomposition, Yamaguchi decomposition, Freeman–Durden decomposition, and Cloude–Pottier decomposition.[24–26] Freeman–Durden decomposition is a superior distributed target decomposition method: it decomposes the target into groups of surface scattering (Odd), dihedral scattering (Dbl), and volume scattering (Vol), under the premise of meeting reflection symmetry based on models.[27,28] In terms of the decomposition theories of the eigenvector of the coherence matrix, Cloude and Pottier presented a decomposition theory that incorporates all scattering mechanisms and better reflects the polarization response characteristics of actual ground objects. In addition, the Cloude–Pottier theory proposed parameters, such as entropy (H), scattering angle (α), anti-entropy (A), and eigenvalue (λ), and provided a perspective on the parameter analysis of the scattering mechanisms of ground objects.[29,30]

The lake basin of Lop Nur is extremely arid and consists of a coarse, dry salt crust with a high salinity, and its scattering mechanisms differ from those of simple dry sand surfaces found in other arid areas and those of common dry lake bed deposits. Moreover, its scattering mechanisms include various scattering situations and are complex. In order to study these problems, this article analyzes the scattering mechanism and polarimetric characteristics of Lop Nur area using full polarimetric ALOS PALSAR data. The applicability of the Freeman–Durden and Cloude–Pottier decomposition methods when applied to the Lop Nur lake basin is analyzed. The qualitative and quantitative comparative analyses of the performances of the two methods are then presented, followed by conclusions regarding the polarimetric decomposition method best suited for analysis of the Lop Nur area. Finally, climatic information of the Lop Nur "Ear" feature was analyzed using the Cloude–Pottier decomposition results.

2 Study Area and Data

2.1 *Study Area: Lop Nur*

Lop Nur is located in the hinterland of Eurasia in the eastern part of the Tarim Basin in Ruoqiang County, Xinjiang Bayingolin Mongol Autonomous Prefecture. Its geographic location is approximately 39.5° to 41.5°N latitude and 88° to 92°E longitude, and its lowest altitude is approximately 785 m. The Lop Nur area is the lowest area in the Tarim Basin and was once the terminus of the Tarim River and other river basins. Because Lop Nur is located far from any ocean and northeasterly winds prevail throughout the year, it is difficult for moist marine air masses to reach the area; thus, the climate is extremely arid. The former lake bed displays features of extreme salinification and severe wind erosion, and a large number of rimous salt crusts are found in the lake basin, resulting in an extremely coarse surface and complex scattering mechanisms that developed during soil formation.

To obtain detailed information on the compositions and structures of surface and subsurface features in the study area, the research group performed five scientific field investigations in Lop Nur, beginning in 2006. Figure 1 shows the investigation routes and distribution of the sampling points, and Fig. 2 shows the surface conditions and outdoor soil sample collection. The HH polarization and ScanSAR mode ALOS PALSAR SAR data obtained on January 15, 2011, were used as a base map as shown in Fig. 1. The field investigations and measurements define the existing recognition and research results from Lop Nur and provide powerful data support for the subsequent quantitative analysis of the scattering mechanisms.

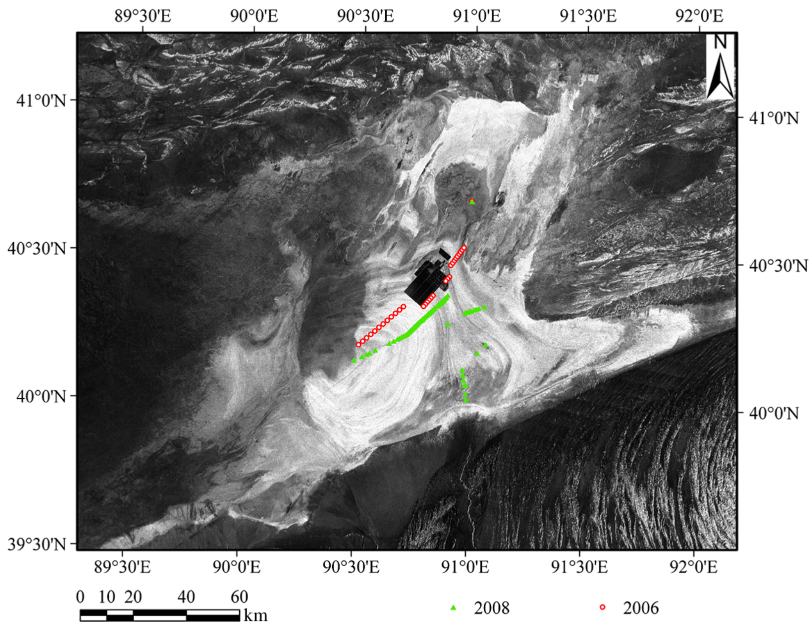

Fig. 1 Overview of the experimental area, routes of field investigations, and sample collection points.

Fig. 2 Photos of surface conditions and field sampling.

2.2 *Data*

Because radar signals at the L-band have relatively high-penetration ability, this study uses ALOS PALSAR remote sensing data to analyze the scattering characteristics of the Lop Nur lake basin and to perform a comparative study based on the target decomposition method. The L-band ALOS PALSAR imagery for Lop Nur area is full polarimetric mode obtained on May 6, 2009, and the off nadir angle is 23.1 deg. Images were reprojected onto the UTM/WGS84 coordinate system after basic radiation, geometric correction, and resampling with PolSARpro v4.0 and ENVI 5.0 software.

3 Methods and Results

This article analyzes the scattering mechanism and polarimetric characteristics of the Lop Nur area. Freeman–Durden and Cloude–Pottier decomposition methods are used and compared, and extended analysis was carried out based on the decomposition results. Figure 3 shows a flow-chart of the study process.

3.1 *Scattering Mechanism and Polarimetric Analysis*

According to the field surveying results of ground penetration radar, it is noted that there are two obviously different layers underneath the surface in Lop Nur, which are dry soil layer with salt

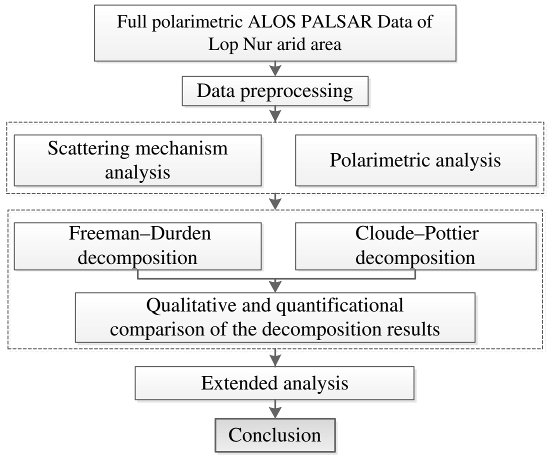

Fig. 3 Flow chart of the comparative study.

crystals on top and moist soil–salt mixture at the bottom. Figure 4 is a geometrical schematic diagram of the two-layer scattering processes consisting of a rough inhomogeneous layer overlying a relatively smoother wet layer, and the scattering physical mechanisms of the upper layer are also depicted. Obviously, the total backscattering intensity is composed of the surface (the two interfaces: top and bottom) and multiple scattering, including necessary transmission and absorption attenuation effects. Therefore, the clearer "Ear" feature on the SAR image is the comprehensive result of both surface and multiple scattering.

According to the backscattering coefficient image of full polarimetric ALOS PALSAR data, as shown in Fig. 5, it can be found that there are several strips with different brightness. Based on the different texture features, the shorelines of Lop Nur Lake can be divided into two types. They are called the bright strip (red-dashed lines) and the gray strip (blue-dashed lines) in this study. The red- and blue-dashed lines in the Fig. 5 are the locations of partial strips.

In order to analyze the characteristics of the bright and the gray strips on the SAR image, the co-polarization correlation was generated and used for a scattering mechanism study of these image texture features. The co-polarization correlation of a different polarization on an orthogonal basis is one of the parameters that represent the properties of a target.[23] Figure 6 shows the co-polarization correlation of the two different strips using full polarization ALOS PALSAR data. The co-polarization correlation coefficients in both the bright and gray strips are larger than 0.5, indicating that the scattering mechanism is very complex all over Lop Nur lake. Based on the scatter distribution feature, it can be found that the Odd mechanism is complex and random. The scattering mechanism in the bright strip is more complex than that in the gray strip owing to the smaller co-polarization correlation coefficient, which provides the small discrepancy between HH and VV polarization modes.

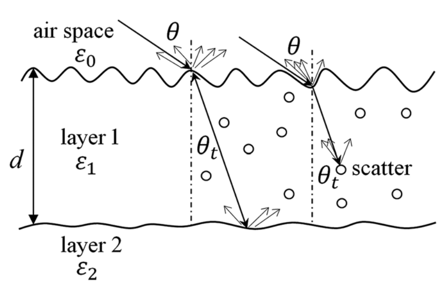

Fig. 4 Geometrical schematic diagram of the two-layer scattering processes consisting of a rough inhomogeneous layer overlying a relatively smoother wet layer, and the scattering physical mechanisms of the upper layer are depicted. The complex dielectric constants (ε) and roughness of the ground surface were measured during the field investigations.

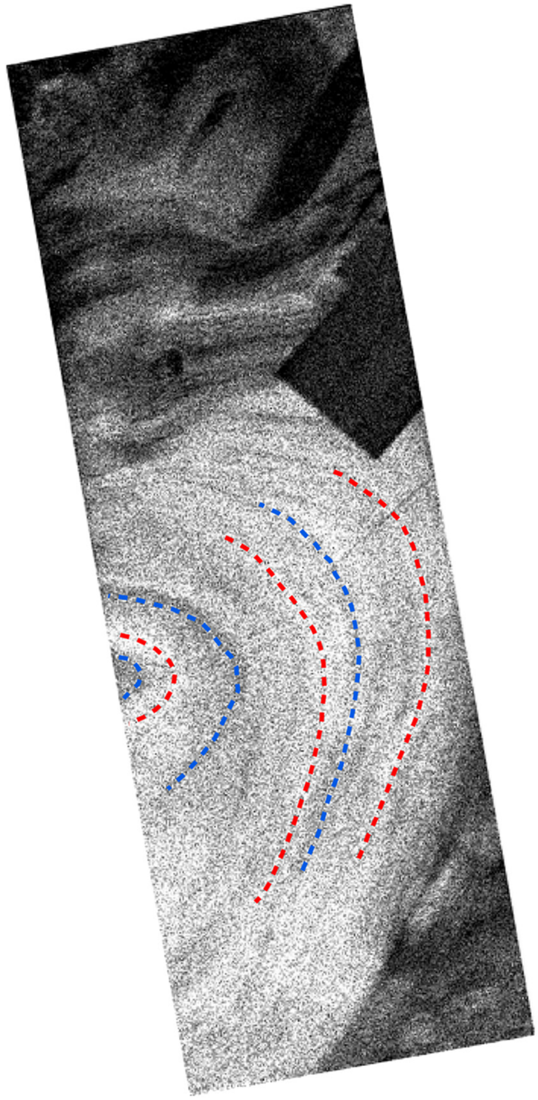

Fig. 5 Backscattering coefficient image of full polarimetic ALOS PALSAR data. The red-dashed line represents the bright strip location, and the blue-dashed line represents the gray strip location in this article.

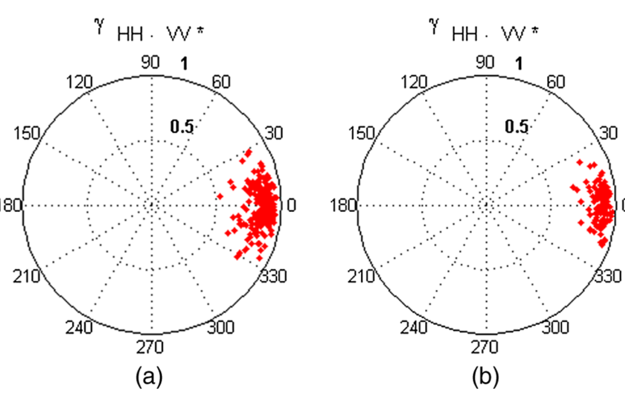

Fig. 6 Geometrical schematic diagram of the two-layer scattering processes: (a) bright strips and (b) dark strips.

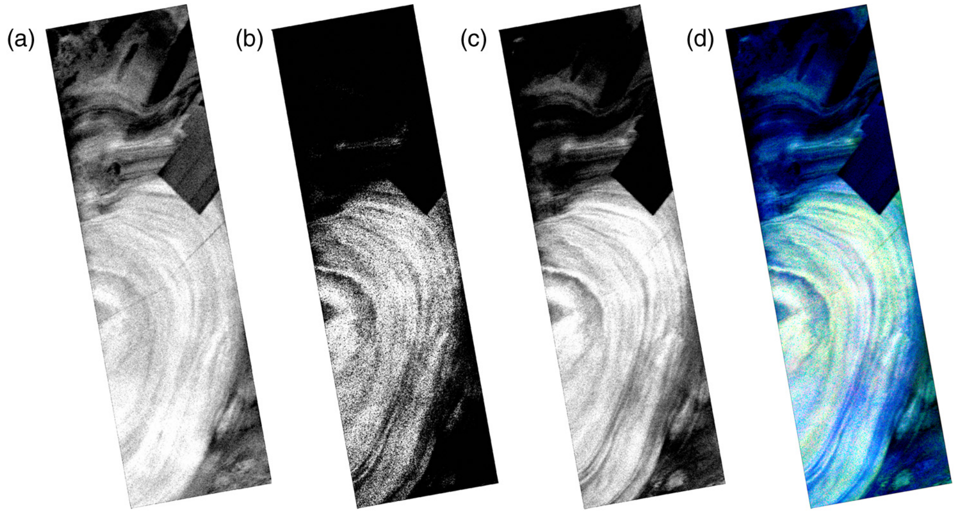

Fig. 7 Three components of the Freeman–Durden decomposition and their respective composite graphs: (a) Odd, (b) Dbl, (c) Vol, and (d) RGB composite graph of the three components (R: Vol, G: Odd, B: Dbl).

3.2 *Polarimetric Target Decomposition*

3.2.1 *Freeman–Durden decomposition*

Freeman–Durden decomposition is a decomposition method based on a physical scattering model and decomposes the target's covariance matrix into three components by meeting reflection symmetry. The advantage of Freeman–Durden decomposition is that it is based on the physical mechanisms of radar backscattering, but it is not a type of mathematical conversion; thus, it is very practical for this application. This article studies the information found in the subsurface materials of the Lop Nur lake basin using Freeman–Durden decomposition combined with the features of Odd, Dbl, and Vol that are present in the surface dry medium of Lop Nur. Figure 7 shows the results when applying Freeman–Durden decomposition to the Lop Nur dry lake basin. The covariance matrix was constructed with a 7×7 Refine Lee filtering treatment before decomposition. The Freeman–Durden decomposition model was built based on ideal scattering; thus, the decomposition results may be explained by the corresponding scattering mechanisms. As shown in Fig. 7, the Odd images are very bright, and the Odd of the interior and surrounding areas of the lake basin is strong. In addition, the Vol images show a clear contrast in brightness, and the interior area of the lake basin deposit is very bright, whereas the other areas are dark. The Dbl image does not show such a clear contrast between the interior and surrounding areas and shows only indistinct ear-shaped textural features, which are difficult to identify. The RGB composite graph of the decomposition results also indicates that the Vol characteristics can characterize the "Ear" textural features very clearly.

3.2.2 *Cloude–Pottier decomposition*

Cloude–Pottier decomposition is a target decomposition method based on eigenvalues and eigenvectors and is capable of incorporating all scattering mechanisms. This method performs eigen-decomposition on the target's coherence matrix, expresses the scattering mechanism with eigenvectors and the contribution of the scattering mechanism represented by the corresponding eigenvector with an eigenvalue, and provides a rotational invariant description for target scattering.[30] The Cloude–Pottier decomposition results obtained from the Lop Nur lake basin are shown in Fig. 8. The coherence matrix was constructed using a 7×7 Refine Lee filtering treatment before decomposition. The three components of the Cloude–Pottier decompositions, T11, T22, and T33 correspond to the sizes of the three scattering mechanisms rather than the special scattering mechanism. They must be analyzed in combination with other scattering characteristics. Figure 9 shows the H-α space of different ground objects found in the lake basin. In the

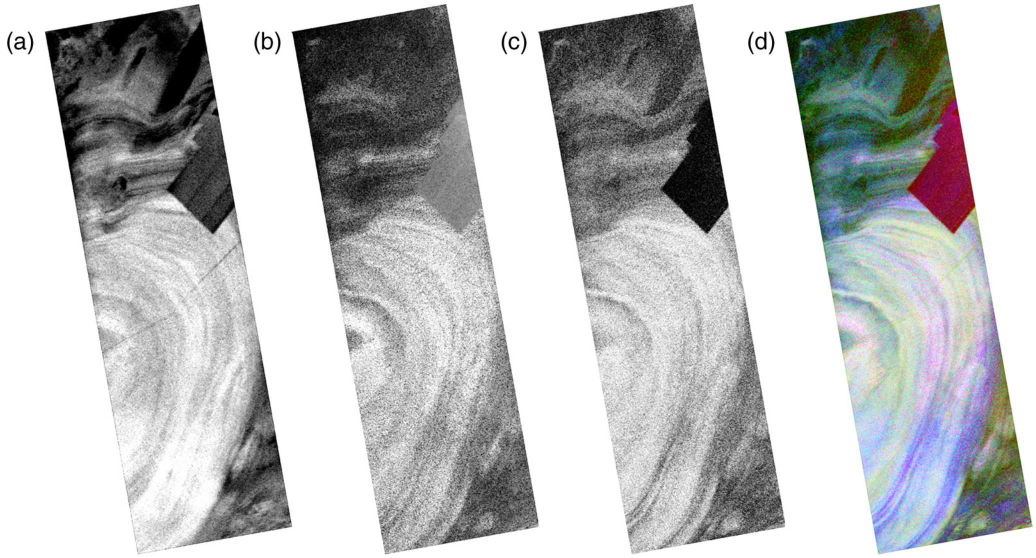

Fig. 8 The three components of the Cloude–Pottier decomposition and their respective composite graphs: (a) first component, T11 (single scattering); (b) second component, T22 (Dbl); (c) third component, T33 (multiple scattering); and (d) RGB composite graph of the three components: R: T11; G: T22; B: T33.

H-α space, we study the lake basin as a whole: the bright strip, dark strip, and salt pond located in the "Ear" area and the characteristics of the bright and dark strips. We use the characteristics of the entire lake basin and salt pond as references.

As shown in Fig. 9, the H value of the whole lake basin is 0.5, and the H values of the bright and dark strips are 0.44 and 0.35, respectively. This indicates that the scattering mechanism of the entire lake basin in the "Ear" area is complex and is between isotropic scattering and completely random scattering, and the scattering mechanism of the dark strip is less complex than that of the bright strip. The anti-entropy A value mainly characterizes the relationship between the two scattering mechanisms and does not include the major one. The A values of the bright and dark strips are 0.28 and 0.38, respectively, indicating that the contribution of the main scattering mechanism of the dark strip is decreasing, whereas the contribution of other scattering mechanisms is increasing. Alpha (α) may be used to identify the scattering mechanism. It is known from the scattering mechanism of the Lop Nur lake basin that when is between 10 deg and 20 deg, primarily Odd is observed. Meanwhile, the scattered points gathered from the subregions, as shown in Fig. 9, also indicate that the main scattering mechanism of both the bright and dark strips is Odd. The comprehensive analysis of H, A, and indicates that the only relationship between the bright and dark strips is a brightness difference, while the general backscattering strengths of both the strips are high. In addition, the other scattering mechanisms of the bright strip also contribute, except for the main Odd mechanism, and should not be ignored. According to the preliminary analysis of the Odd mechanism of Lop Nur and the Freeman–Durden decomposition results, we conclude that the first component, T11, represents single-Odd; the second component, T22, represents Dbl; and the third component, T33, represents multiple scattering.

3.2.3 *Comparative analysis on the two decomposition methods*

This article primarily studies the Freeman–Durden and Cloude–Pottier decompositions, but the two decomposition methods differ in terms of their decomposition mechanisms. The Freeman–Durden decomposition results meet requirements for the mutual independence of statistical significance, while the matrix ranks of the Cloude–Pottier decomposition components are 1 and orthogonal. This condition might not be met by the Freeman–Durden decomposition, resulting in two issues. First, both the surface and Dbl are nondepolarized components, with a rank of 1,

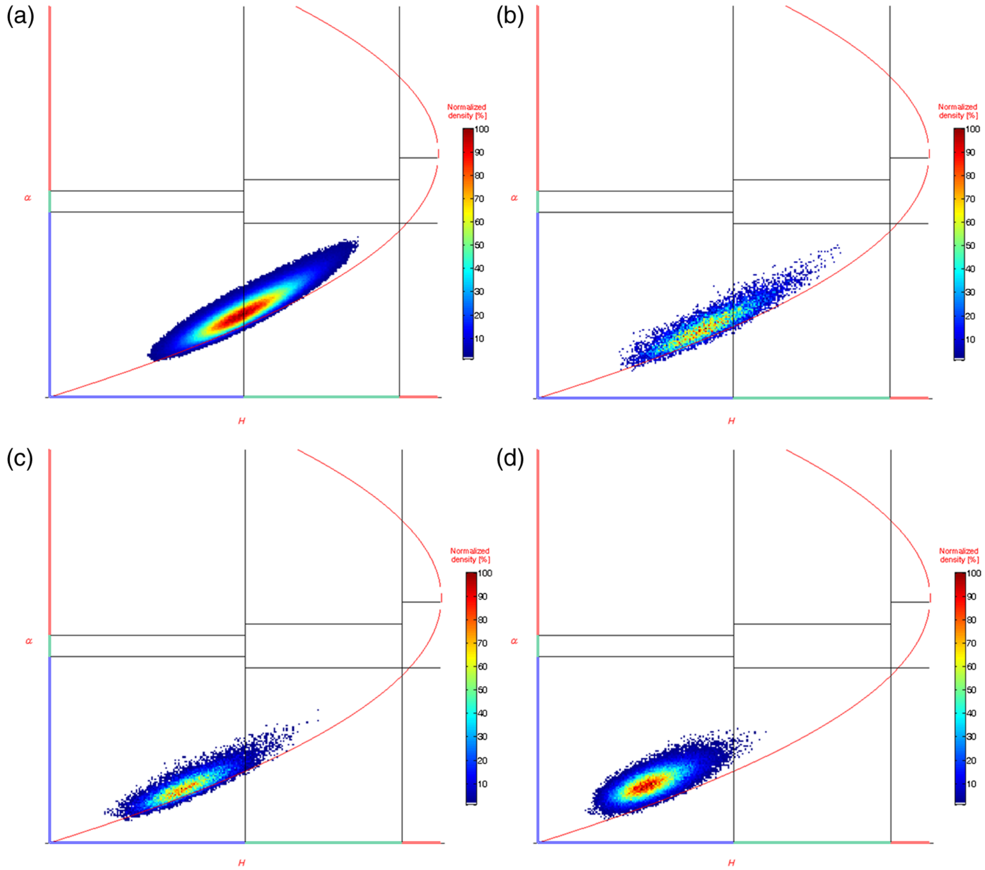

Fig. 9 *H*-α space of the Lop Nur lake basin surface: (a) entire lake basin, (b) bright strip, (c) dark strip, and (d) salt pond.

and are mutually independent, whereas the coherence matrix rank of the Vol components is 3, and the Vol component is partially independent of the surface and the Dbl components. Second, according to the Freeman–Durden decomposition algorithm, cross-polarization is caused by the effects of depolarization, but the depolarization effects of multiple scattering caused by the strong undulations in the ground surface are omitted. Consequently, the third scattering component is simply regarded as Vol. In contrast, Cloude–Pottier decomposition is strictly based on the decomposition principle of eigenvalues or eigenvectors and can separate the independent components in all polarization channels. Moreover, Cloude–Pottier decomposition conforms to rotation invariance, i.e., its decomposition result is independent of the polarization base. The experimental results shown in Fig. 8 indicate that the multiple scattering components found in the Cloude–Pottier decomposition results clearly show the characteristics of the "Ear" feature.

Due to the strong undulation of the Lop Nur surface, the backscattering energy can easily enter a saturated state, i.e., the Odd component has an insufficient dynamic range to specifically characterize the SAR response difference in the different texture areas of the "Ear," while the clear expression of the "Ear" by multiple scattering implies that the multiple scattering may be the main factor resulting in the characteristics of the "Ear." In fact, the contribution of multiple scattering may represent the scattering characteristics of the subsurface target polarization to a certain extent. In terms of statistical analysis, both the Freeman–Durden and Cloude–Pottier decompositions can effectively distinguish between the relative size relationships among the backscattering components of the various ground object categories found in the Lop Nur lake basin, but the scaling relations among the decomposed Odd, Dbl, Vol, and multiple scattering are greatly different, as shown in Table 1.

In the Freeman–Durden decomposition results, other scattering mechanisms also make large contributions relative to the main Odd. However, in the Cloude–Pottier decomposition results,

Table 1 Statistics of different polarimetric decomposition components of the Lop Nur lake basin (unit: dB).

	Freeman-Durden			Cloude-Pottier		
Decomposition method/value of the image	Odd	Dbl	Vol	T11	T22	T33
Minimum value of entire lake basin	−13.64	−13.64	−13.64	−16.38	−49.95	−53.35
Maximum value of entire lake basin	5.69	−5.66	−1.22	5.67	−5.69	−6.41
Mean value of entire lake basin	−1.04	−12.27	−9.01	−1.55	−16.22	−19.83
Bright strip	1.99	−9.63	−4.13	1.00	−9.08	−16.43
Dark strip	0.11	−12.37	−7.81	−0.67	−18.32	−19.92
Salt pond	−3.75	−13.64	−13.41	−3.61	−16.01	−31.27

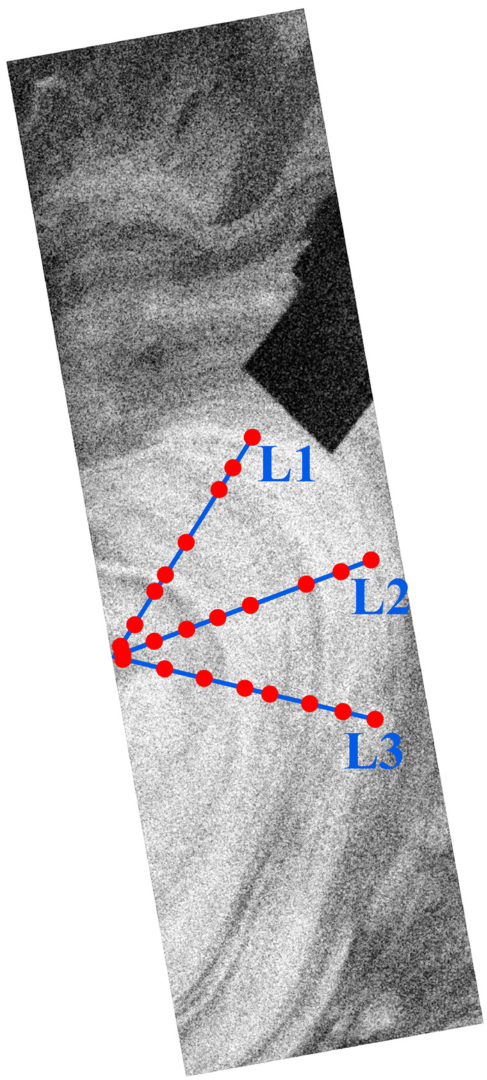

Fig. 10 Distribution of the section lines (blue) and sample points (red). Multiple scattering component image of the Cloude–Pottier decomposition was used as a base map.

Odd plays the greatest role of the sets of scattering mechanisms, and the contributions of the other scattering components are extremely small. This relationship results because the Lop Nur lake bed surface materials are extremely coarse and Odd effects play an important role in back-scattering, as observed in our field investigation. The Freeman–Durden decomposition exhibits a certain degree of deviation from the scaling relations of the scattering component contributions in the Lop Nur lake basin, whereas the Cloude–Pottier decomposition results may more accurately reflect the true conditions of the ground surface. In addition, the Cloude–Pottier decomposition can show the polarization parameters characterizing the Odd mechanism, which is beneficial in the study of complex Odd and can be used for the parametric analysis of the surface polarization characteristics of the Lop Nur lake basin.

3.3 *Extended Analysis*

Based on the results of scattering mechanism analysis, polarimetric analysis and Cloude–Pottier decomposition using ALOS PALSAR data, it can be found that the bright and gray strips are very meaningful for the climatic and environmental studies in Lop Nur area. In order to extract the information contained in these strips, according to the Cloude–Pottier decomposition result, three section lines (L1, L2, and L3) from the center to the edge of the "Ear" feature are used to study the change characteristic of the Lop Nur lake basin. There are eight sample points on each section line, and the points are located on the gray and bright strips from left to right separately, as shown in Fig. 10. The contribution value (dB) of the sample points was extracted from the three components of the Cloude–Pottier decomposition results, as shown in Fig. 11. It is obvious from Fig. 11 that every component can represent the bright and gray strips characteristics of Lop Nur "Ear" feature, the change between the contribution values and strips is similar. Owing to the extremely coarse surface, single scattering is the main scattering mechanism, as shown in Fig. 11(d). The contribution of multiple scattering is close to that of Dbl because of the extremely dry mixture of lacustrine deposits with salts in the upper layer. The roughness and salinity of the sediments indicated the climatic changes between wet and dry environmental conditions. Therefore, the polarimetric characteristics and Cloude–Pottier decomposition results are very important for the study of environmental temperature and rainfall capacity in the past

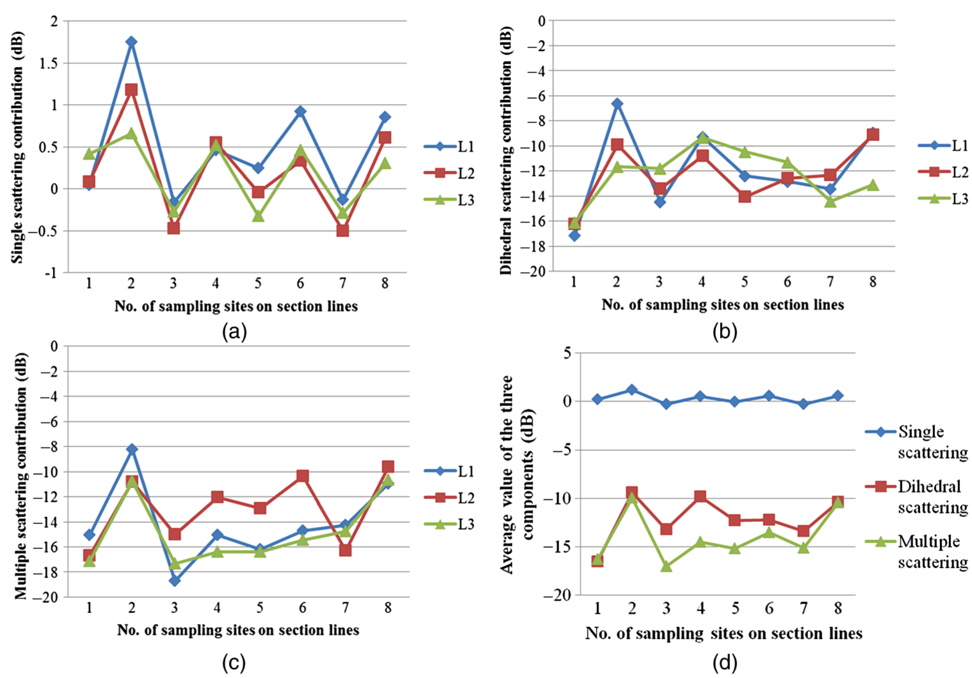

Fig. 11 Statistical results of the sample points from the three components of the Cloude–Pottier decomposition results: (a) single scattering; (b) Dbl; (c) multiple scattering; and (d) average value of the above three components.

climatic change. However, geological age of the different lacustrine deposits and shorelines is still unknown. In the future, geological dating research will be carried out to establish a time scale and to build the time series of ancient lake basin evolution.

4 Conclusions

With the full polarimetric ALOS PALSAR data and field investigation, the two-layer scattering structure, consisting of a rough inhomogeneous layer overlying a relatively smoother wet layer, and the complex scattering mechanism were analyzed. The scattering mechanism in the bright strips is more complex than that in the gray strips, according to the co-polarization correlation analysis. The experimental results show that the Cloude–Pottier decomposition method can more accurately reflect the true conditions of the ground surface and is more appropriate for the study of the Lop Nur area. Moreover, the polarimetric characteristics and Cloude–Pottier decomposition results are very meaningful for the study of the past climatic change in Lop Nur area. The evolutionary process of Lop Nur Lake went through several phases, according to the shoreline loops from the ALOS PALSAR images and decomposition results. Based on the field investigation and experiments results, it can be inferred that the bright strips are lacustrine deposits with high salinity, and may represent a rapid process of lake basin area shrinkage and salt crystallization at dry environmental periods. The gray strips are lacustrine deposits with relatively lower salinity, representing a relatively weak process of lake basin area shrinkage with recharge from rivers and melting snow in Tarim Basin region at relatively wet environmental conditions. Therefore, the bright and gray strips of Lop Nur Lake basin can indicate the climatic changes indirectly between dry and wet environmental conditions.

The significant change of Lop Nur from a large water body to a dry basin is a dramatic indication of the environmental changes that have occurred in the arid areas of northwestern China and the extremely arid areas of Eurasia. Lop Nur potentially contains an abundance of valuable research data for quaternary geology, paleoclimatology, paleontology, and related fields, and its changes are a reflection of global environmental change. However, conditions in the Lop Nur area are harsh, and implementing traditional geological field research in the area is difficult. Therefore, SAR remote sensing technology serves as an important exploration tool for the study and analysis of the Lop Nur area. Polarimetric target decomposition theory is continually being developed to better interpret polarimetric SAR data. The experimental results of this study indicate that the polarimetric SAR data and target decomposition theory provide a new technique for data collection and specifically for the quantitative study of the subsurface characteristics of arid areas.

Acknowledgments

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Biographies of the authors are not available.