Region-based N-cuts Polarimetric SAR Image Segmentation Algorithm

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***Abstract*—Due to the imaging principle, there is a large number of noise points in polarimetric Synthetic Aperture Radar(SAR) images. This coherent noise leads to inaccurate segmentation results. To solve this problem, this paper proposes a region-based N-cuts polarimetric SAR image segmentation algorithm by combining the K-means clustering algorithm and N-cuts algorithm. Firstly, K-means clustering algorithm is used to pre-segment polarimetric SAR images to form segmented regions. Secondly, the similarity measurement matrix is constructed on the basis of pre-segmentation. Finally, the N-cuts algorithm is introduced to cluster regional nodes and to realize image segmentation. This method makes full use of the over-segmentation characteristic of K-means clustering algorithm, and it significantly reduces the computation. Combined with the global optimization of atlas segmentation algorithm, the performance of segmentation results is improved. In this paper, full polarization E-SAR(the Experimental airborne SAR System of DLR) images are used for experiments, and processing results of various polarization characteristics are compared. Experimental results show that region-based N-cuts algorithm is efficient and practical for image segmentation. The results also show that this method has higher level of precision and shorter computation time than both K-means clustering algorithm and N-cuts algorithm.**

Keywords—Polarimetric SAR; Polarization Characteristic; K-means; region-based N-cuts; Image Segmentation

I. INTRODUCTION

Synthetic aperture radar imaging is a kind of microwave remote sensing technology, which has the characteristics of working all day in all weather. It is often used in aviation and space remote sensing. Polarimetric SAR obtains the polarization scattering matrix of the imaging area by adjusting the polarization mode of the working electromagnetic wave. The matrix contains rich ground object information, which improves the ability of SAR to obtain scene target information and is of great significance for improving the accuracy of image interpretation [1].

In recent years, with the maturity of the basic theoretical system of radar polarization measurement, the segmentation and classification of polarimetric SAR images have broad application potentials in unsupervised classification, target detection and recognition.

Due to the imaging principle of SAR images, there are a large number of noise spots in polarized SAR images. This kind of coherent noise brings difficulties to SAR image segmentation. Therefore, the theory of polarization SAR image segmentation based on graph theory is still developing, and many new segmentation methods and optimization algorithms can be tried in the future.

This paper is structured as follows: Section II explains the related works about this paper; Section III introduces the characterization of polarimetric SAR images; Section IV presents the K-means Clustering algorithm and N-cuts algorithm; Section V introduces the Region-based N-cuts algorithm; Section VI presents experimental results and analysis of region-based N-cuts algorithm; and Section VII presents our overall conclusions.

II. RELATED WORK

In recent years of development, many researches combined classic segmentation algorithm and image segmentation algorithm based on specific theory. Zhu [2] used watershed over-segmentation and scattering parameters to carry out iterative classification, which effectively avoided salt and pepper noise, but failed to retain texture feature information. Xi [3] combined mean-shift algorithm and normalized cut algorithm to process ordinary images. Even though the processing effect was good, the images he used were simple-- the number of pixels in the image was small.

In this paper, we use a region-based method to process a set of polarimetric SAR images. K-means clustering is a widely used classical clustering algorithm, which has the characteristics of simple operation and local optimization. However, it is sensitive to noise and outliers. In region-based N-cuts algorithm, K-means clustering is used for over-segmentation, and the subsequent calculation units are converted from pixels to regions. Taking the obtained region into the N-cuts algorithm can effectively reduce the calculation and achieve the globally optimal image segmentation result. According to the polarization characteristics of SAR image data, we extract various polarization characteristics as data sets for image segmentation, which contain more information than ordinary images. Also, the region-based N-cuts algorithm has better processing performance and shorter calculation time than both K-means algorithm and N-cuts algorithm.

III. CHARACTERIZATION OF POLARIMETRIC SAR

Generally, the complex scattering matrix $\vec{S}$ of the target can be directly obtained from the fully polarized SAR measurement data [4]:

$$\vec{S} = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix} \tag{1}$$

where: S_{HV} represents the target backscatter when horizontal *(H)* emission and vertical *(V)* polarization reception, and S_{HH}, S_{VV}, S_{VH} is similar. Considering the situation of static measurement, and the target satisfies the anisotropy $S_{HV} = S_{VH}$

Polarization scattering matrix $\vec{S}$ can represent the total scattering echo power *Span* of an object:

$$Span = |S_{HH}|^2 + |S_{HV}|^2 + |S_{VH}|^2 + |S_{VV}|^2 \quad (2)$$

In order to extract physical information from the complex scattering matrix $\vec{S}$, it is usually constructed three-dimensional Pauli feature vector $\vec{k}$

$$\vec{k} = \frac{1}{\sqrt{2}}[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad 2S_{HV}]^T \quad (3)$$

In practical situations, real objects are often considered as distributed targets. The concept of "distributed target" is derived from the fact that a non-static or unstable radar target changes over time, that is, the target exists in a changing environment, and the target scattering also changes with time and space. Therefore, the use of the scattering matrix $\vec{S}$ to characterize the object is limited, so that the polarization coherence matrix $\vec{T}$ and the covariance matrix $\vec{C}$ are introduced [5]. These two are used as new data representation methods to reflect the scattering mechanism of the distributed target. The polarization coherence matrix and the covariance matrix are obtained by time-averaging or spatial averaging processing on the $\vec{S}$ matrix.

A multi-view polarization coherent matrix can be obtained by performing non-coherent averaging of multiple single-view polarization coherent matrices. For multi-view fully polarized SAR data, the polarization coherence matrix $\vec{T}$ is defined as

$$\langle \vec{T} \rangle = \frac{1}{N}\sum_{i=1}^{N} k_i k_i^{*T} \quad (4)$$

where N is the visual number; k_i is the scattering vector of $N=i$, k_i^{*T} is the conjugate transposition of k_i.

In the practical application of polarization SAR image processing, most of them are studied in the case of single station backscattering system, using the scattering matrix $\vec{S}$, the polarization coherence matrix $\vec{T_3}$ and the covariance matrix $\vec{C_3}$, the combination and operation can extract more polarization characteristics. The comprehensive utilization of ground object polarization information and texture information is of great significance for improving the accuracy of polarimetric SAR image segmentation.

IV. K-MEANS CLUSTERING ALGORITHM AND N-CUTS ALGORITHM

In this section, we introduce two existing image segmentation methods, which are combined in the region-based algorithm.

A. K-means Clustering Algorithm

As a classical clustering algorithm, K-means clustering algorithm is also an effective unsupervised classification method in the field of image processing. The algorithm divides samples into K clusters through an iterative process. It uses the mean of these K clusters to represent samples of each class in the iterative process. The iteration is terminated when the overall error is minimized.

Firstly, let N_i be the total number of samples in the number i cluster Γ_i, and m_i is the mean of samples[6]:

$$m_i = \frac{1}{N_i}\sum_{y \in \Gamma_i} y \quad (5)$$

The sum of the squared errors between each sample y in Γ_i and the mean m_i of the class is added to each category:

$$J_e = \sum_{i=1}^{K}\sum_{j=1}^{N_i} \|y_{ij} - m_i\|^2 \quad (6)$$

where: K is the number of categories ; y_{ij} is the j-th sample in the i-th class.

J_e represents the total squared error produced by K cluster centers $m_1, m_2, \cdots, m_k$, representing K sample subsets $\Gamma_1, \Gamma_2, \cdots, \Gamma_k$, called the sum of squared errors. So that J_e reaches the clustering result of the minimum value is the optimal result under the sum-of-squared-error criterion.

B. Image Segmentation Based on Graph Theory

a) Graph cut

With the development of image segmentation technology, applying graph theory to image segmentation is a hot topic in current research. In the field of graph theory, digital images can be mapped to a weighted undirected graph. The basic processing unit in the image is a pixel, and the basic processing unit in the figure is a vertex, which establishes a one-to-one correspondence between them: pixels in the image are mapped to vertices in the graph, adjacent relation of pixels is mapped to edge, and the similarity of pixel value between them is mapped to the weight on the edge [6].

For the graph $G = (V, E)$ is a weighted undirected graph [7], as shown in Figure 1: the circle represents the vertex, and the line segment connecting the circle represents the edge. Weight of the edge connecting vertices v_i and v_i is represented by w_{ii}, reflecting a certain property between vertices, such as the similarity relation. The degree of a vertex is defined by :

$$d_i = \sum_j w(i, j) \quad (7)$$

The degree of a vertex represents the association of the vertex with other vertices in the graph.

If there are two graphs $G = (V, E)$ and $G_1 = (V_1, E_1)$ that satisfy the relation $V_1 \subseteq V, E_1 \subseteq E$, then graph G_1 is called a subgraph of graph G. When two subgraphs $G_1 = (V_1, E_1)$ and $G_2 = (V_2, E_2)$ satisfy the relation $V_1 \cup V_2 = V$, G_1 and G_2 are called complementary, see Figure 1:

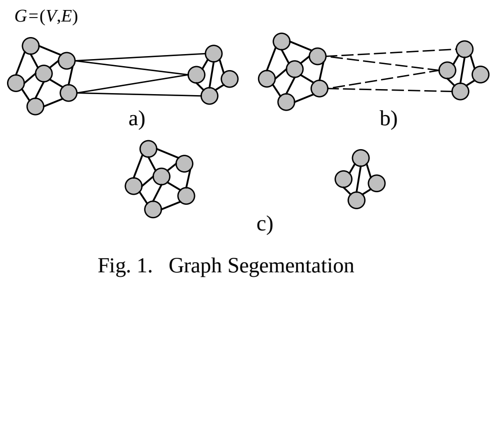


Fig. 1. Graph Segementation

b) N-cuts Criteria

For graph $G=(V,E)$, it is an undirected graph with sideband weight. Remove some edges and divide the graph into two sets of disjoint vertices to satisfy relation $A \cup B = V, A \cap B = \varnothing$. Different cuts can be obtained according to different criteria.

Shi and Malik proposed[8] the normalized cut criterion:

$$Ncut(A,B)=\frac{cut(A,B)}{assoc(A,V)}+\frac{cut(B,A)}{assoc(B,V)} \quad (8)$$

where: *assoc(A,V)* is the sum of the weights of all the vertices in *A* and the vertices of the graph. In this way, the similarity between two classes is defined. The smaller the similarity between classes, the better the segmentation result.

c) Solution of the N-cuts Algorithm

In order to solve the optimal $Ncut(A,B)$ value, the N-cuts algorithm transforms the problem into the field of linear algebra research and becomes a solution to the eigenvector and eigenvalue problems of the matrix. Suppose a graph $G=(V,E)$ is divided into two parts, *A* and *B*, so that we set $N=|V|$ and *x* are N-dimensional indication vectors. When $x_i > 0$, node *i* is in *A*, and when $x_i < 0$, node *i* belongs to *B*.

Let *D* be a diagonal matrix with diagonal elements d_i. A symmetric matrix *W* is called a weight matrix and its element value $W(i,j)=w(i,j)$. The problem of solving the minimum value of *Ncut(A,B)* can be transformed into the form of equation (10):

$$\min_x Ncut(x)=\min_y \frac{y^T(D-W)y}{y^T D y} \quad (9)$$

The above formula must satisfy the two conditions of $y_i \in \{1,-b\}$ and $y^T DI = 0$ [9]. This formula is in the form of Rayleigh quotient. If the value range of *y* is broadened to real number, solving the minimum *Ncut* is equivalent to solving the equation under the generalized eigenvalue system:

$$(D-W)y=\lambda D y \quad (10)$$

The solution of the equation is:

$$y=\arg.\min_{y^T DI=0} \frac{y^T(D-W)y}{y^T D y} \quad (11)$$

N-cuts method obtains the eigenvector corresponding to the second small eigenvalue as the optimal solution for *Ncut(A,B)* by solving the equation under the generalized eigenvalue system. The optimal feature vector *y* is an N-dimensional solution vector. Select a segmentation threshold value *y**, divide vertices with values greater than *y** into set *A*, and divide the rest into set *B*. If the image needs more detailed segmentation, the algorithm can be recursively called to realize multiple segmentation.

d) Construction of Weight Matrix in N-cuts Algorithm

The weight matrix *W* indicates the mapping relationship between pixels in the image and nodes in the constructed network. The smaller the weight, the smaller the degree of similarity between proved nodes. To some extent, it means the smaller probability of being divided into the same class.

We construct the weight matrix W_{ij} as follows:

$$W_{ij}=e^{\frac{-\|F_{(i)}-F_{(j)}\|_2^2}{\sigma_I^2}} * \begin{cases} e^{\frac{-\|X_{(i)}-X_{(j)}\|_2^2}{\sigma_X^2}} & \text{i,j are adjacent} \\ 0 & \text{i,j are not adjacent} \end{cases} \quad (12)$$

where $F_{(i)}$ represents the feature space vector and $X_{(i)}$ represents the position space vector of the pixel point *i*. The weight matrix considers both the feature vector information and the spatial position information. σ_I and σ_X are weight coefficients, according to experience, whose values can be selected according to experience. The range of σ_I is mostly 50~80, and the range of σ_X is usually 80~100.

V. Region-based N-cuts Algorithm

In this paper, a new computational complexity image segmentation method is designed by combining K-means clustering algorithm and N-cuts algorithm. Firstly, we use K-means clustering algorithm to pre-segment the image. The segmented image is divided into several regions. Then, according to the K-means clustering results, the K clustering centers output by the algorithm are taken as representative points of each region to complete the construction of weighted undirected graph. The eigenvalues are used to describe the similarity relation between regional points. Finally, N-cuts algorithm is used to segment these regions.

The implementation of the algorithm and the specific steps are as follows:

(1) preprocessing the image by using a K-means clustering algorithm;

(2) The image clustered by K-means is divided into many regions, and the number of regions is greatly reduced compared with the number of pixel points in the image. Each region is extracted and labeled, and the clustering center of the region is used as a region point to replace the region. The information contained in the regional points includes feature vector information and spatial location information.

(3) According to step (2), the original image becomes an undirected graph composed of region points, which is input as N-cuts. The weight matrix *W* is constructed by using regional points, and then clustering segmentation is carried out by using N-cuts algorithm[11].

The algorithm flow chart is shown in Figure 2

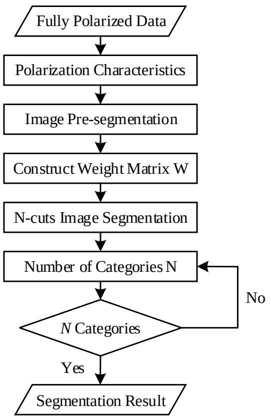


Fig. 2. Flow chart of region-based N-cuts algorithm

Compared with the traditional N-cuts algorithm, the region-based N-cuts image segmentation algorithm has the advantages of less computation and more accurate segmentation effect.

VI. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, we introduce the selection of parameters, experimental process and analysis of experimental results.

A. *Data sets description*

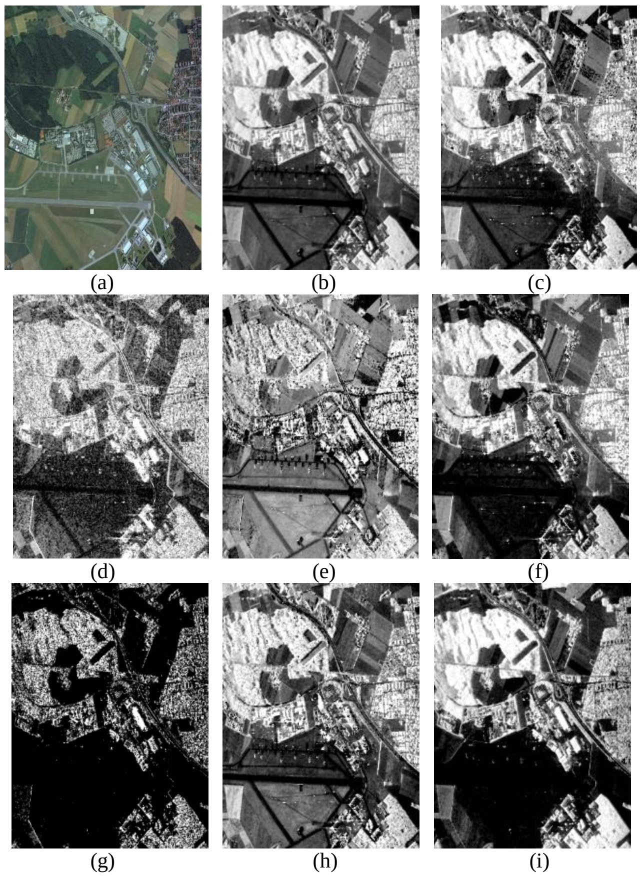
In this experiment, a set of polarization characteristic are selected of a fully polarized SAR image. These polarization characteristic are obtained by several target decomposition methods [8], including Cloud decomposition, Yamaguchi four-component decomposition and Krogager decomposition. We also add the power spectrum image to data sets. These polarization characteristics describe ground objects from the perspective of scattering mechanism and physical structure.

A high-resolution polarimetric SAR image is used in the experiment, and the specific technical indexes are given in Table I:

TABLE I. EXPERIENTAL DATA

Data Source	Resolution/m	Image size	Area/km^2
E-SAR	3×3	1300×1200	39.028

The image used in the experiment is shown in Figure 3(a), which is composed of fully polarized L-band data. The scene in the image is an area of Oberpfaffenhofen, Germany. Under the condition of fine division, there are about 10 kinds of ground objects in the image, including forests, buildings, farmland, bare land (obvious airport runway) and other main ground objects.



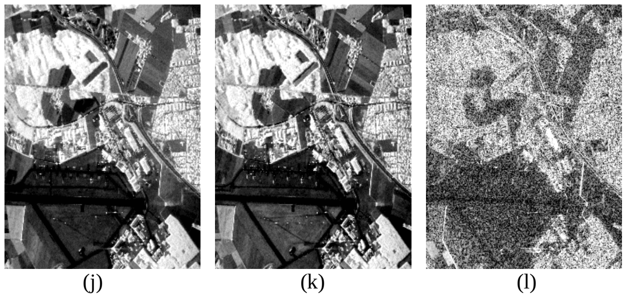


Fig. 3. (a) Original image. (b) Power spectrum image. (c) Bragg scattering for Cloud Decomposition. (d) Dihedral scattering. (e) Volume scattering. (f) Dbl scattering component (g) Hlx scattering component (h) Odd scattering component (i) Vol scattering component (j) K_d dihedral angular scattering component (k) K_h helix scattering component (l) K_s spherical scattering component

- **Power spectrum image.** Figure 3(b) shows the power spectrum image, which use the average power represents the scattering intensity of ground objects directly.
- **Cloud Decomposition** Figure 3(c)(d)(e) shows the results of Cloud decomposition. The results represent three generation factors of the equivalent single scattering target: Bragg scattering C_{11} , dihedral scattering C_{22} , and volume scattering C_{33} , which respectively represent three mutually independent and complementary correlation scattering processes.
- **Yamaguchi Four-component Decomposition.** Figure 3(f)(g)(h)(i) shows the result of Yamaguchi four-component decomposition. Comparing the four images, we find that the urban area has the strongest double-bounce scattering, which is the main scattering mechanism of urban area. Due to the presence of relatively tall vegetation in forest area, the canopy consists of a large number of branches and leaves, mainly characterized by volume scattering. Surface features with less rough surface, such as farmland, bare land and some low vegetation, Bragg scattering is their main scattering mechanism. However, trunks and ground form a dihedral angle, so the radar tilting the scene will cause double-bounce scattering exhibited by such vegetation. The division of vegetation should be dominated by volume scattering, including Bragg scattering and double-bounce scattering. Most of the urban areas should be classified as double-bounce scattering, and should not be classified as volume scattering, which is a mistake with plants. For the helix scattering component, only the forest and urban parts are expressed, and they have certain differences. Applying this feature can effectively distinguish forests, cities and other features.
- **Krogager Decomposition.** Figure 3(j)(k)(l) shows the result of Krogager decomposition. Krogager is decomposed into three coherent components, which correspond to spherical scattering K_s , dihedral angular scattering K_d with a rotation angle θ , and helix scattering K_h . Both the spherical scattering and the dihedral angular scattering in the forest area are strong, while the urban part mainly exhibits dihedral angular scattering. Cultivated land and bare land areas are mainly characterized by spherical scattering. Similar to Yamaguchi decomposition, helix scattering features can exist mainly in forests as well as in urban areas.

B. *Experimental Results of Image Segmentation*

a) Environmental configuration

The hardware environment, where experiments are run is Intel Core i5-5200U CPU @ 2.20GHz 2.19GHz, 8GB RAM and 64-bit operating system. The process of image segmentation runs on Windows 10 operating system and uses Microsoft Foundation Class Library as its development tool. The program has interactive execution function.

b) Experimental Results of Polarization Feature Selection

We use a variety of polarization features to carry out experiments and select the following six better features as image segmentation results, which are segmented by region-based N-cuts algorithm. The parameter settings are shown in Table II:

TABLE II. IMAGE SEGMENTATION PARAMETERS

n	Max	Precision	N	σ_I^2
20	50	0.5	8	50

The results of the experiment are shown in Figure 4:

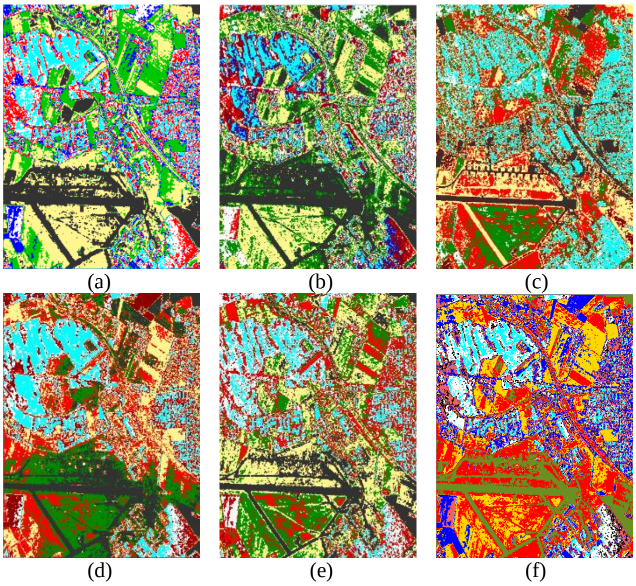


Fig. 4. (a) Krogager_ K_d scattering component (b) Krogager_ K_s scattering component (c) Cloud_ C_{33} scattering component (d) Cloud_ C_{11} scattering component (e) Yamaguchi_Odd scattering component (f) Average power λ

Reasons for selecting the above experimental data:

1) Number of clusters n: The original image has a higher resolution and the number of pixels is 1200×1300 . Based on actual factors, the original polarized SAR image is roughly divided into roughly 10 types of features. Therefore, the number of pre-segmented areas is at least 10. It was found through experiments that clustering numbers $k=100$ and $k=20$ were selected for clustering, and there was no significant difference. Moreover, the split result is used as the input of the subsequent N-cuts algorithm, and the parameter $k=20$ is selected as the number of regions, which can reduce the calculation amount and reduce the computer memory requirement.

2) Maximum number of iterations and precision: Set the number of iterations to 50 and the iteration precision to 0.5 as the iteration termination condition. They can simultaneously define clusters to achieve better results.

3) Selection of the initial cluster center: The number of pixels in the original image is huge, and it is impossible to select a representative representative point based on experience. Therefore, the initial representative points are selected in the natural order of the images[10].

4) Number of times algorithm was called: Set $N=8$, which can roughly cover the total number of features.

5) Selection of polarization characteristics: In the experiment, six different polarization features with large amount of information are selected, including various scattering mechanisms, such as spherical scattering, dihedral angular scattering, Bragg scattering, and volume scattering to distinguish different features. The average power can directly express the scattering intensity of the ground object, which is also a very representative feature.

According to the experimental results, it can be concluded that the average power λ is used for segmentation. Most of the other polarization features can be clearly distinguished for a particular two species, but it is impossible to distinguish between multiple types of features. For example, the Bragg scattering characteristics of Yamaguchi decomposition have a better effect on the division of cultivated land and bare land, but the effect on forest and urban area is poor. Therefore, the average power is selected for the experiment and the overall performance is better.

c) Performance evaluation metric

The experiment also selected the average power λ as the original image, changed the parameter settings in the experiment, and conducted a control experiment. For different cluster numbers K and N values in the N-cuts algorithm, the K-means clustering algorithm, N-cuts algorithm and region-based N-cuts algorithm are used to process the image separately, and the processing time is recorded. The processing results are shown in Table III. It can be seen from the experimental data that the K-means clustering is used for preprocessing, and the calculation time based on the region-based N-cuts algorithm is much shorter than the calculation time of the N-cuts algorithm. The amount of calculation depends on the number of regions. The segmentation accuracy of the region-based N-cuts algorithm is better than the K-means clustering algorithm, and the overall optimal result can be obtained.

TABLE III. ALGORITHM PROCESING TIME

Value of N	Value of k	Time of K-means(s)	Time of N-cuts	Time of region-based N-cuts(s)
2	20	218.42	8902.19	293.17
4	20	236.48	14039.74	324.87
8	20	209.23	26839.25	388.96
8	10	54.04	26839.25	72.74
8	50	440.23	26839.25	637.28
8	100	793.29	26839.25	993.94

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d) Experimental Results of Image Segmentation

The average power is selected as the original image and the N-cuts algorithm is recursively called to get the final segmentation result.

A total of 4 recursive calls are made to the N-cuts algorithm for segmentation, and 20 types of features were divided into 8 categories. Then, based on artificial experience, similar features are combined and to make further fine division of ground objects. The final segmentation results in 9 types of features. The experimental results are shown in Figure 5:

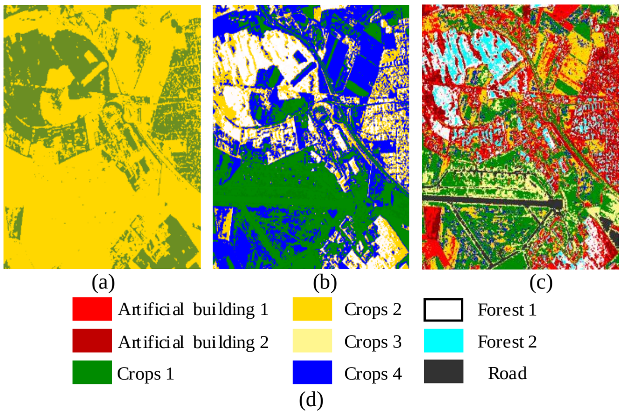

Fig. 5. (a) Segmentation result in *N=2*. (b) Segmentation result in *N=4*. (c) Segmentation result in *N=8*. (d) Category labels

The segmentation result shows that the N-cuts algorithm is continuously called to divide the original image into several parts to achieve the purpose of classification. A better segmentation effect can be achieved by selecting the average power λ as the original image input. Moreover, the algorithm has a short processing time, occupies less computer memory, and is highly efficient.

VII. CONCLUSIONS AND FUTURE WORKS

This section presents our overall conclusions and the works needed in the future.

A. Conclusions

From the perspective of the research problem of polarimetric SAR image segmentation, this paper first analyzes the shortcomings of various existing image processing methods, and then proposes a region-based N-cuts algorithm and applies it to polarimetric SAR images segmentation. The proposed method is validated by E-SAR full polarization data, and this method is compared with other image segmentation algorithm results for evaluation. Experiments show that: experiments are carried out on multiple polarization feature images, and the influence of different features on segmentation results is compared and analyzed. The average power image is used to achieve the best segmentation effect. For polar SAR image processing, region-based N-cuts algorithm is objective and efficient compared to traditional image segmentation algorithms. Applying the mature theory in graph theory to the field of image segmentation, combined with K-means clustering, we can implement region-based image segmentation algorithm. This method can greatly improve the calculation efficiency, reduce the computer memory requirements, and achieve efficient processing. The region-based N-cuts algorithm is continuously called to divide the original image into several parts to achieve the purpose of classification. In addition, the algorithm is highly portable. In different actual scenarios, it can be improved according to specific needs and combined with different algorithms.

B. Future works

In the future experiment about region-based N-cuts image segmentation method, we consider to merge various polarization features to access some more representative new features. Also, other data sets with larger data and some other traditional image segmentation method should be carried out to compare with the proposed method. Moreover, the criteria for performance evaluation [11] need to be improved. In addition, the algorithm has good portability. So according to specific requirements, the algorithm can be improved or combined with other algorithms in different actual scenes.

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