Vegetation Height Extraction of Transmission line Corridor Based on Spaceborne SAR Data

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Abstract. Vegetation encroachment in transmission line corridors may cause electric power blackouts. Currently, manual inspection and airborne LiDAR inspection are used to detect dangerous vegetation, but there are problems of low efficiency and small detection range. With the development of the Ubiquitous power Internet of things, traditional inspection methods will gradually be replaced. The development of synthetic aperture radar (SAR) remote sensing technology makes it possible to efficiently and wide-area monitor the risk of vegetation in transmission line corridors. In this paper, a transmission line corridor with the risk of tree discharge in 220 kV Jiangyou-Tianming transmission line is selected as the research object. Based on the ALOS PALSAR dual-polarized satellite data, the improved three-stage algorithm considering the terrain factor is used to extract the tree height in the sample areas along the transmission line corridor. In addition, the accuracy of the extracted tree height was verified by using the airborne LiDAR data collected in the field. The results indicate that the correlation coefficient R between the extracted tree height and the measured one is 0.835, and the RMSE is 1.923 m. Besides, vegetation height extraction of the transmission line corridor with the spaceborne SAR data is feasible, which can provide some reference for the application of threat warning in transmission line corridors.

Introduction

The overhead transmission line plays the role of power transmission and distribution in the power system, and its safe and stable operation is very important for the transmission system. However, for the transmission line corridor with lush vegetation, the vegetation may be in contact with the transmission line to cause flashover accidents [1], which will greatly threaten the stability of the power system. In severe cases, it may lead to large-scale blackouts and cause huge losses to the national economy. Therefore, it is essential to patrol the transmission line corridor and clean up the dangerous vegetation in time. At present, the transmission line inspection mainly through manual inspection and airborne LiDAR inspection. However, manual inspection has the problems of high labor intensity, low efficiency, and long re-patrol cycle. The airborne LiDAR inspection is limited by battery life, which makes the detection range small. With the construction of the Internet of Things on the transmission line, traditional inspection methods will gradually be replaced [2]. In recent years, the development of spaceborne remote sensing technology has made it possible to efficiently and wide-area detect the vegetation height of transmission line corridors. Among them, the polarization interferometric SAR has attracted extensive attention because it combines the advantages of polarization SAR and interferometric SAR and improves the accuracy of target parameters. Estimating vegetation height using polarization interferometric SAR is one of the most promising applications in microwave remote sensing.

At present, there are two main types of vegetation height estimation algorithms based on polarization interferometric SAR data. One of them is the three-stage algorithm based on RVoG model proposed by Cloude and Papathanassiou [3]. The RVoG model simplifies the vegetation into a two-layer scattering model. The algorithm uses the least squares fitting to extract the ground phase,
and the vegetation height can be extracted by estimating the coherence coefficient. The estimated vegetation height accuracy is highly dependent on the accuracy of the model prediction. Another algorithm is the ESPRIT algorithm proposed by Yamada [4]. Based on the signal processing method, the algorithm estimates the vegetation height by extracting the canopy layer phase and the ground phase of the local scattering phase center. Comparing the two algorithms, the tree height extracted by the three-stage algorithm has higher precision, which is more suitable for practical applications. In practice, the terrain slope will affect the accuracy of vegetation height estimation. Bao et al. [5] proposed the S-RVoG model considering the terrain slope to improve the accuracy of vegetation height extraction. XIE et al. [6] realized the extraction of vegetation height by using airborne E-SAR data and the optimal joint algorithm of PD coherence based on S-RVoG model. However, the above studies are based on simulated data or airborne quad-polarization data, and the research objects are mainly vegetation in a wide range of forest areas. Few studies have used spaceborne SAR data to extract vegetation height in transmission line corridors. The research goal of this paper is to study the feasibility of extracting vegetation height in transmission line corridors based on spaceborne dual-polarization SAR data.

Study Area and Methods

Study Area

The study line of this paper is 220kV Jiangtian transmission line of Mianyang, Sichuan Province. The line starts from Jiangyou Power Plant and ends at 220 kV Tianming Substation with a total length of 21.337 km. The vegetation types along the line are mainly cypress, pine, Qingjiang and alder trees, among which alder trees and pines grow faster and pose a greater threat to the transmission line. The trees in the range of No. 13# - 16# and No. 21# - 28# are flourishing, so the risk of tree discharge is high. In this paper, the transmission line of the tower number 1# - 25# section is selected as the research object. The study area is located between 31°47′49.12″ - 31°51′49.25″ north latitude and 104°44′1.98″ - 104°50′31.52″ east longitude. Fig. 1 shows the SAR intensity image and optical satellite image of the study area.

Figure 1. Study area images
(a) and (b) are SAR intensity image and optical image of the study area, respectively.

RVoG Model

The RVoG model was proposed by Treuhaft et al. [7] in 2000. The model simplifies the overall vegetation structure into a two-layer combination of vegetation layer and surface layer with height $h$. This model is widely used for single baseline polarization interferometric SAR vegetation height inversion. The model can be expressed by Eq. 1 as:

$$
\gamma(\omega) = e^{i\phi} \frac{\gamma_v + m(\omega)}{1 + m(\omega)}
$$

(1)
where $\gamma(\omega)$ is the complex coherence coefficient of the model, $\varphi_0$ is the surface layer phase, $\gamma_v$ is the vegetation volume scattering coherence coefficient, $m(\omega)$ is the ground-to-volume ratio.

$$
\gamma_v = \frac{\int_{z}^{h} e^{i k_z z} e^{2\pi \sigma z} dz'}{\int_{0}^{h} e^{2\pi \sigma z} dz'}, \quad m(\omega) = \frac{m_s}{m_s I_0}
$$

(2)

$$
k_z = \frac{4 \pi \Delta \theta}{\lambda \sin \theta} \approx \frac{4 \pi B_\perp}{\lambda R \sin \theta}
$$

(3)

where $m_s$ is the ground amplitude, $m_v$ is the vegetation layer amplitude, $h$ is the vegetation layer height, $k_z$ is the effective vertical wave number, $\Delta \theta$ is the main and slave image incident angle difference, $\lambda$ is the radar wavelength, $\theta$ is the radar incident angle, $B_\perp$ is the vertical baseline, $R$ is the slant range, $\sigma$ is the vegetation extinction coefficient.

In the RVoG model, the ground is assumed to be flat, but in fact it usually has a certain slope. After considering the terrain slope factor, the RVoG model will change as follows.

1. Effective vertical wave number $k_z$ and vegetation layer height $h$

   When there is a slope on the ground, the local incident angle will change as the slope angle $\alpha$ changes, so that the effective vertical wave number $k_z$ and the vegetation layer height $h$ also change.

   $$
k_z' = \frac{4 \pi \Delta \theta}{\lambda \sin(\theta - \alpha)} \approx \frac{4 \pi B_\perp}{\lambda R \sin(\theta - \alpha)}
$$

(4)

$$
h' = \frac{h}{\cos \alpha}
$$

(5)

2. Complex coherence coefficient $\gamma_v$

   When the slope changes, the corresponding complex coherence coefficient equation is:

   $$
\gamma_v' = \frac{2\sigma}{\cos(\theta - \alpha)} \left( e^{(2\pi \beta k_z')/\cos(\theta - \alpha)} - 1 \right) \int_{0}^{h} e^{i k_z' e^{2\pi \sigma z} \cos(\theta - \alpha)} dz'.
$$

(6)

Improved Three-Stage Algorithm

Cloude and Papathanassiou [3] proposed three-stage algorithm based on the RVoG model, which improved the vegetation inversion efficiency and was widely used in L-band polarization interferometric SAR data processing. The algorithm is mainly divided into the following three steps:

Step 1: Find the best fit straight line for all coherence coefficients using the least squares method in the complex unit circle. The line intersects the complex unit circle at two points $\phi_1$ and $\phi_2$. One of the points is the ground phase point.

Step 2: Find the ground phase $\phi_0$ corresponding to each pixel from the two intersections. The ground phase is related to the relative distance of the HV coherence coefficient on the complex plane, and the point farthest from the HV coherence coefficient is the ground phase.

Step 3: To estimate the tree height and extinction coefficient, it is necessary to first find the volume coherence coefficient $\gamma_v$ that is farthest from the ground phase. Then, a lookup table (LUT) of the complex coherence coefficient $\gamma_v$ and the tree height $h$ and the extinction coefficient $\sigma$ is established by using Eq. 6. The tree height and extinction coefficient are estimated by comparing $\gamma_v e^{i 0\phi_0}$ with the LUT.
For quad-polarization data, according to the reciprocity theorem, the polarization coherence matrix $T_6$ can be represented by the scattering vector $k_p$ of the Pauli polarization [8].

$$k_p = \frac{1}{\sqrt{2}} [S_{HH} + S_{VV}, S_{HH} - S_{VV}, 2S_{HV}]^T$$  \hspace{1cm} (7)

$$k_p = [k_{p1}, k_{p2}]^T$$ \hspace{1cm} (8)

$$T_6 = [k_p k_p^T] = \begin{bmatrix} T_{11} & \Omega_{12} \\ \Omega_{12}^T & T_{22} \end{bmatrix}$$ \hspace{1cm} (9)

where $i=1,2$ represents two images of the interference image pair, $T_{11}$ and $T_{22}$ are semi-positive definite Hermitian matrices, and $\Omega_{12}$ is a polarization coherent matrix.

By projecting the scattering vector $k_{p1}$, $k_{p2}$ onto the normalized unit complex vector $\omega_1$, $\omega_2$, two scattering coefficients $\mu_1$ and $\mu_2$ can be obtained.

$$\mu_1 = \omega_1^* k_{p1}$$

$$\mu_2 = \omega_2^* k_{p2}$$ \hspace{1cm} (10)

where $\omega_i = [\omega_{i1}, \omega_{i2}, \omega_{i3}]^T$ represents the $i$th scattering mechanism and $*$ represents the conjugate complex number.

Assuming $\omega_{i1} = \omega_{i2}$, there will be no more VV channel in the scattering coefficients $\mu_1$ and $\mu_2$.

The two scattering coefficients can be represented only by the HH and HV channel, in which case $\omega_i = [\omega_{i1}, \omega_{i2}]^T$, making the algorithm suitable for dual-polarization SAR data. Correspondingly, Eq. 7 can be simplified as:

$$k_{p1} = \sqrt{2} [S_{HH}, S_{HV}]^T$$ \hspace{1cm} (11)

At this point, the complex coherence coefficient can be expressed as

$$\gamma = \frac{\langle \mu_1^* \mu_2 \rangle}{\sqrt{\langle \mu_1^* \mu_1 \rangle \langle \mu_2^* \mu_2 \rangle}} = \frac{\langle \omega_1^* \Omega_2 \omega_2 \rangle}{\sqrt{\langle \omega_1^* T_{11} \omega_1 \rangle \langle \omega_2^* T_{22} \omega_2 \rangle}}$$ \hspace{1cm} (12)

where $0 \leq \gamma \leq 1$.

For dual-polarization data, the optimal coherence coefficient calculation can be transformed into a 2×2 complex eigenvalue equation as shown in Eq. 13 [9].

$$T_{11}^{-1} \Omega_{12} T_{22}^{-1} \Omega_{22}^T \omega_{ij} = v_j \omega_{ij}$$ \hspace{1cm} (13)

Among them, the vector pair $\omega_{ij}$, $\omega_{ij}$ ( $j$ = 1, 2) represents the optimal scattering mechanism, and the eigenvalue $v_j$ is the optimal coherence in different polarization subspaces.
two points. Finally, the HV channel is selected as the pure volume coherence coefficient, and the LUT established by Eq. 6 is used to estimate the vegetation height and extinction coefficient.

**Results and Analysis**

In this paper, the data is the spaceborne SAR image pair near the Jiangyou-Tianming transmission line acquired by ALOS PALSAR. The study area data is dual-polarization (HH + HV) SAR data. The improved algorithm proposed above is used to extract the vegetation height of the transmission line corridor.

Before the tree height extraction, the two SAR images must be pre-processed, including registration, filtering, interference, flattening, and coherence calculation. To improve the accuracy of the complex coherence, a window size of 11 x 11 is used for calculation. After the tree height extraction, the vegetation height in the sample areas along the transmission line corridor is extracted according to its geographical coordinate information. Finally, the accuracy of the extracted tree height is verified by airborne LiDAR data collected *in situ*. Fig. 2 shows the slope of the study area. The slope value of most areas is below 13 °, which means the terrain is relatively flat. Fig. 3 is a vegetation height map of the study area extracted by the above algorithm, and the average tree height value is 23.6 m. Fig. 4 shows 30 sample areas of 10 m x 10 m with the risk of tree discharge along the transmission line corridor.

Fig. 5 shows the airborne LiDAR *in situ* measurements. Based on this data, the tree height of the sample areas is extracted as real data to verify the accuracy of the tree height of the spaceborne SAR data. Fig. 6 is a comparative analysis of the extracted tree height and the measured one in the sample areas. The correlation coefficient R of the extracted value and the measured value is 0.835, and the RMSE is 1.923 m. The results show that although the root mean square error is relatively large, it is feasible to use the spaceborne SAR data to extract tree height of transmission line corridors. Source of
error in addition to the temporal de-correlation of SAR images acquisition and the tree height extraction algorithms, another major reason is image resolution. The accuracy of the extracted tree height can be improved by using a higher resolution SAR image.

![Figure 6. Comparison of extracted tree height with airborne LiDAR measurements.](image)

**Conclusion**

This paper explored the application of spaceborne L-band SAR data in extracting vegetation height around transmission line corridors. Preliminary research results show that the improved three-stage algorithm considering the terrain slope factor can realize the vegetation height extraction around the transmission line corridor. Comparing the extracted sample areas tree height with the airborne LiDAR measured data, it is found that the correlation coefficient between the extracted tree height and the measured one is high, but the root mean square error is relatively large. This may be related to the temporal de-correlation of SAR image acquisition, vegetation height extraction algorithm, and SAR image resolution.

Further research is needed, such as the use of high-resolution SAR images acquired with dual-antenna satellites to eliminate the effect of temporal decorrelation. In addition, improving the vegetation model can improve the accuracy of tree height extraction. The research results in this paper can provide some reference for the application of satellite remote sensing technology in risk vegetation detection around transmission line corridors.

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