The measurement and model construction of complex permittivity of corn leaves at the main frequency points of L/S/C/X-band

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Abstract. The complex permittivity of target has a crucial influence on its microwave radiation characteristics. In the quantitative research of microwave remote sensing, the study of the dielectric properties of vegetation to establish the relationship between its specific physical parameters and complex permittivity is the basic work in this field. In this study, corn leaves samples of different types and heights were collected at the city of Zhangye which is the key study area of the Heihe watershed allied telemetry experimental research and also the largest breeding base of hybrid corn seeds in China. Then the vector network analyzer E8362B was used to measure the complex permittivity of these samples from 0.2 to 20 GHz by coaxial probe technique. Based on these measurements, an empirical model of corn leaves which describes the relationship between the gravimetric moisture and both the real part and imaginary part of complex permittivity at the main frequency points of L/S/C/X-band was established. Finally, the empirical model and the classical Debye-Cole model were compared and validated by the measured data collected from the Huailai county in Hebei province. The results show that the empirical model has higher accuracy and is more practical than the traditional Debye-Cole model.

1. Introduction
In the quantitative research of microwave remote sensing, the study of the dielectric properties of the observed objects, especially vegetation, is the basic work in this field. The dielectric properties of vegetation play a key role in the coupling between the electromagnetic properties of the vegetation canopy and its physical characteristics. In addition, the complex permittivity of the vegetation is one of the most important elements which control the scattering and emission by the canopy [1]. Thus, it is very important to understand the dielectric properties of vegetation and develop the dielectric model to describe the relationship between its specific physical parameters and its complex permittivity.

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The permittivity of object is a complex quantity represented as \( \varepsilon = \varepsilon' - j\varepsilon'' \). The real part \( \varepsilon' \) is the dielectric constant and the imaginary part \( \varepsilon'' \) is the dielectric loss factor [2]. The major measuring methods of material complex permittivity include the lumped circuit, resonant cavity, free-space, waveguide transmission/reflection, and coaxial probe method [3]. The most widely used technique for complex permittivity measurement of vegetation are the waveguide transmission/reflection method [4]-[5] and the coaxial probe method [1]-[2],[6]-[10]. However, the waveguide transmission/reflection technique has the problem that the sample preparation is very tedious [6]. The advantage of the coaxial probe method is that it can measure samples within a wide range of frequencies and doesn't bring any damage to the measured materials [7]. Furthermore, El-Rayes and Ulaby [1] used both the two methods to measure the dielectric properties of vegetation and pointed out that the coaxial probe method is much more accurate, easier to use and more time saving than the waveguide transmission/reflection technique.

In this study, corn leaves samples of different types and heights were collected at the city of Zhangye. Then the vector network analyzer E8362B was used to measure the complex permittivity of these samples from 0.2 to 20 GHz by coaxial probe technique. Based on the measurements, an empirical model used for describing the relationship between the gravimetric moisture and both the dielectric constant and dielectric loss factor of corn leaves was established at the main frequency points of L/S/C/X-band. Finally, the empirical model and the classical Debye-Cole model were compared and verified by the measured data collected from the Huailai county of Hebei province, which is another typical corn production region besides Zhangye in China.

2. Materials and methods

2.1. Sample materials

The corn leaves samples were collected from Zhangye city in Gansu province, which is the key study area of the Heihe watershed allied telemetry experimental research and also the largest breeding base of hybrid corn seeds in China. These corn leaves were sampled from various corn types and different corn heights ranged from 0.95 m to 2.05 m. In order to prevent the physical characteristics of these samples from changing, they were transported to the laboratory for measuring on the same day.

2.2. Measurement methods

Because coaxial probe method assumes that the measured sample is electrically infinite in depth [1]. In order to investigate the effective penetration depth of the probe, the dielectric constant of white bond paper with varying thickness which represent the low-loss material was tested with two contrasting materials (copper and Teflon) under it over the entire frequency range of 0.2 to 20 GHz. It was found that the influence of the background materials could be neglected when the paper thickness reached 3.0 mm. Thus, a sample thickness of 3.0 mm was chosen to simulate an infinite sample.

In addition, it is very important to apply appropriate pressure on the probe to measure the samples for the purpose of insuring no air gaps among them and avoiding excess pressure to alter the structure of the tissues which may change the dielectric properties of the material being measured [1]. In order to reduce human errors and systematic errors, complex permittivity measurements for corn samples were averaged to provide mean values representing 10 measurements.

Furthermore, different gravimetric moisture of the corn leaves samples was obtained by using the automatic drying oven. Finally, the dry weights of samples were recorded after drying in the oven for 48 h at 70 °C [9].

3. Measurement results and model construction

3.1. Measurement results

Although the complex permittivity of vegetation at a specific frequency is controlled by the gravimetric moisture, bulk density of the dry vegetation material, salinity and temperature, the
gravimetric moisture is the dominant factor [11]. Furthermore, in order to facilitate the practical application, only gravimetric moisture of the samples were measured in the study. The research focuses on finding the relationship between the complex permittivity of corn leaves and its gravimetric moisture, thereby develops the empirical model. The range of the gravimetric moisture of core leaves samples were from 2.33% to 71.39% and all the samples were measured by the vector network analyzer E8362B at 22 °C. Parts of the measurement results are shown in figure 1 (other results are similar).

As can be seen from figure 1, the dielectric constant of the corn leaves decreases as the frequency increases, while the dielectric loss factor does not change monotonously as the frequency changes. It decreases as the frequency increases in the low frequency range. After reaching the minimum value, it increases as the frequency increases and finally tends to be stable. Additionally, figure 1 also indicates that the gravimetric moisture has a great impact on the dielectric properties of the corn leaves. Both the dielectric constant and dielectric loss factor increase as the gravimetric moisture increases.

### 3.2. Model construction

The research is devoted to establishing an empeicial model of corn leaves at the frequceny points which are commonly used by microwave sensors, namely L=1.26 GHz, S=3.2 GHz, C=5.3 GHz and 6.9 GHz, X=9.6 GHz. The relationship between the gravimetric moisture and both the dielectric constant and dielectric loss factor of the corn leaves samples at 5.3 GHz is shown in figure 2 (the results of remaining main frequency points are similar).

![Figure 2. The relationship between the gravimetric moisture and both the dielectric constant and dielectric loss factor of the corn leaves samples at 5.3 GHz.](image)
As can be seen from figure 2, the relationship between both dielectric constant and dielectric loss factor of corn leaves and its gravimetric moisture can fit well with a simple exponential function based on a specific frequency, which can be expressed as:

\[ \varepsilon' = a_M e^{a_M M_g} \]
\[ \varepsilon'' = b_M e^{b_M M_g} \]  

(1)

where \( \varepsilon' \) and \( \varepsilon'' \) denote the dielectric constant and dielectric loss factor, respectively, \( M_g \) is the gravimetric moisture, \( a_1, a_2, b_1, b_2 \) are the coefficients which need to be calibrated.

We select the measured data to obtain the coefficients in equation (1) at the main frequency point of L/S/C/X-band by the least square method. Then the lookup table at these main frequency points was established, shown in table 1. The determination coefficient \( R^2 \) and root mean square error (RMSE) illustrated in table 1 demonstrate that the exponential function fit the data very well.

Table 1. The look-up table of the empirical model of corn leaves at the main frequency points of the L/S/C/X-band

| f(GHz) | \( a_1 \) | \( a_2 \) | \( R^2 \) | RMSE | \( b_1 \) | \( b_2 \) | \( R^2 \) | RMSE |
|--------|--------|--------|--------|------|--------|--------|--------|------|
| 1.26   | 1.048  | 4.098  | 0.968  | 1.537| 0.335  | 3.730  | 0.909  | 0.463|
| 1.4    | 1.124  | 3.969  | 0.967  | 1.516| 0.330  | 3.710  | 0.911  | 0.447|
| 3.2    | 1.128  | 3.844  | 0.968  | 1.339| 0.291  | 3.673  | 0.928  | 0.341|
| 5.3    | 1.134  | 3.767  | 0.966  | 1.407| 0.293  | 3.881  | 0.938  | 0.365|
| 6.9    | 1.107  | 3.694  | 0.967  | 1.293| 0.317  | 3.882  | 0.937  | 0.398|
| 9.6    | 1.010  | 3.766  | 0.949  | 1.774| 0.342  | 3.768  | 0.928  | 0.424|

4. Validations and discussions

4.1. Debye-Cole model

Ulaby and El-Rayes [8] developed the Debye-Cole dual-dispersion dielectric model (i.e. Debye-Cole model) which is the one of the most widely used vegetation dielectric models. This model was built based on the measurements of corn leaves using the vector network analyzer HP8410C by coaxial probe method. In the model, the vegetation is treated as a mixture of bulk vegetation, free water component and bound water component. At room temperature (22 °C), the model can be expressed as:

\[ \varepsilon_v = \varepsilon_r + \nu_{f_v} [4.9 + 75.0 \frac{18 \sigma}{1+jf/18}] + \nu_{b} [2.9 + 55.0 \frac{1}{1+jf/0.18}] \]  

(2)

\[ \varepsilon_r = 1.7 - 0.74 M_g + 6.16 M_g^2 \]  

(3)

\[ \nu_{f_v} = M_g (0.55 M_g - 0.076) \]  

(4)

\[ \nu_b = 4.64 M_g^2 / (1 + 7.36 M_g^2) \]  

(5)

Where \( \varepsilon_v \) represents the complex permittivity of vegetation, \( \varepsilon_r \) is the nondispersive residual component, \( \nu_{f_v} \) is the volume fraction of free water, \( \nu_b \) is the volume fraction of the bulk vegetation-
bound water mixture, $f$ denotes frequency and the unit is GHz, $\sigma$ is the conductivity of the free water, $\sigma = 1.27$ and the unit is S/m, $M_g$ is the gravimetric moisture.

4.2. Comparison and validation

In order to verify the practicality of both the empirical model and the Debye-Cole model, the measured data collected from Huailai county in Hebei province which is a typical corn production region in China were used. These samples were also obtained from different heights and types of corn and were processed using the same method mentioned in section 2.2. The comparison of the empirical model of corn leaves and the Debye-Cole model with the measured data at 5.3GHz is displayed in figure 3 (the results of remaining main frequency points are similar to them). It can be seen that the empirical model presents a better fit to the measured data than Debye-Cole model. The empirical model is more consistent with the measured data, while the Debye-Cole model appears to overestimate both the dielectric constant and dielectric loss factor of the corn leaves. Additionally, Colpitts and Coleman [9] also found that the Debye-Cole model cannot fit the complex permittivity of potato leaves well. Moreover, the $R^2$ and RMSE at all the main frequency points of L/S/C/X-band illustrated in table 2 further demonstrate a comprehensive improvement in the estimation of complex permittivity of corn leaves using the empirical model in comparison to the Debye-Cole model.

![Figure 3](image_url)

**Figure 3.** The comparison and verification of the empirical model of corn leaves and the Debye-Cole model with the measured data at $f=5.3$GHz

**Table 2.** The comparison results of the empirical model of corn leaves and the Debye-Cole model with the measured data at the main frequency points of the L/S/C/X-band

| $f$(GHz) | $\varepsilon'$ | $\varepsilon''$ | $\varepsilon'$ | $\varepsilon''$ |
|---------|----------------|----------------|----------------|----------------|
|         | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE | $R^2$ | RMSE |
| 1.26    | 0.930 | 1.546 | 0.875 | 3.391 | 0.940 | 0.346 | 0.882 | 1.102 |
| 1.4     | 0.926 | 1.548 | 0.876 | 3.332 | 0.941 | 0.335 | 0.882 | 1.058 |
| 3.2     | 0.918 | 1.484 | 0.872 | 3.103 | 0.937 | 0.295 | 0.892 | 0.856 |
| 5.3     | 0.914 | 1.446 | 0.871 | 2.914 | 0.930 | 0.366 | 0.893 | 0.904 |
5. Conclusions
An empirical model of corn leaves which describes the relationship between the gravimetric moisture and its complex permittivity was developed in the study. The corn leaves samples of different types and heights used for model building were collected from Zhangye which is the largest breeding base of hybrid corn seeds in China. The vector network analyzer E8362B was used to measure the complex permittivity of these samples from 0.2 to 20 GHz by coaxial probe technique. Based on the measurement results, it was found that the relationship between both the dielectric constant and dielectric loss factor of corn leaves and its gravimetric moisture can fit well with a simple exponential function at a specific frequency. Finally, the established empirical model and the classical Debye-Cole model were compared and validated by the measured data collected from another typical corn production region named Huailai. The results show that the empirical model has higher accuracy and is more practical compared to the traditional Debye-Cole model.

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