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POLARIZATION METHOD FOR DETERMINATION AND VISUALIZATION OF COMPLEX PERMITTIVITY IN REMOTE SENSING ISSUES

L.P. LIGTHART[1], A.I. KOZLOV[2], A.I. LOGVIN[2], I.V. AVTIN[2]
[1]Delft University of Technology, Delft, Netherlands
[2]Moscow State Technical University of Civil Aviation, Moscow, Russia

When using remote radiophysical methods in problems of monitoring the environment, the central place belongs to solving problems of determining its electrophysical characteristics, i.e. dielectric permittivity ε, conductivity σ (complex permittivity εk). The complex dielectric permittivity ε, determined in one way or another, serves as the basis for determining the physical characteristics of the medium under study: temperature, humidity, salinity, hardness, etc. The method for remote determination of complex dielectric permittivity is proposed based on relative amplitude-phase relations in the radar receiver channels (orthogonal in polarization) (we call it determination of the polarization phasor). Knowledge of the polarization phasor makes it possible to determine uniquely both the permittivity and the conductivity of the surface under investigation. The latter is presented in the form of a series of universal graphs which allow one to directly interpret the physical characteristics of surfaces. It shows how the polarization phasor is placed on the KLL-sphere. In addition, the trajectory of the phaser on this sphere is investigated in the case when the physical characteristics of the investigated surface change. The random nature of local changes in the electrophysical properties of the surface under study leads to random fluctuations of the polarization phasor. The paper contains a two-dimensional density distribution of the permittivity and conductivity, as well as the corresponding one-dimensional densities. A graphic illustration of the relations obtained is given.

Key words: polarization, remote sensing, complex permittivity, KLL-sphere, Fresnel coefficients, amplitude-phase ratio.

INTRODUCTION

The main objective of remote sensing is to determine physical, mechanical, chemical and other properties of the ambient medium and objects. Solving these issues necessitates the analysis of various characteristics of radio waves scattered by the objects under study. These characteristics are associated with geometrical parameters and complex permittivity of the objects. Knowledge of complex permittivity will allow determination of the main electric characteristics of the observed radar targets. Earlier the authors introduced a new method useful in radar earth observation for determining complex permittivity on the basis of relative measurements of signals in two receiver channels for two orthogonal polarizations (relative means that only the ratio of receiver voltages and the phase difference in the channels are needed) [1, 3, 7]. The basic idea of the proposed method consists of the selection of such type of radiated wave polarization, for which the cross component is practically absent in the reflected signal. This means that it is necessary to select that type of radiated wave polarization for which the orthogonal components in the eigen polarization basis of the scattering matrix of the object have equal powers and phases. After selecting this specific transmit polarization, the phase difference and the ratio of the voltage amplitudes in the orthogonal channels of the receiver are measured. This method allows for the determination of complex permittivity by making use of the measured complex polarization ratio.

In general, the polarizing factor represents itself as a random variable. Two major reasons may cause the stochastic character of this factor. At first, the presence of noise in the receiver, and secondly, the stochastic character of the changes in the dielectric characteristics of the surface under study. As the statistical behavior of the signal reflected from the surface is significantly different from the effects caused by the receiver noise, the second reason is given major attention.

Therefore, by investigating the statistical characteristics of the polarizing factor or (stated differently) by studying the statistical characteristics of parameters describing the polarization of reflected waves (as projection at a surface called the KLL-sphere), it is possible to visualize the statistical characteristics of dielectric permittivity of the surface under study.

In the first part of the paper the results obtained earlier are briefly summarized [1]; in the second part new results are shown, giving a possibility to connect the statistical characteristics of the polarizing factor with statistical characteristics of dielectric permittivity by using the real and imaginary parts of this permittivity of the surface observed by polarimetric radar.

MEASURING THE COMPLEX DIELECTRIC PERMITTIVITY OF SURFACES BY USING POLARIMETRIC RADAR EARTH OBSERVATIONS

The new-developed method of determining complex dielectric permittivity of surfaces leans on the following. In the broad class of radar remote sensing issues to study the underlying surfaces, the reflection coefficient of radio waves in the direction of the receiving antenna may be represented by a product of two multiplicands [1, 2]. The first multiplicand is the Fresnel coefficient for the mirror "reflection angle", which depends on the type of polarization of the transmitted radio wave and the angle of observation. The second multiplicand depends on the geometry of the surface structure and is assumed to be independent on the polarization type of the transmitted radio wave.

It is obvious that the received reflected radio wave signals in orthogonal (in polarization sense) channels will be proportional to the reflection coefficients at the surface under study. Assuming equality in the powers of both orthogonal components of the transmitted radio wave (for example if we use a linearly polarized radio wave with an angle of declination of 45° or a radio wave with circular polarization), the relation of the signals in the orthogonal channels of the receiving device will represent the relation of the Fresnel coefficients (when using circular polarization, there is an additional phase shift of 90° to be taken into account). The measured relation we shall name the polarizing factor of the phazor. For surfaces for which the reflection coefficient may be represented by a product of the two mentioned multiplicands, the phazor determines the type of polarization of the reflected radio wave.

In references [1, 7], it has been shown that there is the following functional dependence between the Fresnel coefficients for horizontal polarization R_{HP} and for vertical polarization R_{VP} assuming that the observation is conducted under an angle θ with respect to the vertical axis perpendicular to the surface.

$$R_{VP} = R_{HP} \frac{\cos 2\theta - R_{HP}}{1 - R_{HP} \cos 2\theta} \tag{1}$$

The polarizing factor (phazor) for these linear polarizations is equal to:

$$f = |f| e^{i\psi} = \frac{R_{VP}}{R_{HP}} \tag{2}$$

We pay further attention only to the phazor as the parameter to be measured by the polarization radar. Using equation (1), it is possible to determine the Fresnel coefficients through measuring of R. We obtain:

$$\begin{cases} R_{HP} = \dfrac{\cos 2\theta - f}{1 - f \cos 2\theta} \\ R_{VP} = f \dfrac{\cos 2\theta - f}{1 - f \cos 2\theta} \end{cases} \tag{3}$$

Using formula (3) and the known expressions for the Fresnel coefficients, it is possible to derive the expression for complex dielectric permittivity just by measuring the complex polarizing factor i.e. the ratio of the amplitudes of the signals in the orthogonal polarization receiver channels and the phase difference between these signals). We may find [1, 4, 5]:

$$\varepsilon = \left[1 + \frac{4f}{(1-f)^2}\sin^2\theta\right]\tan^2\theta. \tag{4}$$

If we use waves with circular polarization formula (4) will change into:

$$\varepsilon = \left[1 + q^2\tan^2\theta\right]\sin^2\theta, \tag{5}$$

where $q = |q|e^{i\delta}$ is the polarizing factor for circular polarization (meaning that we use here the ratio of the orthogonal components in the two receive channels with the right and left hand circular polarization). From formula (5), it is possible to derive rather compact formulas for the real part of complex dielectric permittivity and for medium conductivity σ. The new result becomes:

$$\begin{cases} \operatorname{Re}\varepsilon = \left[1 + q^2\cos 2\delta\tan^2\theta\right]\sin^2\theta \\ \sigma = \dfrac{1}{60\lambda}q^2\sin 2\delta\tan^2\theta\sin^2\theta \end{cases}. \tag{6}$$

At last, the complex dielectric permittivity can be expressed immediately in the parameters of the polarization ellipse characterizing the reflected radio wave. These parameters in the polarization ellipse are ellipticity coefficient K and declination angle γ. The newly developed expressions are summarized in the following formulas:

$$\begin{cases} \varepsilon = \left[1 + \left(\dfrac{1-K}{1+K}\right)^2 e^{4i\gamma}\tan^2\theta\right]\sin^2\theta \\ \operatorname{Re}\varepsilon = \left[1 + \left(\dfrac{1-K}{1+K}\right)^2\cos 4\gamma\tan^2\theta\right]\sin^2\theta. \\ \sigma = \dfrac{1}{60\lambda}\left(\dfrac{1-K}{1+K}\right)^2\sin 4\gamma\tan^2\theta\sin^2\theta \end{cases} \tag{7}$$

These formulas enable us to determine complex dielectric permittivity of the surface under study using one radar measurement only. In Figure 1 (given for illustration only) the dependence of dielectric permittivity of a medium with small conductivity (almost dielectric) is shown as a function of the phazor module $|f|$ and with various angles of observation θ as a parameter.

Figure 2 gives the dependence of the dielectric permittivity of the same medium but now as function of the ellipticity coefficient (of the received electromagnetic wave) K and as function of the polarizing factor $|q|$ when circular polarizations are being used [1, 15].

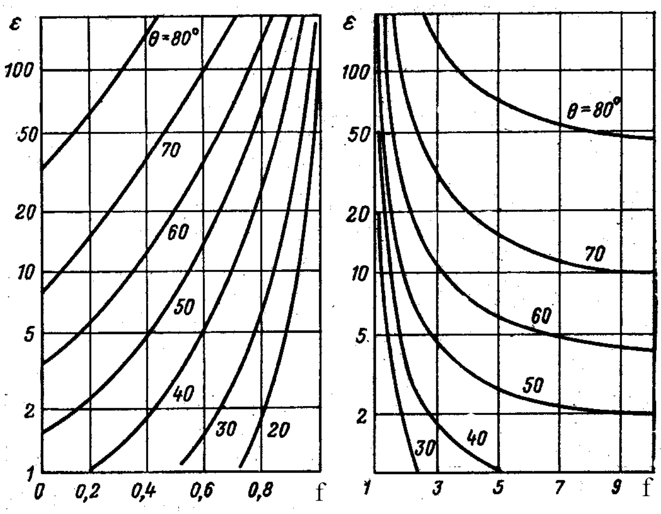

Fig. 1. Dependence of dielectric permittivity ε as function of f with angle θ as parameter (linear polarization)

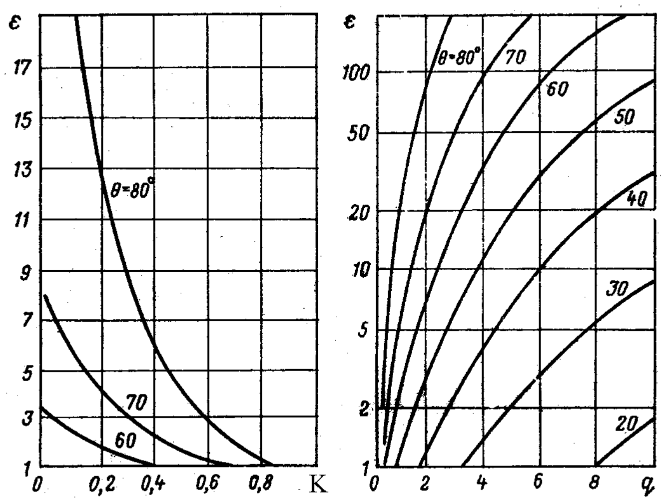

Fig. 2. Dependence of dielectric permittivity ε as function of the polarizing parameters K, q with angle θ as parameter (circular polarization)

KLL-SPHERE

The polarization ratio f represents a complex number and determines in a unique manner a certain point located on the Poincare sphere. At the same time, it determines the complex permittivity of the underlying surface. This connection allows us to construct another sphere (which we called the KLL-sphere) for which any type of earth surface is uniquely corresponded to a certain point located on this sphere surface. It means [3, 6, 14] that a change on the KLL-sphere is equivalent to a change in the physical and/or chemical characteristics of the researched surface. By doing so we are able to construct a sphere on which in real-time phazor f can be projected. This results into a direct remote sensing of the surface permittivity. Variations in the measured f can be projected on the KLL-sphere. These projections show the changes in measured permittivity.

$$\left.\begin{aligned} 2\beta &= \arctan\frac{2|f|\cos\psi}{1-|f|^2} \\ \phi &= \arctan\sqrt{\frac{\tan^2\beta-2|f|\tan\beta\cdot\cos\psi+|f|^2}{1+2|f|\tan\beta\cdot\cos\psi+|f|^2\tan^2\beta}} \end{aligned}\right\}. \tag{8}$$

Equations (4), (5) and (8) relate uniquely f and so the permittivity to the KLL spherical coordinates [1, 8, 13].

STATISTICAL CHARACTERISTICS OF THE ELECTRICAL PARAMETERS OF THE RADAR-SENSED SURFACES

As was already said in the introduction, the fluctuations of radio wave parameters after reflection from the surface may be caused by variations in the physical and chemical properties of these surfaces, i.e. by variations in dielectric permittivity.

There is much literature paying attention to the development of statistical (and physically reasonable) models [2, 3, 8, 9, 10], which make use of orthogonal components of partially polarized waves. By relating the statistical signal behavior to the statistics of the electric permittivity of the surfaces, statistical models of surface covers can be developed. For the construction of such statistical surface models based on signal models with partially polarized radio waves, knowledge of appropriate analytical relationships is required.

For deriving such associate relations, it is convenient to start from formulas (5) and (6) which are valid for circular polarizations. With equation (5) we may find for q:

$$\begin{cases} |q| = \dfrac{\sqrt[4]{\left(\varepsilon - \sin^2\theta\right) + \left(60\sigma\lambda\right)^2}}{\sin\theta\tan\theta} \\ \delta = 0,5\arctan\dfrac{60\sigma\lambda}{\varepsilon - \sin^2\theta} \end{cases}. \tag{9}$$

Using known rules for transformation of the probability density function PDF, we write:

$$W\left(\varepsilon,\sigma\right) = W\left(\left|q\left(\varepsilon,\sigma\right)\right|, \delta\left(\varepsilon,\sigma\right)\right)\left|\frac{\partial\left(|q|,\delta\right)}{\partial\left(\varepsilon,\sigma\right)}\right|. \tag{10}$$

Implicitly we have assumed in formula (10) that the PDF of the reflected radio wave parameters $W(|q|,\delta)$ are known. For determining the one-dimensional PDF $W(|q|)$ and $W(\delta)$ it is necessary to integrate formula (10) so that we can eliminate one variable. However, this generalized problem represents serious mathematical difficulties and the results of integration can not be written in a closed form.

By way of illustration we shall consider a special case, in which we define a PDF of the dielectric permittivity assuming that the surface has a small medium conductivity. This situation is often met in practice. We suppose also, that the deterministic component is in the orthogonal channels and that the components of partially polarized waves are absent. The PDF $W(|q|,\delta)$ can then be described by [2, 11, 12]:

$$W\left(|q|,\delta\right) = \frac{qh^2\left(1-R^2\right)}{\pi\left(1-2qhR\cos\delta + q^2h^2\right)^2}, \tag{11}$$

where R is the correlation coefficient of the orthogonal components, h -is the ratio between the mean square signal deviations in the orthogonal channels. In this case the required PDF becomes:

$$W\left(\varepsilon\right) = \frac{h^2\left(1-R^2\right)\sin^2\theta\tan^2\theta}{8\sqrt{\varepsilon-\sin^2\theta}\left[\sin^2\theta\tan^2\theta - 2hR\sin\theta\tan\theta\sqrt{\varepsilon-\sin^2\theta} + h^2\left(\varepsilon-\sin^2\theta\right)\right]^2}. \tag{12}$$

Various $W(|q|,\delta)$ expressions as function of h and R can be found for other statistical PDF's than given in equation (11).

Further experimental investigations are needed to generalize the validity of our approach.

CONCLUSION

It is shown that using relative measurements of signals in orthogonal channels of a receiving device of a radar station, it is possible to unambiguously determine the complex permittivity and conductivity of the surface, measured during its remote sensing. The values found can serve as a basis for determining physical characteristics such as humidity, salinity, strength, temperature. Errors in the determination of the unknown quantities arising as a result of inaccuracy in measuring the ratio of the amplitudes and the phase difference in the orthogonal channels are given.

Knowledge of the polarization phasor makes it possible to uniquely determine both the permittivity and the conductivity of the surface under investigation. The result is presented in the form of universal graphs, allowing to directly interpret the physical characteristics of surfaces.

These graphs show how the polarization phasor is displayed on the KLL-sphere. In addition, the trajectory of the phaser on this sphere is investigated in the case when the physical characteristics of the investigated surface change. The trajectory of the phasor makes it possible to visualize local changes in the physical properties of the underlying surface when it is probed.

The random nature of local changes in the electrophysical properties of the surface under study leads to random fluctuations of the polarization phasor. The two-dimensional density distribution of the permittivity and conductivity determined in the paper, as well as the corresponding one-dimensional densities, make it possible to obtain more realistic estimates of the measured quantities.

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INFORMATION ABOUT THE AUTHORS

Leo P. Ligthart, PhD, Delft University of Technology, International Research Centre for Telecommunications-Transmission and Radar, l.p.ligthart@its.tudelft.nl.

Anatoliy I. Kozlov, Doctor of Physical and Mathematical Sciences, Professor of Technical Maintenance of Radio Electronic Equipment of Air Transport Chair, Moscow State Technical University of Civil Aviation, vilandes@yandex.ru.

Alexander I. Logvin, Doctor of Technical Sciences, Professor of the Air Traffic Management Chair, Moscow State Technical University of Civil Aviation, vilandes@yandex.ru.

Igor V. Avtin, Post-graduate student of Technical Maintenance of Radio Electronic Equipment of Air Transport Chair, Moscow State Technical University of Civil Aviation, igarrykavt@gmail.com.

ПОЛЯРИЗАЦИОННЫЕ МЕТОДЫ ДЛЯ ОПРЕДЕЛЕНИЯ И ВИЗУАЛИЗАЦИИ КОМПЛЕКСНОЙ ДИЭЛЕКТРИЧЕСКОЙ ПРОНИЦАЕМОСТИ В ВОПРОСАХ ДИСТАНЦИОННОГО ЗОНДИРОВАНИЯ

Л.П. Лигхарт[1], А.И. Козлов[2], А.И. Логвин[2], И.В. Автин[2]

[1]*Делфтский технологический университет, г. Делфт, Нидерланды*

[2]*Московский государственный технический университет гражданской авиации, г. Москва, Россия*

При использовании дистанционных радиофизических методов в задачах мониторинга окружающей среды центральное место принадлежит решению задач определения ее электрофизических характеристик, т. е. диэлектрической проницаемости ε, проводимости σ (комплексной диэлектрической проницаемости $\varepsilon_к$). Дистанционно определенное тем или иным способом значение $\varepsilon_к$ в дальнейшем служит основой для определения физических характеристик исследуемой среды: температура, влажность, соленость, твердость и т. д. В работе предлагается метод дистанционного определения комплексной диэлектрической проницаемости на основании относительных амплитудно-фазовых отношений в ортогональных по поляризации каналам приемника радиолокационной станции (определение поляризационного фазора). Знание поляризационного фазора дает возможность однозначно определить как диэлектрическую проницаемость, так и проводимость исследуемой поверхности. Последнее отражено в виде ряда универсальных графиков, позволяющих непосредственно интерпретировать физические характеристики поверхностей. Показывается, как поляризационный фазор отображается на KLL-сфере. Кроме того, исследуется траектория фазора на этой сфере при изменении физических характеристик исследуемой поверхности. Случайный характер локальных изменений электрофизических свойств исследуемой поверхности приводит к случайным флуктуациям поляризационного фазора. В работе находятся двумерная плотность распределения диэлектрической проницаемости и проводимости, а также соответствующие одномерные плотности. Приводится графическая иллюстрация полученных соотношений.

Ключевые слова: поляризация, дистанционное зондирование, комплексная диэлектрическая проницаемость, KLL-сфера, коэффициенты Френеля, амплитудно-фазовое соотношение.

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СВЕДЕНИЯ ОБ АВТОРАХ

Лигхарт Лео Петрус, доктор философских наук, Делфтский технологический университет, Международный исследовательский центр телекоммуникаций и связи и радиолокации, Делфт, Нидерланды, l.p.ligthart@its.tudelft.nl.

Козлов Анатолий Иванович, доктор физико-математических наук, профессор кафедры технической эксплуатации радиоэлектронного оборудования воздушного транспорта МГТУ ГА, vilandes@yandex.ru.

Логвин Александр Иванович, доктор технических наук, профессор кафедры управления воздушным движением МГТУ ГА, vilandes@yandex.ru.

Автин Игорь Викторович, аспирант кафедры технической эксплуатации радиоэлектронного оборудования воздушного транспорта МГТУ ГА, igarrykavt@gmail.com.

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