THEORY AND METHODS OF SIGNAL PROCESSING

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SPECTRAL-POLARIMETRIC APPROACH TO REMOTE SENSING OF NATURAL OBJECTS AND PHENOMENA

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Abstract— *This paper introduces a new approach to remote sensing that combines spectral and polarimetric features of signals received from distant objects, providing spectral analysis of polarimetric variables. The detailed theory has been developed for the case of rain observation by active monostatic radar, however generalization for other objects and methods is made, and some examples of spectral polarimetric approach application in different fields are presented.*

Index Terms— Radar; remote sensing; Doppler polarimetry; spectral polarimetry; natural targets.

I. INTRODUCTION

Remote sensing as the process of obtaining information about distant objects without direct physical contact with them has received wide development. It includes the study of the earth's surface from flying vehicle, obtaining information about the atmosphere and the objects in the atmosphere, astronomical and astrophysical observations, and more. Normally a radiation of electromagnetic nature, including light, is used as a carrier of information in remote sensing. Sometimes radioactive radiation or acoustic oscillations (for example, in the atmosphere or in a water medium) can be used. Our approach assumes electromagnetic radiation as information carrier.

Active and passive remote sensing techniques have been developed and applied in a wide range of operating frequencies of electromagnetic oscillations. Various characteristics of radiation are used as informative parameters. Spectral analysis of signals is probably one of the most popular signal processing procedures to obtain information about the object under study. In active radar, polarization remote sensing techniques are widely used. Numerous polarimetric parameters are known. They carry diverse information about characteristics of objects.

Research of polarization features of electromagnetic radiation, more exactly, microwave scattering by non-spherical water droplets has actually been begun in 50th of last century. The period of fast development in polarimetric radar was from the middle of 70th to the middle of 80th when potential possibilities of differential reflectivity Z_{DR} estimation were researched [1]. Then a lot of work was made on the development and research of different directions of meteorological application of radar polarimetry. In addition to differential reflectivity, some other polarimetric parameters were proposed, in particular: Linear Depolarization Ratio L_{DR} and Specific Differential Phase K_{DP}, and later the coefficient of mutual correlation ρ_{HV} of signals with orthogonal polarization. Since that time, slow but stable progress was observed in the field of radar polarimetry.

While the first polarization and polarimetric methods were developed for incoherent (conventional) radars, nowadays one can see increasing activity in polarimetric observations with application of coherent radar [2]. Advent of coherent polarimetric means of observation was accompanied with fast increasing number of measurable parameters. It was necessary to research the relationships between different Doppler and polarimetric parameters, and possibly to find new measurable quantities that are characteristic and suitable for Doppler polarimetry. This was done and described in [3], where new measurable quantities: spectral differential reflectivity $sZ_{DR}(v)$ and spectral linear depolarization ratio $sL_{DR}(v)$ were introduced. These quantities are functions of Doppler frequency or velocity. In more general case the frequency can be caused by other factors, not obligatory by Doppler velocity, that is why generally speaking, we can consider $sZ_{DR}(f)$, $sL_{DR}(f)$, etc. Also some other Doppler-polarimetric parameters were proposed, for example, Differential Doppler Velocity (DDV) and Slope of Spectral Differential Reflectivity $Slope\, sZ_{DR}$, or shortly – SLP.

Parameter DDV (in a little bit different definition) was proposed in [4] and researched as a measurand for estimation of drop size distribution. The idea to present differential reflectivity and specific differential phase as distributions over Doppler frequencies was proposed in [5] though without essential analysis.

Doppler-polarimetric approach that was developed for remote sensing of clouds and precipitation [3], [6] – [11] allows us to obtain information about velocities and shape of the scatterers in the resolution volume.

In this paper we attempt to generalize this approach to a broad class of problems in remote sensing of natural phenomena and objects. It will be shown that the proposed spectral-polarimetric approach is useful to exploring remote objects and natural phenomena. This paper is an extended version of conference publications [12] and [13].

The paper is organized as following. Section 2 describes the statement of the problem in case of spectral-polarimetric approach. In section 3 a special case of rain observation, which reduces the problem of spectral polarimetry to Doppler polarimetry, is considered in detail. Section 4 is devoted to generalization of the problem to different methods of remote sensing, variety of objects under study, etc. Section 5 proposes the formulation of conclusion.

II. Statement of the Problem

Suppose that there is real world, some aspects of which we would like to explore. A part of the real world (system) is the object of study. In this statement, the term 'to explore' means to construct some mathematical models that improve our understanding of the object under study, allows to make predictions about its future state or behavior, and in some cases can provide information to control the object. The exploration (as a process) can be implemented by collecting data, the introducing these data into the mathematical model, analysis of the model to adjust the data collection procedures, including conducting experiments on the system, if possible. The problem becomes much more complicated, if the object is remote, inaccessible to direct physical contact as well as for the controlled change of its state. However, for specific objects and situations, it is possible to construct a phenomenological model to calculate the informative parameters that can be assessed with some accuracy using the results of experimental observations.

Let us focus onto the polarimetric informative parameters that are known to carry information about the nature of forming the electromagnetic signal, such as the shape and spatial orientation of the object, or a scatterer in the case of active radar. Practically in all cases the received signal is not monochromatic. This opens the key possibility to improve the analysis: we can analyze density of the polarimetric parameter over its frequency components, ie the spectral density of a polarimetric parameter. Thus, we arrive at the notion of spectral polarimetric characteristics. While a conventional polarimetric parameter (Z_{DR}, L_{DR}, etc.) characterizes the integral properties of the resolution volume of the object under study, a spectral-polarimetric characteristic ($sZ_{DR}(f)$, $sL_{DR}(f)$, etc.), which is a function of frequency, gives an idea of the fine structure of the scatterers within the resolution volume. Thus, this approach provides a kind of the super-resolution, when it is possible to distinguish between scatterers within a resolution volume, though without specifying the exact location of them inside this resolution volume.

The physical interpretation of the results of spectral-polarimetric analysis should depend on the nature of the object and essence of the problem being solved. Special case when the resolution volume is filled with non-spherical (in general case) scatterers that can move with different velocities, leads to Doppler polarimetry. In this case, the physical meaning of the argument of the spectral density of a Doppler-polarimetric parameter is the frequency associated with the radial velocity of the scatterers corresponding to their shape and orientation.

III. Spectral Polarimetry in Case of Rain Observation: Doppler Plarimetry

A. *Doppler approach*

Doppler radar is able to measure important parameters of target speed, however radial velocity depends on the number of factors and moreover, there are a number of scatterers in a resolution volume. In reality we deal with Doppler spectrum $S(*)$ which is power spectrum of complex signal that is expressed as function of Doppler frequency f or Doppler velocity v.

In case of the velocity as the argument, $S(v)$ is interpreted as reflectivity weighted distribution of radial velocities of scatterers in resolution volume. Thus, $S(v)dv$ means received power in the velocity interval dv. In case of such definition $S(v)$ is normalized as

$$\int_{-\infty}^{\infty} S(v)dv = \overline{P}_{Rx}, \quad (1)$$

where $\overline{P}_{Rx}$ is mean received power.

Doppler spectrum definition given above yields the following Doppler spectrum model of rain with $N(D)$ as drop size distribution, $p_p(v/D)$ as probability density of radial velocity of a droplet of given size (equivalent diameter) D, and $\sigma(D)$ as RCS of the droplet:

$$S_v(v) \sim \int_{D_{\min}}^{D_{\max}} p_p(v/D)\sigma(D)N(D)dD. \qquad (2)$$

This model is useful for interpretation of measured estimates $\hat{S}_v(v)$ based on Fourier transform over the received signal.

In meteorological practice, only three Doppler spectrum parameters are normally used: zero moment (mean power or reflectivity factor), first ordinary moment (mean Doppler velocity) and second central moment (Doppler velocity variance) [8] though there are plenty research works, for example, [15] – [17] describing more complete application of Doppler spectrum.

Nevertheless, the main problems of Doppler approach are: influence of carrier velocity of the radar and antenna beam scanning; widening spectrum width due to limited (non-infinitely narrow) breadth of the antenna beam; influence of the sounding waveform and antenna pattern; influence of wind; ambiguity of velocity measurement because of sounding waveform modulation; inertia of scatterers when evaluating turbulence parameters.

B. Polarimetric approach

Complete description of a radar target can be done with the help of eight numbers, which constitute the scattering matrix:

$$[S] = \begin{bmatrix} s_{HH} & s_{HV} \\ s_{VH} & s_{VV} \end{bmatrix}, \qquad (3)$$

where quantities s_{xy}, $x = H;V$, $y = H;V$ are in general complex with modulus S_{xy} and argument ψ_{xy}. In expression (3) indexes mean polarization of receive component of scattered signal (first one) and sounding wave (second one), say, H = horizontal and V = vertical. In general case any orthogonal polarization basis can be use.

Scattering matrix is individual for each object or a class of objects and provides a target signature. Perfect reflectors reflect waves in such a fashion that an incident wave with H polarization remains H, and an incident wave with V polarization remains V but is phase shifted 180º.

In reality it is difficult to measure absolute values of amplitudes and phases. That is why relative measurables are often used, for example, such values as S_{HH}/S_{VV}, S_{HY}/S_{VV}, $\psi_{HH} - \psi_{VV}$. For example, a typical polarimetric variable is differential reflectivity that is defined as

$$Z_{DR} = 10\log\frac{|s_{hh}|^2}{|s_{vv}|^2} \qquad (4)$$

and related with shape and orientation of a scatterer. For spherical scatterer Z_{DR}=0.

A number of other important polarimetric variables are known and used [2]. Polarimetric approach is attractive because it is associated with relative measurements and multi-parametric systems; it is very sensitive to the shape and orientation of scatterers and is able to provide the signature of a target. However, it does not give any information about target speed. Polarimetric approach can be implemented with conventional (non-coherent) radar. However, nowadays application of coherent radar with polarization diversity is not a rarity. The question is how to use the advantages of such radar by the best way.

C. Doppler-polarimetric approach

Operational Doppler radars with polarization diversity, more often, just dual-polarization Doppler radars, are normally able to provide users with standard Doppler and polarimetric information in different modes. In contrast to that, Doppler (spectral) polarimetry tries to answer a new interesting question about the behavior of polarimetric parameters in case of reflection from scatterers that are within the resolution volume but are moving with different velocities.

For example, in the radar system with linear orthogonal polarization, instead of differential reflectivity (4) in works [6], [8] the following function is used

$$sZ_{DR}(f) = 10\log\frac{S_{hh}(f)}{S_{vv}(f)}, \qquad (5)$$

that first was named 'specific differential reflectivity' [3] (in terms of frequency per unit), but later – spectral differential reflectivity [4]; it also can be named as spectral density of differential reflectivity [18].

A major improvement for understanding the microstructure of precipitation can be achieved by combining simultaneous Doppler and polarimetric information. Two power Doppler spectra, *hh* and *vv* must be measured simultaneously in order to obtain the Doppler velocity spectrum of Z_{DR}, that is, $sZ_{DR}(v)$. Thus, the spectral differential reflectivity is defined for each Doppler velocity. Figure 1 shows the results of calculation $sZ_{DR}(v)$ in rain at different intensity of turbulence that is given by eddy dissipation rate ε. Solid and dashed lines correspond to different parameters of the model, which can be tuned to different conditions of observations, parameters of radar and known parameters of the object under study (for example, rain intensity, wind speed, etc.). One can see that the slope (SLP) of the linear part of the $sZ_{DR}(v)$ curve depends on turbulence intensity. It is clearly seen from Fig. 2 where slope of the spectral differential reflectivity (SLP) and Doppler spectrum width are shown as functions of eddy dissipation rate. The behavior of curves is opposite and indicates that SLP is more sensitive than ΔV_{hh} relative to eddy dissipation rate. But the most important is the fact of independence of these two parameters between themselves.

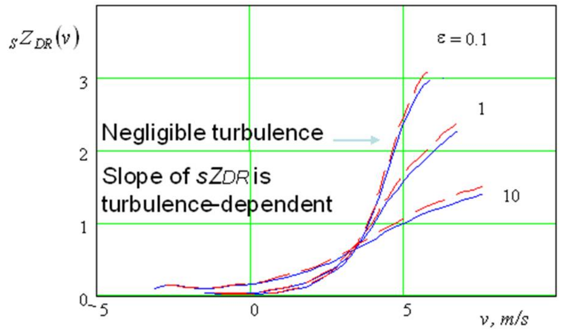

Fig. 1. Spectral differential reflectivity of raindrops as function of radial velocity at three values of intensity of turbulence (ε = 0.1; 1; 10 cm^2/s^3)

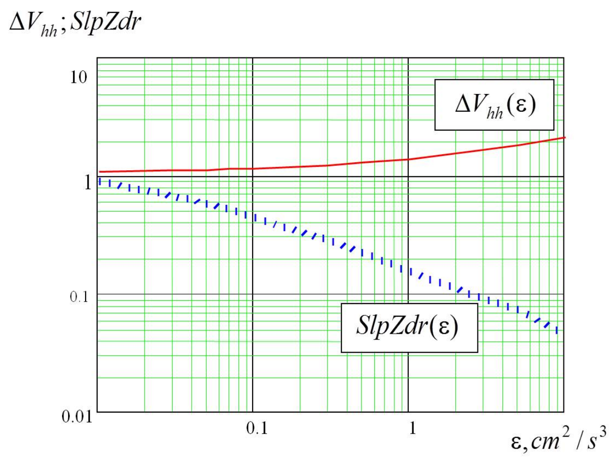

Fig. 2. Slope of spectral differential reflectivity *SlpZdr* and Doppler spectrum width ΔVhh at horizontal polarization as functions of turbulence intensity ε

A lot of other Doppler-polarimetric functions and parameters were proposed and studied, for example, spectral differential phase (or spectral density of differential phase) [5], [6], [16], spectral linear depolarization ratio [3], [19], spectral covariance matrix [20], spectral density of the copolar correlation coefficient [16], differential Doppler velocity [4], [9], etc.

An example of Doppler-polarimetric model application for data interpretation at remote sensing of rain is shown in Fig. 3.

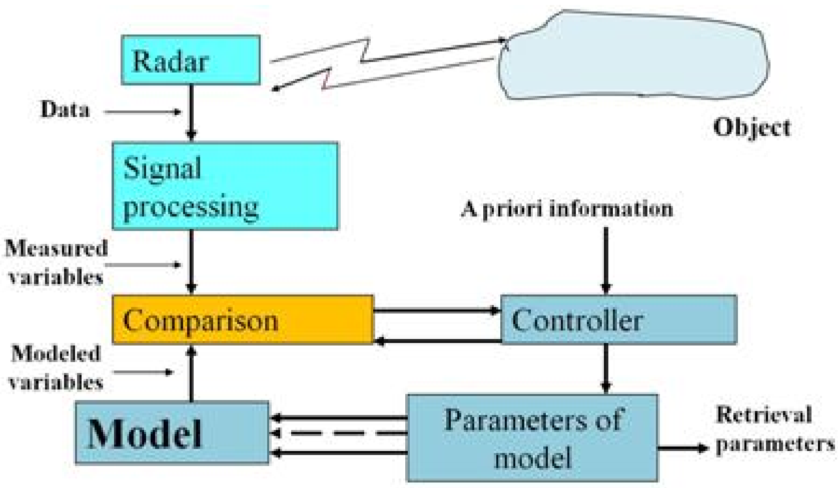

Fig. 3. Combining Modeling and Measuring at Remote Sensing of Rain

The phenomenological model takes into account different parameters of the object like dropsize distribution, turbulence, wind, etc. It also depends on known parameters of radar and conditions of observation. The data obtained at the output of the radar during object observation are processed to get the measured variables. The model, using a priori information and estimated data, produces modeled variables. The modeled variables are subjected to comparison with the results of measurement and the difference is used to control the parameters of the model. During such operation, the parameters of the model are adjusted to correspond to parameters of the real object under observation. Thus, parameters of the model can be used to retrieve the required parameters of the object.

Figure 4 represents the results of comparison modeled and measured data using results [8].

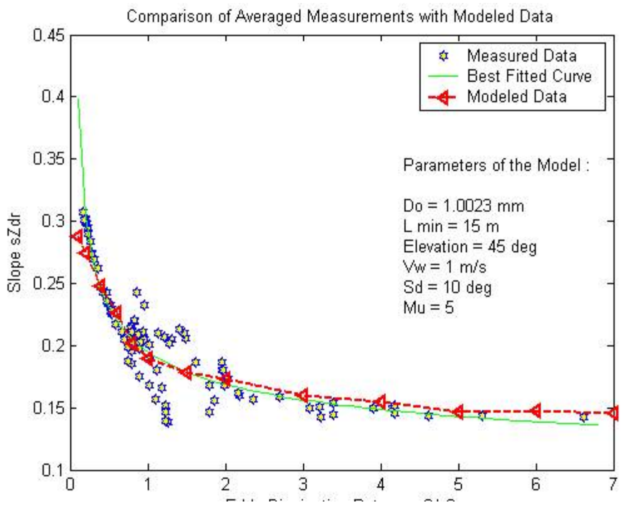

Fig. 4. Comparison of modeled and measured data of rain observation

The parameters of the adjusted model include median drop diameter D_0, shape parameter μ of the dropsize distribution, turbulence intensity ε, etc. Antenna elevation and parameters of the radar are known. One can see good correspondence of measured and modeled results.

It was shown that spectral polarimetric approach can be used for detailed measures of the microstructure of precipitation and melting layer zone [6], turbulence intensity estimation [8], [11], microstructure of rain determination [4], [11], [21], for retrieving winds and determination of scatterer types, separating birds and insects [18], recognition of hydrometeor type [22]. The main works carried out in this area are based on the use of microwave radar technology (*S*-band, *C*-band, *X*-band, and sometimes even mm-wave band).

Detailed theory was developed relatively Doppler-polarimetric sounding of rain [11]. However, successful experimental works are known for different tasks of atmosphere remote sensing.

IV. Generalization of the Spectral Polarimetric Approach

In this section we try to show that the spectral polarimetric approach is more general than the application of microwave Doppler-polarimetric radar remote sensing of the atmosphere considered above. It is reasonable to discuss the generality of the spectral-polarimetric approach, basing on the following characteristics:

– objects of study;

– methods of remote sensing;

– operational frequency-bands;

– physical meaning of the frequency in the spectrum;

– application areas.

A. Extension to other object of observation

First of all, note that it is logically to extend this approach not only to other meteorological objects, but also to any objects of research. Strictly speaking, the above problem of recognition between insects and birds [16], [18] (which are not really meteorological objects) in the atmosphere confirms that such an approach is effective for the detection of any objects having a complex shape and moving with different velocities.

B. Possibility to Use Different Methods of Remote Sensing

Doppler polarimetric meteorological radar uses active methods of sounding. However the spectral polarimetry is suitable not only for active, but also for semi-active and possibly passive systems of remote sensing. Semi-active we mean a system that receives the signal scattered by the observation object that is illuminated by outside source of artificial radiation, which is initially designed and used for other purpose. Passive systems are taking the natural radiation of the object of observation.

C. Extension to Wide Spectrum of Electromagnetic Radiation

For the spectral polarimetry is essential that the information carrier is characterized by a polarization capability. Therefore, it is clear that this approach is suitable for electromagnetic waves of any frequency-bands, including light. Unfortunately, it is not applicable to acoustic waves.

D. Interpretation of Frequency Spectrum

Especially interesting to note that in case of general spectral-polarimetric approach, in contrast to special case of Doppler, the spectral frequencies can characterize not only velocities of the scatterers (that is characteristic for Doppler polarimetry), but very different properties of the object of study, for example, the chemical composition of substances, through which the radiation. Therefore, the interpretation of analysis results and their physical meaning can be completely different, unconnected with velocities of the scatterers.

E. Interpretation of Frequency Spectrum

Application areas of spectral-polarimetric approach to remote sensing are extremely diverse. Even if you only rely on the results of Doppler-polarimetric radar, it can be argued that these results are important for aviation, meteorology, climatology, hydrology and agriculture. They are useful for communications, radar and navigation, as they allow to diagnose the state of the atmosphere especially the conditions of propagation, as well as for radar target detection in clouds and precipitation. Astronomy and astrophysics [23] is a separate interesting area of spectral-polarimetric method application.

The phenomenon known as planetshine occurs when reflected sunlight from a planet illuminates the night side of one of its moons. Typically, this results in the moon's night side being bathed in a soft, faint light. The best known example of planetshine is earthshine, which can be seen from Earth when the Moon is a thin crescent because the Moon is illuminated not only by the Sun light directly but also by the light reflected from the Earth that illuminates slightly the shadowy side of the Moon. Related with this phenomenon, a very illustrative example of the use of spectral polarimetry in astrophysics to search for life in the universe was recently published in 'Nature' journal [24]. After reflection from the Earth the colors in the light are significantly changed. By observing earthshine astronomers can study the properties of light reflected from the Earth as if it were an exoplanet and search for signs of life. The reflected light is also strongly polarized in contrast with Sun light. Studying the polarization as well as the spectrum, that is, the intensity at different colors allows for much more sensitive tests for the presence of life.

In the atmosphere of a planet, the main biologically produced gases are oxygen, ozone, methane and carbon dioxide. But these can all occur naturally in a planet's atmosphere without the presence of life. What constitutes a biosignature is the simultaneous presence of these gases in quantities that are only compatible with the presence of life [24]. If life were suddenly to disappear and no longer continuously replenish these gases they would react and recombine. Some would quickly disappear and the characteristic biosignatures would disappear with them.

This example provides the highest generalization level of spectral polarimetry.

V. CONCLUSION

A new generalized method of remote sensing that combines spectral and polarimetric features of signals received from distant objects and phenomena has been described. It has been shown that, producing spectral analysis of polarimetric variables, it is possible to derive important information about properties of distant objects and phenomena. The detailed theory was developed for the case of rain observation, however generalization for other objects has been done, and some examples of spectral polarimetric approach application in very different fields has been presented.

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Ф. Й. Яновський. Спектрально-поляриметричний підхід до дистанційного зондування природних об'єктів і явищ

Представлено новий підхід до дистанційного зондування, який поєднує поляризаційні та спектральні особливості сигналів, що приймаються від віддалених об'єктів, з використанням спектрального аналізу поляризаційних

змінних. Докладну теорію розроблено для випадку зондування дощу активним моностатичним радіолокатором. Виконано узагальнення для інших об’єктів і методів. Представлено деякі приклади застосування спектрального поляриметричного підходу у різних областях.
Ключові слова: радіолокація; дистанційне зондування; доплерівська поляриметрія; спектральна поляріметрія; природні цілі.

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Напрямки наукової діяльності: радіолокація, дистанційне зондування, обробка сигналів, адаптивні вимірювання, електрика атмосфери.
Кількість публікацій: понад 500, включаючи 10 книг і 40 винаходів.
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Ф. И. Яновский. Спектрально-поляриметрический подход к дистанционному зондированию естественных объектов и явлений

Представлен новый подход к дистанционному зондированию, который сочетает поляризационные и спектральные особенности сигналов, принимаемых от удаленных объектов, с применением спектрального анализа поляризационных переменных. Детальная теория разработана для случая зондирования дождя активнымо моностатическим радиолокатором. Сделано обобщение для других объектов и методов. Представлены некоторые примеры применения спектрального поляриметрического подхода в различных областях.
Ключевые слова: радиолокация; дистанционное зондирование; доплеровская поляриметрия; спектральная поляриметрия; естественные цели.

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Направления научной деятельности: радиолокация, дистанционное зондирование, обработка сигналов, адаптивные измерения, электричество атмосферы.
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