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Retrieving Information about Remote Objects from Received Signals

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***Abstract*—This paper considers generalized coherent-polarimetric method of retrieving information about remote objects using electromagnetic waves. Both active and passive electronic systems as well as different objects under observation, operating frequency bands, and physical meaning (interpretation) of the frequency as spectral argument can be used. As an example, retrieving information about turbulence using microwave weather radar is considered.**

Keywords—coherent polarimetry, radar, remote sensing, signal processing, meteorological radar

I. Introduction

Suppose that it is necessary to carry out the task of research a certain object or system that is part of the natural or artificial real world. In this formulation, the term "research" means the creation of some mathematical models that improve our understanding of the object under study, allow us to make predictions about its future state or behavior, and in some cases can provide information for managing this object. The research process can be implemented by collecting data, entering this data into a mathematical model, analyzing the model to adjust the data collection procedure, including conducting experiments on the object, if possible. The problem becomes much more complicated if the object is located at a considerable distance, is not available for direct physical contact, and the researcher does not have the ability to change the state of the object under study in a controlled manner. The situation turns out to be not so hopeless, since for specific objects and situations it is possible to build an individual phenomenological model for estimating informative parameters that can be estimated with a certain accuracy from the results of experimental observations.

This paper generalizes the results published earlier [1-8] and proves such generalization using some special examples.

Doppler-polarimetric remote sensing has been the subject of a huge number of works, but setting priorities for certain issues is not the purpose of the article. Therefore, quoting the works of our team is done only for the purpose of contacting, if necessary, to obtain more detailed information. In these cited works there are necessary references to the works of other authors, especially priority ones.

After considering the motivation of the coherent-polarimetric method for remote sensing, the theoretical study, modeling & computer simulation, and then experimental study are done. Coherent-polarimetric tools for detection and recognition of natural and artificial objects and phenomena are discussed. Then concluding remarks are done.

II. Theoretical Study

Let us focus onto the radar polarimetric informative parameters, which carry information about the features of forming the electromagnetic signal. In particular, polarization of the reflected signal is associated with the shape and spatial orientation of the object, or a scatterer in the case of active radar. In case of dual polarization radar, four combinations of signal polarization components of transmit and receive are possible: transmitted horizontal, received horizontal HH; transmitted horizontal, received vertical HV; transmitted vertical, received vertical VV; transmitted vertical, received horizontal VH.

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 spectral-polarimetric parameter is the Doppler frequency, associated with the radial velocity of the scatterers corresponding to their shape and orientation.

Application of microwave Doppler-polarimetric radar for remote sensing of the atmosphere is known as Doppler Polarimetry. It is a combination of the Doppler approach and Polarimetric approach [1, 2]. By saying 'Doppler' one normally means that physical interpretation of a frequency shift or an argument in Doppler spectrum is a velocity.

The question arises: how to improve or enhance the notion of Doppler-polarimetry and expand its practical application? In this paper it is shown that by answering this question we arrive at the concept of spectral polarimetry.

Let us recollect initial basic notions first.

A. Doppler Spectrum

Doppler spectrum $S(*)$ is a power spectrum of complex signal that is expressed as function of Doppler frequency f or velocity v. This spectrum $S(v)$ is interpreted as reflectivity

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weighted distribution of radial velocities of scatterers in a resolution volume. Value $S(v)\,dv$ means received power in the velocity interval dv. Doppler spectrum is normalized as

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

where $\bar{P}_{Rx} = (C/R^2)\cdot Z \cdot |K|^2$ is average reflected power from a resolution volume filled with scatterers (hydrometeors) that depends on the reflectivity factor *Z*, slant range *R*, radar parameters *C*, and the state of aggregation of hydrometeor matter $|K|^2$.

Doppler spectrum model $S_v(v)$ can be represented as

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

where $p_p(v/D)$ is conditional probability distribution of scatterer radial velocity, $\sigma(D)$ is RCS of a scatterer, $N(D)$ is scatterer size distribution, and integration over all sizes from minimum to maximum.

This model later is compared with an estimation, which is obtained by Fourier transform over the received signal $\hat{S}_v(v)$. Normally three parameters of Doppler spectrum are more often used in meteorological practice, in particular, zero moment $\int_{-\infty}^{\infty} S_v(v)dv = Z$, first ordinary moment $(1/Z)\int_{-\infty}^{\infty} vS_v(v)dv = \bar{v}$, and second central moment $(1/Z)\int_{-\infty}^{\infty} (v-\bar{v})^2 S_v(v)dv = \sigma_v^2$, that is, reflectivity Z, mean velocity $\bar{v}$, and velocity variance σ_v^2 correspondingly.

B. Polarimetric Approach

While Doppler approach gives a possibility to get information related with radial velocities of scatterers, the polarimetric approach allows to feel the differences in the shape and orientation of scatterers.

As an example, the most common polarimetric parameter, which is differential reflectivity *ZDR*=10*log*(Z_{hh}/Z_{vv}), can be considered for the case of rain. Small raindrops are practically spherical, so ratio of reflectivity at horizontal Z_{hh} and vertical Z_{vv} polarization is unity, that is, *ZDR* equals (or is very close) to zero. Lager droplets are more oblate in vertical plane during falling down, so *ZDR*>0 dB, and for the largest drops *ZDR*>>0 dB. From this example one can see that *ZDR* is a measure of the mean shape of scatterers.

There are many other polarimetric parameters (measurable variables) like linear depolarization ratio, cross-correlation coefficient between signals at orthogonal polarizations at zero-time shift, specific differential phase that opens wide possibilities to derive information about the object under study. In application to hydrometeors, it is obvious because they may have very different and specific shapes as is shown in Fig. 1 for hailstones (after partial melting during falling down), water droplets, which are more oblate in case of larger size, snowflakes, and ice crystals.

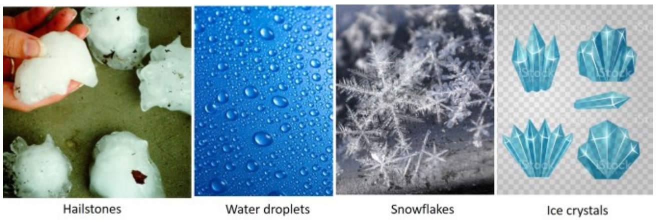

Fig. 1. Hydrometeors of different shapes

C. Spectral-polarimetry

Polarimetric measurable variables are integral parameters over the all scatterers in the resolution volume. Individual scatterers cannot be resolved by their location inside the resolution volume. However, one can try to analyze the density of any polarimetric parameter over the its Doppler frequency components, more generally, the spectral density of a polarimetric parameter.

Thus, we arrive at the notion of spectral polarimetric characteristics. It can answer, for example, the question: what is the behavior of polarimetric parameters for different groups of scatterers that are characterized by different radial velocities? Such spectral characteristics are called bellow spectral polarimetric parameters. For example, spectral differential reflectivity is obtained as ratio of spectra at orthogonal polarizations instead of the ratio of reflectivity factors or powers or squares of co-polarized members of scattering matrix of the reflected signal. Such a transition from integral parameters to their spectra can be done also for other polarimetric parameters.

III. Modeling and Simulation

Objectives of math modelling in the context of this paper are to relate coherent - polarimetric parameters of the signal with wanted characteristics of the object under study. It is obvious that different parameter and characteristics can be interested, and should be used, depending on the particular scenario.

As an example, it is reasonable to consider a comparatively simple object under observation. Let us take it from atmosphere precipitation. There are many kinds of precipitation. The simplest, better to say the most completely mathematically described one, of these objects, is rain. Rain of given intensity (rain rate) looks like a simple enough object suitable for computer modeling. Thus, the purpose of the simulation is to relate Doppler-polarimetric observables with rain parameters for further data interpretation. It is good to underline that the models for different types of precipitation would be different depending on the type of scatterers and scenarios.

As the result of the modeling, it should be at least components of scattering matrix $S_{hh}(v)$, $S_{vv}(v)$, $S_{hv}(v)$, $S_{vh}(v)$, which contains full information and from which it is possible to calculate all polarimetric parameters indicated above.

The approach to the modelling in case of rain is described in [1] and [2]. The general model contains partial models of: 1) turbulence, 2) drop size distribution, 3) drop diameter – drop shape, 4) drop diameter – drop fall velocity, 5) inertia of drops, and 6) conditions of sounding. Application of these models gives initial information for the models of probability distribution of radial drop velocities caused by different factors (drop fall velocity, turbulent velocity, wind).

Then, combination of the conditional probability density distribution of velocity with RCS (which depends on drop size, polarization and other factors) and drop size distribution according formula (2) allows calculating Doppler spectra at different combinations of polarization on transmit and receive.

Examples of Doppler spectra calculated using developed software are shown in Fig. 2.

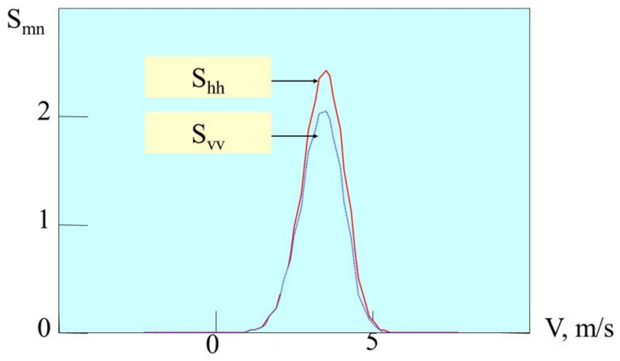

Fig. 2. Modeled Doppler spectra of reflections from rain at horizontal and vertical polarizations

Ratio of co-polar Doppler spectra (horizontal to vertical) in dB gives spectral differential reflectivity *Zdr*(*v*) and ratio of cross-polarized Doppler spectrum to Doppler spectrum at principal polarization (in dB) gives linear depolarization ratio *Ldr*(*v*). Examples of calculations these Doppler-polarimetric parameters using the model and corresponding software are shown in Fig. 2 at different intensity of turbulence in the rain zone expressed by its eddy dissipation rate ε.

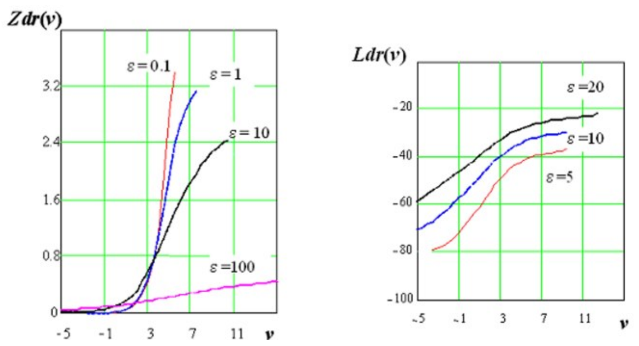

Fig. 3. Modeled spectral differential reflectivity and spectral linear depolarization ratio

One can see that the more turbulence intensity the less steepness of the *Zdr*(*v*)=*sZdr* curves. The dependence of *Ldr*(*v*) on the turbulence is also obvious but *Ldr*(*v*) looks like a very small value to be effectively used in practices.

IV. Experimental Study

Experiments were done with fully polarimetric coherent radars (DARR, TARA and PARSAX) in the Delft University of Technology [1, 2] and in NOAA's National Severe Storms Laboratory [7]. They demonstrate fruitfulness of such approach. However, the modeled smoothness of curves in Fig. 2 is confirmed only after averaging. Just as an example, in Fig. 4, non-averaged measured *sZdr* curve is presented. Numerous measurements confirmed the relationship between the slope of the smoothed *sZdr* and turbulence intensity.

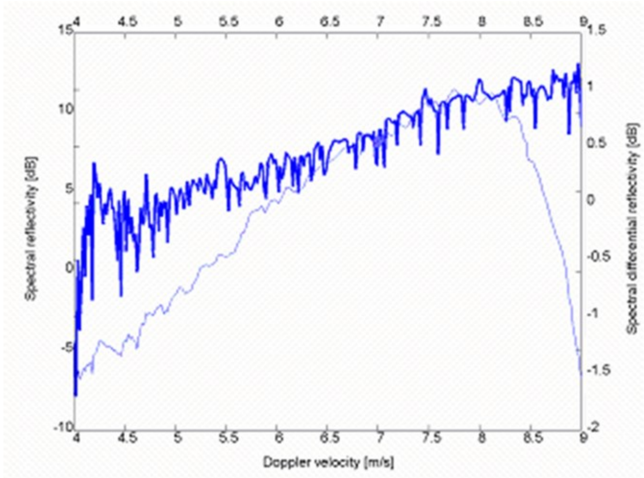

Fig. 4. Non-averaged measured spectral differential reflectivity *sZdr* and the corresponding main part of Doppler spectrum

Thus, Doppler polarimetric approach was developed first for atmospheric radar, when variability of frequencies in the spectrum of the signal reflected from hydrometeors is interpreted as caused by the diversity of hydrometeors' velocities. However more generally such approach is named as spectral-polarimetric [9]. In the next section the generality of the spectral-polarimetric approach is considered.

V. Coherent-Polarimetric Tools for Detection and Recognition of Natural and Artificial Objects

Talking about the generalization, we discuss coherent-polarimetric radar means as the tools for detection and recognition of a variety of natural and artificial objects and phenomena as objects under observation. But such a generalization is not limited to the variety of objects under observation. It is appropriate to point out by what signs we can justify a rather large generality, and therefore the directions of further development of such an approach.

A. Directions and signs of generalization

Taking into account that Doppler-polarimetric approach has been developed for meteorological radar and the majority of measurements were fulfilled with S-band and X-band active radar systems, the generalization of the spectral-polarimetric approach is reasonable to substantiate over the following signs:

1) diversity of hydrometeor types;
2) diversity of the objects under observation;
3) diversity of the methods used for object observation;
4) variaty of operating frequency bands;
5) different interpretations of physical meaning of the frequency shift as the argument of signal spectral density;
6) different practical applications.

Let us consider the features of these five signs in more details.

B. Diversity of hydrometeor types

First of all, it is reasonable to consider other meteorological objects in addition to the rain, which has been modeled and researched in detail. The math and computer models can be developed for different meteorological objects. For example, in addition to raindrops, we have developed models for particles of complex structure [6], in particular those contained water-air-ice mixture (Fig. 5).

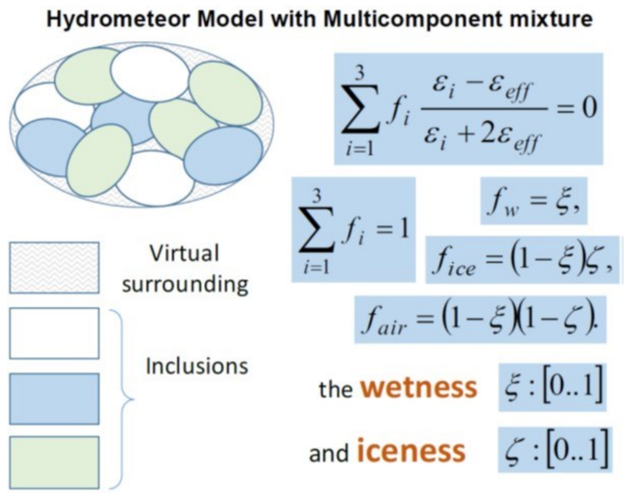

Fig. 5. Hydrometeor model as a mixture of three component: water, air and ice on the background of virtual surrounding

A hydrometeor is modeled as a mixture of three types of inclusions (water, air and ice) in different amounts each. This is described mathematically using value f_i, $i = 1$, 2 or 3 that corresponds f_w, f_{ice}, f_{air}, that is water, ice, air; and introduced values of wetness ξ:[0..1] and iceness ζ:[0..1], more exactly, their relation, define what kind of hydrometeor is it: from waterdrops through wet snow and snowflakes to dry ice crystals.

Using this approach, we modernized the model, described in section III, and the calculations of *sZdr* and *slope sZdr* at different wetness, iceness, and Eddy Dissipation Rate ε, indicated as EDR were done. Some results are shown in Fig. 6.

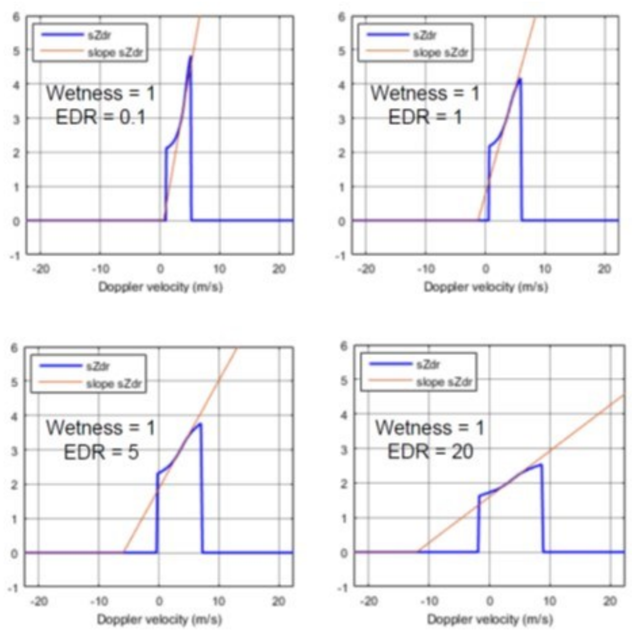

Fig. 6. Spectral differential reflectivity *sZdr* and *Slope sZdr* calculated using modernized model with mukticomponent mixture

The calculations have shown that characteristic influence of turbulence on the slope of the spectral differential reflectivity is saved also in the case of hydrometeors other than raindrops, although it is manifested less clearly than for pure waterdrops [6].

C. Diversity of the objects under observation

It is logically to suppose that coherent-polarimetric approach is applicable not only to different weather objects, but also to any real objects of observations. It can be used to solve a problem of object recognition. As an example, in the work [7], similar approach has been used to solve a task of distinction between insects and birds in the atmosphere. This positive result confirms that spectral polarimetry can be effective for detection of any objects having a complex shape and moving with different velocities.

Of course, there are no doubt that the spectral polarimetric approach is applicable to both natural and artificial objects.

D. Variaty of operating frequency bands

Application of spectral polarimetric approach requires two basic properties from the carrier radiation: it should be a kind of wave process able for propagation with the ability to be polarized. Particularly, the polarization is essential for polarimetric approach supposing that any changeable process can be analyzed using its spectrum. Frequency in principle is not critical if polarization is still applicable. So, electromagnetic waves of any frequency band, including infrared, visible light, and ultraviolet radiation can be used. In contrast to acoustic or hydroacoustic waves which are not subjected to polarization.

E. Different methods of remote sensing

Doppler-polarimetric weather radars, which were used for doing measurements in the atmosphere [1, 2, 7] implemented active radar principle, when radar system is equipped with a transmitter, which generates a sounding waveform, and a receiver, which detects and processes the reflected signal (a primary radar principle).

However, one can suppose that the spectral polarimetry can be applied also in the semi-active radar, which does not have its own transmitter and uses some outer radiation from the third object (artificial or natural) that illuminates the object under study. Then the receiving channel of the system detects and analyzes this radiation after it was reflected from the object of observation. As examples of sources of such outer radiation we can name: TV stations, GPS transmitters, Sun, etc.

Moreover, there are no principal limitations to use also classical passive remote sensing systems, which use the self-radiation generated by the object under observation itself, with application the spectral polarimetric approach.

An example of spectral-polarimetric passive (or semi-active) remote sensing in astrophysics is discussed below when considering physical meaning of the frequency as the argument of the spectrum.

F. Different interpretations of physical meaning of the frequency shift as the argument of signal spectral density

Radio engineers know exactly that frequency in a signal spectrum can be changed due to some non-linear transformation or due to Doppler phenomena caused by a mutual movement transmitter and receiver (or a reflecting object which play role of both receiver and transmitter). However, chemists use spectral analysis to understand the composition of substances. Frequencies can meet not only Doppler velocities, but they can characterize completely different properties of the object under study.

If polarized electromagnetic radiation propagates in a medium, for example, a composition of gases, the spectrum of the radiation will contain frequency components that are characteristic for the gases constituting the medium.

According to [8], the spectral polarimetric approach is suitable in astrophysics to analyze the earthshine for searching life in the universe. They use a phenomenon known as a 'planetshine', which occurs when the light from the star, such as sunlight reflected from the planet, illuminates a night side of its satellite.

Fig. 7. The Moon illuminated by the Sun directly (Sunshine) and by the reflected sunlight from the Earth (Earthshine)

The scheme of this phenomenon is shown in Fig. 8, where the Sun is located right-hand. After the reflection from the Earth the spectrum of the sunlight is changed that is shown in the picture by colors: they are significantly changed.

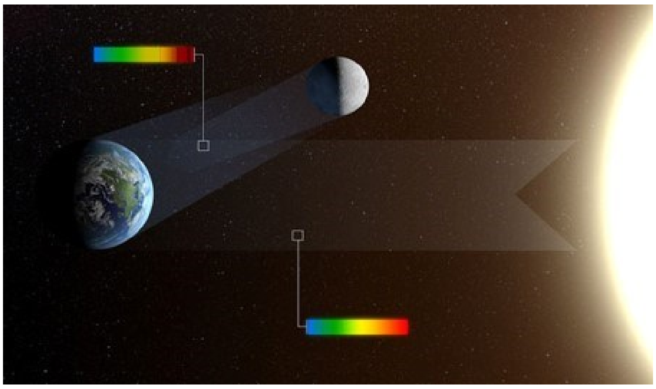

Fig. 8. Moon shining in reflected light from the Earth

Polarization also plays important role here. Initially, the sunlight is not polarized. However the reflected from the Earth sunlight becomes strongly polarized as a result of passing through the atmosphere.

It turns out that by studying the changes in the spectrum and in the polarization is a rather sensitive tests for the presence of life on a planet [8]. It should be explained in more detail.

Why studying such spectral polarimetric data is useful for searching life in the universe? This is because by observing the earthshine, researchers can study the properties of light reflected from the Earth as if it were an exoplanet.

The fact is that in the presence of life on the planet (first of all, we are talking about plant life) certain gases are formed in the planet atmosphere as a result of biological processes. Such biologically generated gases are mainly oxygen, ozone, methane and carbon dioxide. Is this really a reliable sign of life? It turns out not, because the same gases can be formed naturally and without the participation of living objects. A reliable biological sign of the presence of life (biosignature) is the simultaneous presence of these gases in well-defined proportions that are compatible only with the presence of life [8]. If life on the Earth suddenly disappeared (including plants), then the replenishment of these gases in the atmosphere would cease. Then the processes of recombination would begin, some gases would quickly disappear, which means that the characteristic signs of life (biosignatures) would also disappear.

Astrophysicists can try to detect such biosignatures in the universe and use them as a tool of searching signs of life on exoplanets.

This example clearly shows that spectral polarimetry can be used to obtain a variety of information about completely different objects of observation. And this is actually quite a high level of generalization of this approach to remote sensing.

G. Different practical applications

The spectral-polarimetric approach to remote sensing can be successfully applied in almost many areas. Obviously, even just meteorological applications can be quite varied and fruitful.

The information being received is necessary to ensure aviation safety. Further development of radio meteorological facilities can be provided. This will provide useful information for meteorology, climatology, hydrology and agriculture. They are useful for communications, radar and navigation, as they allow diagnosing the state of the atmosphere, especially propagation conditions.

Moreover, data obtained can be used as a priori information for effective radar detection of targets in clouds and precipitation. A separate interesting field of application of the spectral-polarimetric method is astronomy and astrophysics.

This method can make a new contribution to further development of microwaves for many applications [10].

V. CONCLUSION

The remote sensing method, which uses combining the joint analysis of the spectral and polarimetric properties of signals received from remote objects and phenomena, has been discussed in this paper.

The demonstration of possibility to get important and various information about the properties of remote objects and phenomena has been provided on specific examples by performing a spectral analysis of polarimetric measurands.

Although the theory has been developed in detail for the case of precipitation surveillance, however, the generality of the proposed approach has been shown relative to many other objects and phenomena as objects of observation. Moreover, some examples of practical application of the developed spectral-polarimetric approach in various areas of human activity have been presented.

Spectral polarimetry is a promising method of remote sensing with its specific and sophisticated and sometimes complicated signal processing to obtain information about different remote objects and phenomena.

Theory and mathematical models have been demonstrated for the case of rain observations and also for multicomponent hydrometeors.

Similar approach can be developed, adopted and used for variety of other cases, conditions, methods, and applications.

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