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MULTI POLARIZATION MEASUREMENTS AND ESTIMATION OF REFLECTED SIGNAL MAGNITUDE VARIATIONS CAUSED BY TURBULENCE

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Abstract

The aim of this paper is the development of new polarization approach to evaluate the impact of dynamic atmosphere phenomena including turbulence into reflected radar. In this paper the liquid hydrometeors (raindrops) are considered as objects with unstable shape. Therefore, parameters of liquid hydrometeors are *random characteristics that are susceptible to dynamic atmospheric phenomena influence. The expressions for the electromagnetic field scattered by liquid hydrometeors for the multi polarization radar system as well as a variable component of scattered field are obtained. The expression of phase detection for separation of turbulence from other factors that cause the reflected signal variation is obtained. Calculation of the relation between the average signal value and the vibrations magnitude in decibels was made to demonstrate the possibility to fix the reflected electromagnetic wave energy variation caused by wind and turbulence. The results of the paper can be used for segregation of reflected signal magnitude variation due to the wind related phenomena including turbulence and other factors.*

Keywords: hydrometeor; meteorological radar; polarimetry; turbulence

1. The problem statement and analysis of the research and publications

Flight operation, economy, regularity, and safety depend on atmospheric conditions and phenomena significantly [1]. Nowadays information for flight planning consists of actual aerodrome weather and the set of prognoses including aerodrome forecast, takeoff and landing forecasts, prognostic charts for different flight levels. Actual information can be presented as well in aviation warnings that are composed on the base of pilot's observations or have prognostic character. But the atmosphere is very dynamic medium. The processes in it are constantly changes as well as location, intensity, and character of atmospheric phenomena. Therefore, it is crucial to have operational information about atmospheric dangerous phenomena along the flight route.

Dangerous for flight atmospheric phenomena are aircraft icing, atmospheric turbulence, wind shear, thunderstorm. A thunderstorm is complex atmospheric phenomena and usually is associated with strong up- and downdraughts, turbulence, wind shears, icing above zero isotherm and hail.

Since the middle of 20th century, the meteorological radars have become the main tools for atmospheric processes and phenomena watching and study [2]. Nowadays meteorological radars are widely used in aviation to obtain operational information about weather situation and dangerous atmospheric phenomena that mostly include significant clouds, strong precipitation, and thunderstorm activity. During the last decades the meteorological radars have evolved and now Doppler and even combined Doppler and Polarimetric radar systems are used [2]. Doppler radars allow obtaining information about a radial component of wind vector. Polarimetry is used to make weather object microstructure identification [2, 3]. The research in the field of radar meteorology hasshown the progress in the development of Doppler and Polarimetric algorithms and signal processing. The latest studies demonstrated the ability of modern radars to obtain information about icing-in-flight, turbulence, ash cloud presence

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[4 - 6]. In these papers information about wind related phenomena is extracted using the Doppler methods. But in the paper [7, 8] it was shown that taking into account physics of atmosphere and hydrometeors behavior under the wind phenomena effect it is reasonable to use polarimetric method additionally to Doppler for deeper analysis of wind related phenomena.

The aim of this paper is the development of new polarization approach to evaluate the impact of dynamic atmosphere phenomena including turbulence into reflected radar.

2. Liquid hydrometeors as the objects with unstable shape

It is shown in [9] that the drop that is in the air flow vibrates constantly. This fact allows us to consider the drops as the objects with the unstable or changeable shape. The drop vibrations are revealed in the drop-spheroid axes fluctuations. These fluctuations include the important information about the drop behavior, structure, and characteristics. The vibration character is provided by the object characteristics and the object interaction with the surrounding medium. The medium characteristics are the dynamic atmospheric phenomena as well – wind, turbulence, and others.

It is shown and substantiated in [9, 10] that liquid hydrometeor shape parameters are not fixed characteristics [7] and can be considered as the random characteristics. The wind or other atmospheric dynamic phenomena influence on the random process of drop vibration can be observed as the variations of frequency, polarization or amplitude of the reflected electromagnetic wave.

3.Calculation of the field scattered by liquid hydrometeors

Let us consider the case with a single sounding antenna with polarization angle δ_i and multiple receiving antennas with the set of polarization angles $\{\delta_{r_k}\}$. The operation of the multi polarization radar system is depicted in [11]. Let us make a mathematical analysis of the field scattered by liquid hydrometeors for the multipolarization system. In order to simplify the analysis, we selected the zero azimuthal and elevation angles. The direction of y axis is the same as the sounding direction, z axis directed to the zenith, and x axis is perpendicular to the both previous. According to [10], we can write the following expressions for the x- and z-components of scattered by rain-drop field:

$$E_x = E_x^{sph}\left[1 + 0.4\frac{\varepsilon - 1}{\varepsilon + 2}\rho(t)\right],$$

$$E_z = E_z^{sph}\left[1 - 0.8\frac{\varepsilon - 1}{\varepsilon + 2}\rho(t)\right].$$

Here:

$$E_x^{sph} = E^{sph}\sin\delta_i,$$

$$E_z^{sph} = E^{sph}\cos\delta_i,$$

$$E^{sph} = E_0\frac{D^3}{8}\frac{\varepsilon - 1}{\varepsilon + 2}\cos[\omega_0 t + 2k_o r(t)],$$

$$\rho(t) = \rho_0 + \Delta\rho\cos[\Omega t + \varphi],$$

D - equivalent spherical rain-drop of the same volume diameter,

ε - relative dielectric permittivity of water,

ω_0 - sounding angular frequency,

k_0 - sounding wave number,

$r(t)$ - rain-drop radius-vector projection to the sounding direction,

ρ - rain-drop form factor that is equal to the ratio between the vertical and horizontal rain-drop sizes,

ρ_0 - mean rain-drop form factor,

$\Delta\rho$ - magnitude of form factor variation,

Ω and φ - angular frequency and the initial phase of rain-drop vibration, respectively.

The scattered field received by k-th antenna can be expressed as:

$$E_k = E_x\sin\delta_{r_k} + E_z\cos\delta_{r_k},$$

Using above expressions for the E_x and E_z, we can obtain the following:

$$\begin{aligned} E_k = E^{sph}\Big[&\cos(\delta_{r_k} - \delta_i) - \\ &- \frac{\rho(t)}{2}\left\{\cos(\delta_{r_k} - \delta_i) + 3\cos(\delta_{r_k} + \delta_i)\right\}\Big] = \\ &= E^{sph}\left[A_0(\delta_i, \delta_{r_k}) - \rho(t)A_1(\delta_i, \delta_{r_k})\right] \end{aligned} \quad (1)$$

The dependencies of polarization coefficients $A_1(\delta_i, \delta_{r_k})$ and $A_0(\delta_i, \delta_{r_k})$ on sounding and receiving antennas polarization angles are shown in [11]. As it can be seen from equation (1), there is the single combination of incident and receiving antennas polarization angles both equal to about the 54.7^0, that give the response the same as from spherical rain-drop of the corresponding volume. This is in agreement with the [10].

The atmospheric dynamic phenomena cause the deformation of liquid hydrometeors. The deformation is revealed in a change of linear sizes of drops. The reflection from deformed hydrometeors, in turn, change the polarization of incident radar signal such a way that the maximum energy level of received radar signal corresponds to the case when the polarization of the reflected signal coincides with the polarization of the sounding waveform. Otherwise, the energy level is defined as the projection of the electric field strength vector on the main axis of the corresponding antenna pattern. Turbulence is the presence of chaotic vortices that affect the drops axes randomly and causes the drop vibration. This vibration resulted in the appearance of the variable component of the scattered field.

To obtain information about a variable component of the scattered field, we need to consider the situation with a zeroth $A_0(\delta_i, \delta_{r_k})$ coefficient. So, the polarization angle of receiving antenna should be at 90^0 greater than the one of thesounding antenna. In this case, we can write the following expression for the "vibration component" of scattered field:

$$E_k\Big|_{\delta_{r_k}=\frac{\pi}{2}+\delta_i} = E^{sph}\left[\rho(t)\{3\sin(\delta_i)\cos(\delta_i)\}\right] = \\ = E^{sph}\rho(t)A_{vib}(\delta_i).$$

In a real situation, the radar signal is reflected from hydrometeor assemble that consists of many drops of different sizes. For multiple drops, under single scattering assumption, the magnitude of electric field component at the receiver side can be represented by the following expression:

$$E_k = \sum_{n=1}^{N} E_n^{sph}\left[A_0(\delta_i, \delta_{r_k}) - \right. \\ \left. - A_1(\delta_i, \delta_{r_k})\{\rho_{0n} + \Delta\rho_n \cos[\Omega_n t + \varphi_n]\}\right],$$

where the n index corresponds to the n-th drop, E_n^{sph} accounts for the raindrop Doppler shift frequency ω_n.

There are some different factors in nature that can cause drops vibration and shape deformation. It is important to separate the factors for the task of dangerous phenomena detection. Atmospheric turbulence can be separated from other factors that cause the drops vibration taking into account the frequency characteristics of the turbulence [11]. Following the turbulence frequency characteristics that can be found in the lower part of the frequency spectrum, we use the phase detection for separation turbulence from other factors that cause the reflected signal variation. The following dependence of output detector signal can be written as:

$$U_k = \sum_{n=1}^{N}\left|E_n^{sph}\right|\left[A_0(\delta_i, \delta_{r_k}) - \right. \\ \left. - A_1(\delta_i, \delta_{r_k})\rho_{0n}\right]\cos(\omega_n t + \psi_n) + \\ + \frac{1}{2}A_1(\delta_i, \delta_{r_k})\sum_{n=1}^{N}\left|E_n^{sph}\right|\Delta\rho_n\{\cos[(\omega_n + \Omega_n)t + \\ + \psi_n + \varphi_n] + \cos[(\omega_n - \Omega_n)t + \psi_n - \varphi_n]\}$$

4. Simulation results and analysis

The computer model of the reflections from the liquid hydrometeors that are deformed and vibrate due to the turbulence influence was developed in Simulink. Receiving antenna polarizations were taken with 15^0 interval: 54.7^0, 69.7^0, 84.7^0, 99.7^0, 114.7^0, 129.7^0, and 144.7^0 .

In this paper, we show the simulation results for drops 2 and 4 mm to compare and demonstrate the turbulence impact.

In Figure 1 the redistribution of power received by the antennas of polarimetric radar is shown. These results are for hydrometeor ansemble of 2 mm.

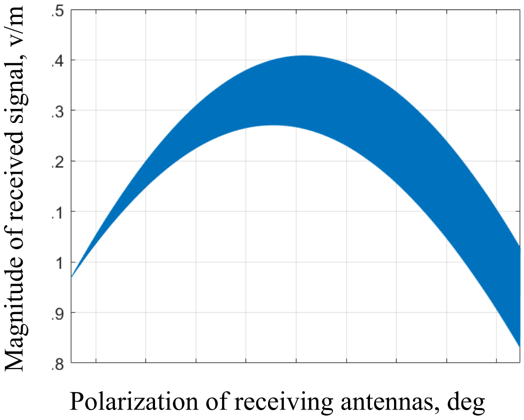

Fig.1. Envelope of signal at receiving antenna after phase detector

The increase in energy is observed at the antennas with polarization about 45 degree difference from the principle polarization, then we observe the decrease in the energy level.

The sizes of the drops are quite large to give significant magnitude variations. In the considered simulated situation this variations are in the limits 0.84-1.4.

The change in „width” of the curve demonstrates the impact of drop vibration in the reflected signal. The wider curve is the more impact of drop vibration in the reflected signal is. The maximum of impact corresponds to the 144.7^0-polarized receiving antenna (polarization of the sounding wave is 54.7^0).

In figure 2 the relation between the average signal value and the vibrations magnitude in decibels for drops 2 mm is shown.

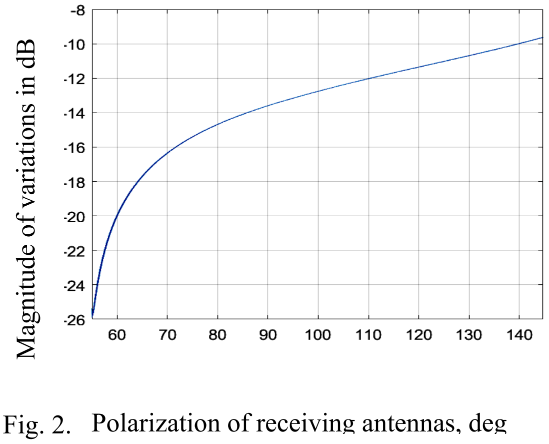

Fig. 2. he vibrations magnitude

The same results for the drops with diameter 4mm are shown in figure 3 and 4.

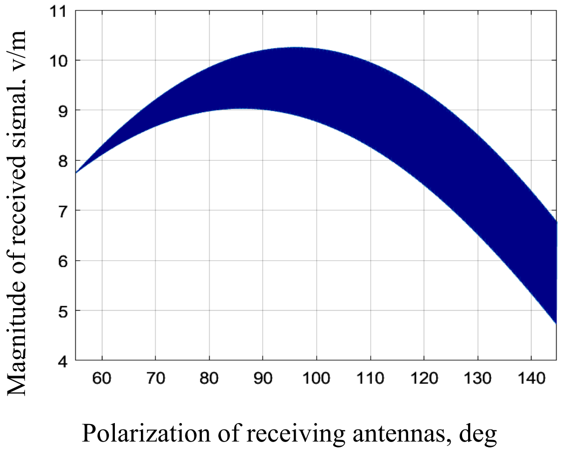

Fig. 3. Envelope of signal at receiving antenna after phase detector

From Figure 3 it is possible to see the larger energy variation between antennas with different polarization (within 4.8 and 10v/m). This is because the larger drops can be deformed significantly comparing to the smaller ones and, thus make stronger impact into reflected signal polarization change. In Figure 4 the relation between the average signal value and the vibrations magnitude in decibels for drops 4 mm is shown.

From the comparison of Figure 2 and Figure 4 it is possible to say that the better relationship between the average signal value and the vibrations magnitude is observed when receiving with 144.7^0-polarized receiving antenna.

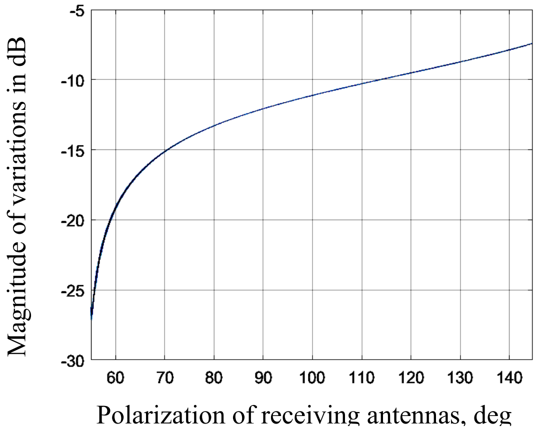

Fig. 4. Relation between the average signal value and the vibrations magnitude

This corresponds to the situation of registration of the contribution of drop nonsphericity and vibration into the field reflected from hydrometeors only. The best result corresponds to the larger drops and equal to -8dB. This magnitude of the depolarized signal is much larger than, for example, real measurements of LDR for oblate dry hail with the axes ratios are as high as 2.5 or 6 [2].

5. Conclusions

In this paper, the simulation of energy redistribution of power received by the antennas of multi polarimetric radar is shown and analyzed to demonstrate the impact of drop vibration in the reflected signal and possibility to register this impact by selection of polarization of receiving antenna.

The values of vibration magnitude with respect to the average level of the reflected signal in decibels for conditions of the stable and turbulent atmosphere was calculated, presented and analyzed. The simulation results prove the supposition that reflected electromagnetic wave energy variation caused by wind and wind related phenomena can be registered by polarimetric radar and then used for further processing.

The results of the paper can be used for segregation of reflected signal magnitude variation due to the wind related phenomena including turbulence and other factors.

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Багатополяризаційні вимірювання та оцінка зміни величини відбитого сигналу за рахунок турбулентності

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Метою цієї роботи є розробка нового поляриметричного підходу щодо оцінки внеску динамічних атмосферних явищ в відбитий радіолокаційний сигнал при мікрохвильовому дистанційному зондуванні хмар та опадів. В роботі рідкі гідрометеори (краплі дощу) розглядаються як об'єкти з нестійкою формою, параметри форми яких є випадковими величинами, що чутливі до впливу динамічних атмосферних явищ включно турбулентність. В роботі одержано математичні вирази для опису електромагнітного поля, що розсіюється рідкими гідрометеорами, а також для змінної (вібруючої) компоненти поля для випадку багатоплрязиційної радіолокаційної системи. Одержано математичний вираз для сигналу після фазового детектору для сепарації вібруючої компоненти, що викликана турбулентністю від змін сигналу, які викликані іншими факторами. Для демонстрації практичної можливості реєстрації зміни відбитої електромагнітної енергії за рахунок турбулентності або інших явищ, що пов'язані з вітром проведено розрахунок співвідношення між середнім рівнем сигналу та величиною вібрацій в децибелах. Результати роботи є корисними для вирішення питань, що пов’язані з сепарацією вібрацій відбитого радіолокаційного сигналу, що викликані динамічними атмосферними явищами, наприклад турбулентністю, від інших факторів.

Ключові слова: гідрометеор; метеорологічний радіолокатор; поляриметрія; турбулентність

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Многополяризационные измерения и оценка изменения величины отраженного сигнала, вызванного турбулентностью

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Цель данной работы – разработка нового поляриметрического похода к оценке вклада динамических атмосферных явлений в отраженный радиолокационный сигнал при микроволновом зондировании облаков и осадков. Жидкие гидрометеоры рассматриваются, как объекты с нестабильной формой. Параметры формы этих объектов являются случайными величинами и также зависят от влияния динамических атмосферных явлений, включая атмосферную турбулентность. В работе получены математические выражения для описания электромагнитного поля, которое рассеивается жидкими гидрометеорами и для переменной составляющей поля для случая многополяризационной радиолокационной системы. В работе получено математическое описание сигнала после фазового детектора для сепарации переменной составляющей, которая вызвана турбулентностью от тех изменений сигнала, что вызваны другими факторами. Для демонстрации практической возможности регистрации изменений отраженной электромагнитной энергии, которая вызвана турбулентностью или другими ветровыми явлениями проведено расчет отношения между средним уровнем сигнала и величиной вибрации в децибелах. Результаты данной работы могут использоваться для решения вопросов связанных с сепарацией вибраций отраженного радиолокационного сигнала, которые вызваны динамическими атмосферными явлениями (в рассмотренном случае турбулентностью) от других факторов.

Ключевые слова: гидрометеор; метеорологический радиолокатор; поляриметрия; турбулентность

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