ТЕОРЕТИЧНИЙ І НАУКОВО-ПРАКТИЧНИЙ ЖУРНАЛ
ІНЖЕНЕРНОЇ АКАДЕМІЇ УКРАЇНИ

THEORETICAL AND APPLIED SCIENCE JOURNAL
ENGINEERING ACADEMY OF UKRAINE

В І С Н И К

ІНЖЕНЕРНОЇ АКАДЕМІЇ УКРАЇНИ

ВИПУСК 3-4

BULLETIN OF ENGINEERING ACADEMY OF UKRAINE

Issue 3-4

За матеріалами науково-практичної конференції,
присвяченної 15-річчю Інженерної академії України

Київ 2007 Kyiv

ТЕОРЕТИЧНИЙ І НАУКОВО-ПРАКТИЧНИЙ ЖУРНАЛ ІНЖЕНЕРНОЇ АКАДЕМІЇ УКРАЇНИ

THEORETICAL AND APPLIED SCIENCE JOURNAL ENGINEERING ACADEMY OF UKRAINE

Журнал друкує статті науковців вузів та установ України, інших країн відповідно до рубрик:

Авіаційна й космічна техніка
Військово-технічні проблеми
Геологія, видобування та переробка корисних копалин
Інженерні проблеми агропромислового комплексу
Інформаційні системи, обчислювальна й електронна техніка, системи зв'язку та приладобудування
Комунікації (транспортні системи та ін.)
Матеріалознавство
Машинобудування
Медична інженерія
Металургія
Нафтогазові технології
Охорона навколишнього середовища (інженерна екологія) і ресурсозбереження
Стандартизація, метрологія і сертифікація
Будівництво і будіндустрія
Технологія легкої промисловості
Технологія харчової промисловості
Хімічні технології й інженерна біотехнологія
Економіка, право та керування в інженерній діяльності
Енергетика

Journal submits articles of researchers of universities and institutions of Ukraine and other countries in accordance with headings:

Aviation and Space Engineering
Military and Engineering Problems
Geology, Mining and Processing of Minerals
Engineering Problems of Agroindustrial Complex
Information Systems, Computer and Electronic Engineering, Communication Systems and Instrument Engineering
Communications (Transport Networks and others)
Material Science
Mechanical Engineering
Medical Engineering
Metallurgy
Oil-and-Gas Technologies
Preservation of Environment (Ecological Engineering) and Resource Saving
Standardisation, Metrology and Certification
Building and Construction Engineering
Technology of Light Industry
Technology of Food Industry
Chemical Technologies and Engineering Biotechnology
Economics, Law and Management in Engineering
Power Engineering

Матеріали друкуються українською, російською або англійською мовами.

Materials are submited in Ukrainian, Russian or English languages.

Номер затверджено на засіданні Вченої ради Кіровоградського національного технічного університету

The issue is approved at the meeting of Academic Council of Kirovograd National Technical University

Протокол № 1 від 24.09.2007 р

Protocol No. 1 dated 24.09.2007

Вісник Інженерної академії України включений у Перелік № 12 наукових фахових видань ВАК України, в яких можуть публікуватися результати дисертаційних робіт на здобуття наукових ступенів доктора і кандидата наук в галузі технічних наук (Постанова президії ВАК України № 1-05/6 від 11.06.2003 р.)

Bulletin of Engineering academy of Ukraine is included into the List No. 12 of Scientific special editions of Higher Certification Committee of Ukraine, in which results of dissertation works may be published for to be confered with academic degrees of doctor and candidate of sciences in the field of engineering sciences (Decree of presidium of the Ukraine HCC No. 1-05/6 dated 11.06.2003)

Співзасновники:
Кіровоградський національний технічний університет
Інженерна академія України
Університет внутрішніх справ

Cofounders:
Kirovograd National Technical University
Engineering Academy of Ukraine
University of Internal Affairs

ISBN 5-7763-8361-7

Редакційна колегія:

Головний редактор – д.т.н., проф. ***В.П. Квасніков***
Відповідальний секретар – к.т.н., доц. ***М.К. Князєв***
Редактор – ***І.О. Чередніков***

Члени редколегії:

***Г.К. Агаджанов** - д.т.н., проф. (комунікації, транспортні системи та ін.),*
***А.І. Бабушкін** - д.т.н., проф. (авіаційна і космічна техніка),*
***Р.Б. Гевко** - д.т.н., проф. (машинобудування),*
***М.М. Гіроль** - д.т.н., проф. (комунікації, транспортні системи та ін.),*
***М.С. Голубенко** - к.т.н. (енергетика),*
***В.О. Гольцов** - д.т.н., проф. (матеріалознавство),*
***А.М. Золотарьов** - д.е.н., проф. (економіка, право і управління в інженерній справі),*
***Євг. Красовський** (Польща) - д.т.н., проф. (інженерні проблеми агропромислового комплексу),*
***В.І. Литвиненко** - д.х.н. (хімічні технології та інженерна біотехнологія),*
***А.П. Мельник** - д.т.н., проф. (нафтогазові технології),*
***В.М. Мельник** - д.т.н., проф. (геологія, добування та переробка корисних копалин),*
***В.І. Мещеряков** - д.т.н., проф. (інформаційні системи, обчислювальна й електронна техніка, системи зв'язку та приладобудування),*
***І.С. Мисак** - д.т.н., проф. (енергетика),*
***Ф.М. Муравченко** - д.т.н., проф. (авіаційна і космічна техніка),*
***П.Л. Носко** - д.т.н., проф. (машинобудування),*
***О.О. Панасенко** - д.т.н., проф. (інформаційні системи, обчислювальна й електронна техніка, системи зв'язку та приладобудування),*
***І.Ф. Підпалий** - д.с-г.н., проф. (інженерні проблеми агропромислового комплексу),*
***Х.К. Радєв** (Болгарія) - д.т.н., проф. (стандартизація, метрологія і сертифікація),*
***С.О. Саприкін** - к.т.н. (нафтогазові технології),*
***В.В. Соловей** - д.т.н., проф. (охорона навколишнього середовища і ресурсозбереження),*
***В.І. Ступа** - д.т.н., проф. (технологія легкої промисловості),*
***І.О. Харченко** - к.т.н. (військово-технічні проблеми),*
***М.І. Хвисюк** - д.м.н., проф. (медична інженерія),*
***В.М. Чепела** - к.т.н. (стандартизація, метрологія і сертифікація),*
***М.І. Черновол** - д.т.н., проф. (матеріалознавство),*
***О.Л. Шагін** - д.т.н., проф. (будівництво і будіндустрія),*
***Є.П. Шольц-Куліков** - д.т.н., проф. (технологія харчової промисловості),*
***С.Л. Ярошевський** - д.т.н., проф. (металургія)*

Підписано до друку 27.09.2007

Ціна договірна

Адреса редакції: просп. Космонавта Комарова, 1,
корп. 11, кімн. 402, м. Київ, 03058, Україна
Тел.: +38(044)406-71-58
E-mail: kvp@nau.edu.ua

Editorial board:

Editor-in-chief – Dr. of Eng., Prof. ***V.P. Kvasnikov***
Executive secretary – Cand.of Eng., Assist.Prof. ***M.K. Knyazyev***
Editor – ***I.O. Cherednikov***

Members of editorial board:

***G.K. Agadjanov** – Dr. of Eng., Prof. (Communications, Transport Networks and others),*
***A.I. Babushkyn –** Dr. of Eng., Prof. (Aviation and Space Engineering),*
***R.B. Gevko** – Dr. of Eng., Prof. (Mechanical Engineering),*
***M.M. Girol** – Dr. of Eng., Prof. (Communications, Transport Networks and others),*
***M.S. Golubenko** – Cand. of Eng. (Power Engineering),*
***V.O. Goltsov** – Dr. of Eng., Prof. (Material Science),*
***A.M. Zolotaryov** – Dr. of Econ., Prof. (Economics, Law and Management in Engineering),*
***Eugeniusz Krasowski** (Poland) – Dr. of Eng., Prof. (Engineering Problems of Agroindustrial Complex),*
***V.I. Lytvynenko** – Dr. of Chem. (Chemical Technologies and Engineering Biotechnology),*
***A.P. Melnyk** – Dr. of Eng., Prof. (Oil-and-Gas Technologies),*
***V.M. Melnyk** – Dr. of Eng., Prof. (Geology, Mining and Processing of Minerals),*
***V.I. Meshcheryakov** – Dr. of Eng., Prof., (Information Systems, Computer and Electronic Engineering, Communication Systems and Instrument Engineering),*
***I.S. Mysak** – Dr. of Eng., Prof. (Power Engineering),*
***F.M. Muravchenko –** Dr. of Eng., Prof. (Aviation and Space Engineering),*
***P.L. Nosko** – Dr. of Eng., Prof. (Mechanical Engineering),*
***O.O. Panasenko** – Dr. of Eng., Prof. (Information Systems, Computer and Electronic Engineering, Communication Systems and Instrument Engineering),*
***I.F. Pidpaly** - Dr. of Agr., Prof. (Engineering Problems of Agroindustrial Complex),*
***H.K. Radev** (Bulgaria) – Dr. of Eng., Prof. (Standardisation, Metrology and Certification),*
***S.O. Saprykin** – Cand. of Eng. (Oil-and-Gas Technologies),*
***V.V. Solovey** – Dr. of Eng., Prof. (Preservation of Environment (Ecological Engineering) and Resource Saving),*
***V.I. Stupa** – Dr. of Eng., Prof. (Technology of Light Industry),*
***I.O. Kharchenko** - Cand. of Eng. (Military and Engineering Problems),*
***M.I. Khvysuk** – Dr. of Med., Prof. (Medical Engineering),*
***V.M. Chepela** – Cand. of Eng. (Standardisation, Metrology and Certification),*
***M.I. Chernovol** – Dr. of Eng., Prof. (Material Science),*
***O.L. Shagin** – Dr. of Eng., Prof. (Building and Construction Engineering),*
***Ye.P. Sholts-Kulikov** – Dr. of Eng., Prof. (Technology of Food Industry),*
***S.L. Yaroshevsky** – Dr. of Eng., Prof. (Metallurgy)*

Signed for printing on 27.09.2007

Agreed price

Address of Editorial Staff: Cosmonaut Komarov St., 1,
build. 11, 402 room, Kyiv, 03058, Ukraine
Tel.: +38(044)406-71-58
E-mail: kvp@nau.edu.ua

Зміст

АВІАЦІЙНА Й КОСМІЧНА ТЕХНІКА

Yahya S. H. Khraisat, Felix J. Yanovsky 9
SPECTRUM WIDTH OF RADAR RETURNS FROM RAIN WITH TURBULENCE

Felix J. Yanovsky, Vitaly V. Marchuk, Yaroslav P. Ostrovsky, Alexander A. Pitertsev, Yahya S. H. Khraisat, Leo P. Ligthart 16
MICROWAVE SCATTERING FROM PARTICLES IN TURBULENT ATMOSPHERE AND ITS APPLICATION FOR HYDROMETEOR TYPE RECOGNITION AND TURBULENCE DETECTION

Князев М.К. 24
ИЗМЕРЕНИЕ ПОЛЕЙ ДАВЛЕНИЯ ПРИ ИМПУЛЬСНОМ НАГРУЖЕНИИ НА КРИВОЛИНЕЙНЫХ ПОВЕРХНОСТЯХ С ПОМОЩЬЮ МЕМБРАННЫХ ДАТЧИКОВ

Колотуша В.П., Рудас С.И., Ярощук О.П. 28
УЧЕТ КОНФЛИКТНЫХ СИТУАЦИЙ В ЭКСПЕРИМЕНТАЛЬНЫХ ИССЛЕДОВАНИЯХ ПРОПУСКНОЙ СПОСОБНОСТИ СЕКТОРОВ ОВД

Колотуша В.П., Коломієць А.В., Рудас С.І., Ярощук О.П. 33
ВИКОРИСТАННЯ СПЕКТРУ ПОМИЛОК ДИСПЕТЧЕРА УПРАВЛІННЯ ПОВІТРЯНИМ РУХОМ ПРИ ОЦІНЦІ ЙОГО ДІЙ

ГЕОЛОГІЯ, ВИДОБУВАННЯ ТА ПЕРЕРОБКА КОРИСНИХ КОПАЛИН

Калько А.Д. 36
ПАРАМЕТРИ ПІДВИЩЕННЯ ДОСТУПНОСТІ АЛМАЗОНОСНОГО РОДОВИЩА ЗА РАХУНОК ЗАХОРОНЕННЯ РАВ

Лустюк М.Г. 44
АСПЕКТИ ВИБОРУ І ПРОЕКТУВАННЯ СИСТЕМ ОПРОБУВАННЯ І РОЗРОБКИ РОДОВИЩ БУРШТИНУ

Петривский Я.Б. 51
ИССЛЕДОВАНИЕ ДОСТУПНОСТИ ЗАПАСОВ УРАНА ЗА СЧЕТ ГЕОТЕХНОЛОГИЧЕСКОЙ ПОДГОТОВКИ ТЕХНОГЕННОГО МЕСТОРОЖДЕНИЯ

Петривский Я.Б. 51
ТЕХНОЛОГИЧЕСКАЯ СХЕМА СОЗДАНИЯ ТРЕЩИН В ПОДСТИЛАЮЩИХ ПОРОДАХ ТЕХНОГЕННОГО МЕСТОРОЖДЕНИЯ

ІНФОРМАЦІЙНІ СИСТЕМИ, ОБЧИСЛЮВАЛЬНА Й ЕЛЕКТРОННА ТЕХНІКА, СИСТЕМИ ЗВ'ЯЗКУ ТА ПРИЛАДОБУДУВАННЯ

Бабенко В.Г., Дахно Т.В., Рудницький В.М. 65
АЛГОРИТМИ СИНТЕЗУ ЛОГІЧНИХ ФУНКЦІЙ ДЛЯ СИСТЕМ ЗАХИСТУ ІНФОРМАЦІЇ

BULLETIN OF ENGINEERING ACADEMY OF UKRAINE

АВІАЦІЙНА Й КОСМІЧНА ТЕХНІКА

UDC 621.396.96

[#] **Yahya S. H. Khraisat**, Ph.D.
[*]**Felix J. Yanovsky**, Ph.D., D.Sc.

SPECTRUM WIDTH OF RADAR RETURNS FROM RAIN WITH TURBULENCE

[#] Al_Balqa Applied University / Al-huson University College, P.O.1375, Irbed 2110, Jordan, yahya114@hotmail.com
[*]National Aviation University, Prospect Komarova 1, Kiev, 03680, Ukraine, felix.yanovsky@ieee.org

This paper presents the developed model description and the calculation results of the joint influence that both rain intensity and turbulence produce on the spectrum width of the reflected signal in microwave frequency band. The model provides the possibility to calculate backscattered signal parameters at wide variety of the initial data. Results are useful for radar, telecommunications, radar meteorology and remote sensing of the atmosphere.

Introduction

Returns from rain are very common clutters that are important in different tasks of radar observation and telecommunications. From another point of view they carry extremely important information about the source of the reflecting phenomenon itself what is necessary also in the problems of remote sensing of the atmosphere. The inverse problems in such tasks are very difficult. They can be solved successfully if the reliable models are developed that can be used for better data interpretation.

Analysis of Previous Results in the Field

Any rain consists of droplets that can be of different size, have different speeds and may be affected by wind and turbulence. This paper considers spectra of radar signal that is reflected from such a complicated target as rain with turbulence. The backscattering models of the totality of hydrometeors in turbulent medium were described in [1]. The paper [1] considers the model of isotropic homogeneous turbulence, which satisfies to the Kolmogorov law of minus five third. In work [2] it was shown that the shape of the initial energetic spectrum of turbulence can have an influence upon the velocity spectrum of scatterers. However for the tasks of the remote sensing of the atmosphere it is important to know the Doppler spectrum in different cases [3]. Scatterer velocity spectrum is a source of Doppler spectrum that can be measured by Doppler radars. However, in order to calculate the Doppler spectrum, one should make a number of suggestions about characteristics of microstructure of the object under study as well as on radar parameters. An approach to analyse the influence of the shape of turbulence spectrum onto the Doppler spectrum of the radar echo-signal reflected from rain was worked out in [4]. In paper [5] the developed model was applied to calculate Doppler spectra under the different conditions. Nevertheless, further development of the model is necessary to estimate Doppler spectrum width at different rain rate and turbulence intensity. Moreover, the model should be checked and verified by using experimental data.

Problem Definition

The objective of this paper is to present the results of further development of the suggested approach particularly at different intensity of turbulence and rain rate to investigate their influence upon the spectrum width of the received signal. In particular this paper presents the signal spectrum model in case of returns from rain with turbulence taking into account the inertia of droplets, results of measurements as well as the extraction of information about turbulence from the returns. Separation and extraction of turbulence contribution and gravity contribution from the measured Doppler spectrum width is finally provided based on the developed model.

Signal spectrum model

Doppler spectrum is defined as a weighted radial velocity distribution of scatterers in the reflected radar volume [6]. It can be written as

$$S(v,\varepsilon) = \int\limits_{D_{\min}}^{D_{\max}} p(v,\varepsilon,D)\sigma(D)N(D)dD\,, \tag{1}$$

were $p(v,\varepsilon,D)$ is droplet radial velocity v probability distribution that depends on eddy dissipation rate ε as turbulence intensity parameter, and equivalent diameter D of droplet; $\sigma(D)$ is radar cross section (RCS) of a droplet of given diameter; $N(D)$ is drop size distribution, that is a number of droplets of given diameter in a unit of radar volume. The limits of integration $D_{\min}$ and $D_{\max}$ are the smallest and the biggest possible droplet diameter correspondingly.

Assuming $\lambda >> D$, RCS can be calculated as

$$\sigma(D) = \frac{\pi^5 D^6}{\lambda^4}\left|\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right|^2, \tag{2}$$

where λ is wavelength, and ε_r is relative complex permittivity of the material of a droplet.

As it was done in the previous works [3], [4], the drop size distribution is modeled by gamma distribution in the form

$$N(D,D_0) = N_0 D^{\mu} \exp\left(-\frac{3.67+\mu}{D_0}D\right), \tag{3}$$

and we use a partial case with $N_0 = 8000$ and $\mu = 0$ that corresponds to the Marshall-Palmer exponential drop size distribution, which is the most often used by many authors. Median drop diameter D_0 is an important parameter of the drop size distribution. Actually D_0 can be associated with the amount of falling water and hence with the rain rate R as can be seen from the model [4]

$$R(D_0) = 6\cdot 10^{-4}\pi \int\limits_{D_{\min}}^{D_{\max}} N(D,D_0)D^3 V(D)dD\,, \tag{4}$$

where $V(D)$ is empiric dependence between the droplet size and droplet fall speed

$$V(D) = 6.65 - 10.3\exp(-0.6D). \tag{5}$$

Expressions (4) and (5) were derived under the condition that drop size (D, D_0, $D_{\min}$ and $D_{\max}$) is measured in [mm], velocity $V(D)$ in [mps], and rain rate R in [mm per hour].

Turbulence spectrum model

In this consideration we take into account only turbulent component of radial droplet velocity because we are interested by the influence of turbulence spectrum shape onto the Doppler spectrum width, and such influence is important for turbulence component only. In pursuance of previous work [2], let us express analytically the turbulence spectrum as

$$S(\Omega) = C_0 \varepsilon^{2/3}\Omega^{-K}, \tag{6}$$

where C_0 is dimensionless factor of the order of unity, and the exponent of power K defines the shape of turbulence spectrum. The law of Kolmogorov is a partial case of (6) if $K = 5/3$. As it was done in [2], we again consider three partial cases of the model (6):

- Quadratic model $K = 2$ (later on, model *q*);
- Kolmogorov model $K = 5/3$ (model *k*);
- Four third models $K = 4/3$ (model *f*).

For each model S_q, S_k, and S_f one can find density of turbulent scales $w(L)$ if considering L and Ω as functionally related random values. In this case, the value $w(L,\varepsilon) = S(\Omega)/|dL/d\Omega|$ after the substitution $L = f(\Omega)$ and normalization can be interpreted as a probability density of scales for each of turbulence models:

$$w_q = \frac{1}{L_m}; \; w_k = \frac{2}{3} L^{-1/3} L_m^{-2/3}; \; w_f = \frac{1}{3} L^{-2/3} L_m^{-1/3}. \tag{7}$$

In expression (7) L_m is a maximal scale of turbulence that is taken into account. For calculation, it can be chosen from physic consideration; it should be in the limits of inertial range of turbulence where ε does not depend on turbulence scale.

Inertia of droplets

Movements of droplets cannot immediately follow to turbulent movements of air. Based on the results of [1], probability density function (PDF) of turbulent droplet velocity $p(v_T)$ can be written as:

$$p\left(\vec{v}_T\right) = \int_{L_{\min(D)}}^{L_{\max}} w_g\left(\vec{v}_T / L, \varepsilon\right) w(L)\, dL, \tag{8}$$

where $w_g(*)$ is Gaussian PDF with zero mean and the variance $\sigma_T^2 = C_0 \varepsilon^{2/3} L^{2/3}$. Upper limit of integration in formula (8) restricts the scale of turbulence $L_{\max} \le L_m$. Lower limits of integration in formula (8) are important for taking into account inertia of droplets. Function $L_{\min}(D)$ reflects the fact that the more the size (and mass) of a droplet the higher the inertia of the droplet [1].

By substituting values w_q, w_k or w_f from (7) to (8), after normalization one can get three expressions of PDF for turbulent velocity of droplet $p(v, \varepsilon, D)$ at each of three considered models: *q*, *k*, and *f*. Correspondent analytical expressions were obtained and analyzed in [2]. Let us designate them as $p_q(v, \varepsilon, D)$, $p_k(v, \varepsilon, D)$, and $p_f(v, \varepsilon, D)$ correspondingly. By substituting (2) and $p_n(v, \varepsilon, D)$, $n = q; k; f$ to (1), we obtain expressions of Doppler spectra for three models of turbulence spectrum: $S_q(v,\varepsilon)$, $S_k(v,\varepsilon)$, and $S_f(v,\varepsilon)$. Calculations show that PDF of droplet turbulent velocity $p_q(v, \varepsilon, D)$, $p_k(v, \varepsilon, D)$, and $p_f(v, \varepsilon, D)$ are rather different at three considered models *q*, *k*, and *f*. This result actually confirms the conclusion made in [2]. The results of calculating Doppler spectrum caused by turbulence were presented in the previous work [5]. Comparison of different turbulence spectrum models at different D_0 and different ε shows that influence of the turbulence spectrum shape is rather weak in comparison with influence of the parameters of turbulence intensity and rain rate

Spectrum width calculations

Spectrum width is calculated as the rms W_K of the K -th spectrum (K =2; 5/3; 4/3).

$$W_K^2 = \int_0^{v_m} v^2 S_K(v) dv - \left[\int_0^{v_m} v\; S_K(v) dv\right]^2. \tag{9}$$

Fig. 1 shows spectrum width versus rain rate at different turbulence intensity defined by eddy dissipation rate ε at Kolmogorov turbulence model.

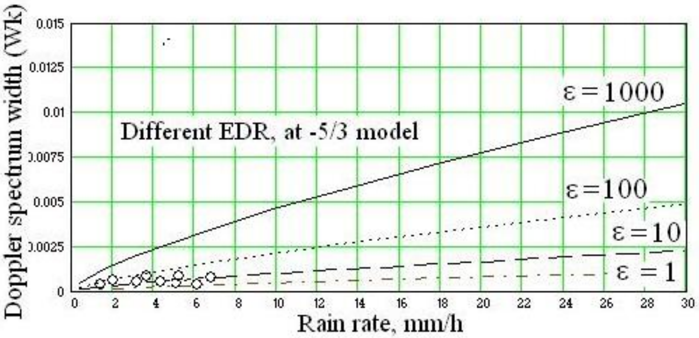

Fig. 1 Spectrum width as function of rain rate and eddy dissipation rate.

Validation of the model at different rain rate and turbulence intensity was done with radar data provided by the International Research Centre for Telecommunications and Radar at the Delft University of Technology. The data are indicated as circles in Fig. 1.

Figure 2 represents the dependence between spectrum width and rain rate at different intensity of turbulence and for three considered above models of turbulence spectrum. Wide range of rain rates is presented. Figure 3 shows spectrum width versus eddy dissipation rate at two values of rain rate: 1 mm/h and 120 mm/h.

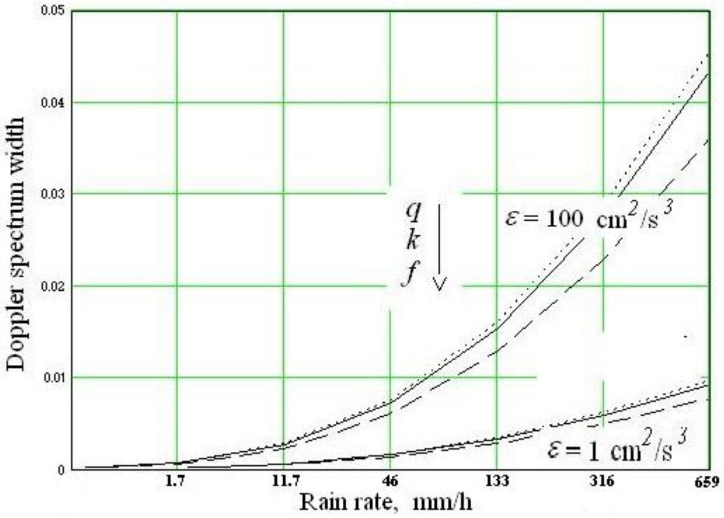

Fig. 2. Spectrum width as function of rain rate and eddy dissipation rate.

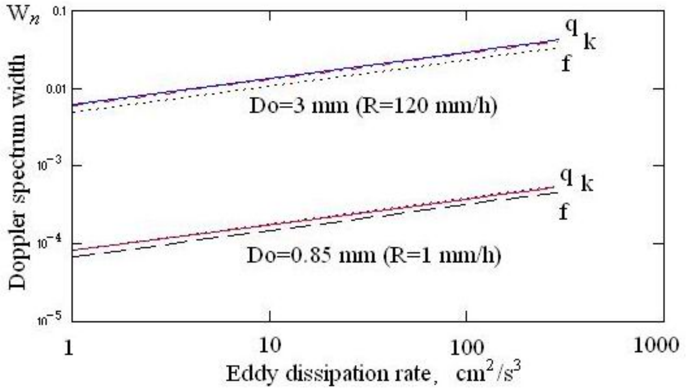

Fig. 3 Spectrum width as function of eddy dissipation rate at two values of rain rate and different shapes of turbulence spectra.

Analyzing these figures, one can see the influence of both parameters: rain rate and eddy dissipation rate, that is, intensity of turbulence upon such important measurable variable of radar signal as spectrum width. These results can be useful for the interpretation of the data of atmosphere remote sensing with microwave Doppler radar. However further validation in different weather situations still is necessary.

The developed model gives also the possibility to calculate Doppler spectra under the different conditions. Interesting results are presented in Figures 4 and 5. In accordance with expression (4) median drop diameter D_0=1 mm corresponds to rain rate R=2 mm/h, and D_0=2 mm corresponds to R=50 mm/h. Comparison of different turbulence spectrum models at different D_0 (Fig. 4) and different ε (Fig. 5) confirms that influence of the turbulence spectrum shape is negligible in comparison with influence of the parameters of turbulence intensity and rain rate. In contrast, both rain rate and turbulence significantly affect Doppler spectrum.

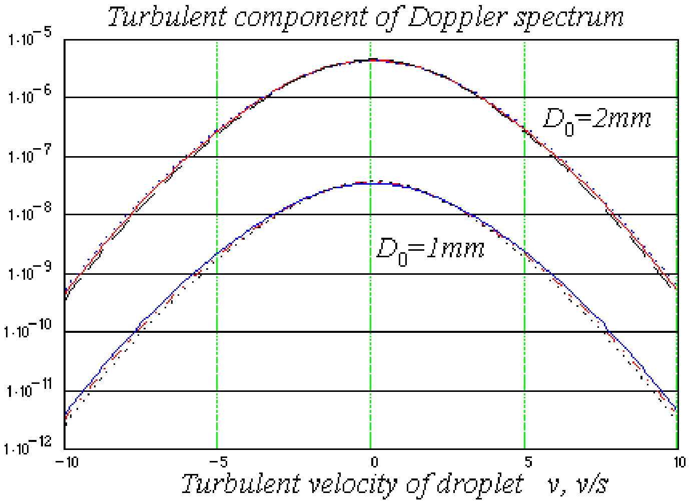

Fig. 4. Doppler spectrum at different rain rate (D_0=1 mm, R =2 mm/h).

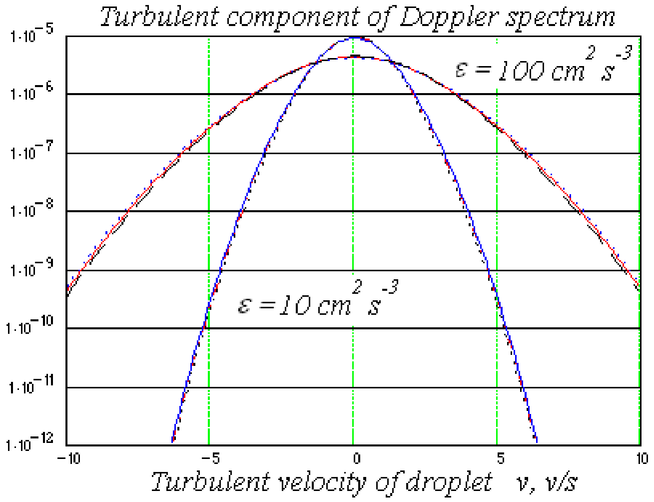

Fig. 5. Doppler spectrum at different turbulence intensity.

Deriving Turbulence Information from Doppler Spectrum Width Measurements

Now we have all necessary formulas to extract turbulence contribution from measured Doppler spectrum width. The methodology is clearly demonstrated in Fig. 6 as a calculation procedure [7], which uses measured reflectivity Z, height h, and Doppler velocity variance W. In accordance with this procedure, having estimates of D_o, h, and W, we can calculate drop fall velocity distribution N_f, variance Q_f of drop fall velocity, and then the contribution of turbulence W_{Turb} to the measured variance of Doppler velocity W as a difference $W_{Turb} = W - Q_f$. Finally, the estimate of the Doppler spectrum width caused by turbulence is $\hat{\sigma}_{Turb} = (W_{Turb})^{1/2}$.

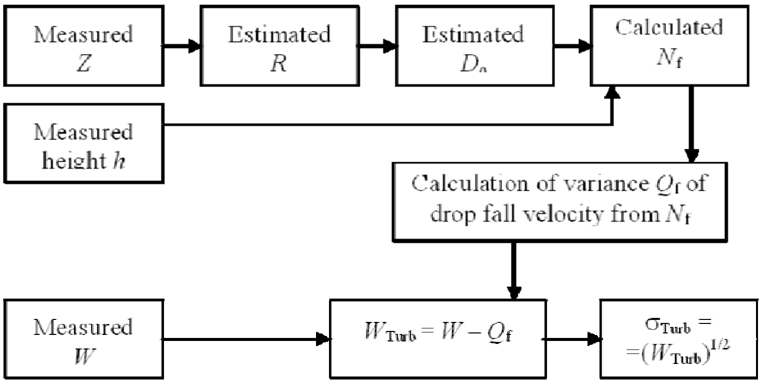

Fig. 6. The procedure for the extracting turbulence contribution σTurb from measured Doppler spectrum width [W = (Doppler spectrum width) 2].

The results of signal processing of the reflections from rain in accordance with this algorithm are presented in Fig. 7 and 8.

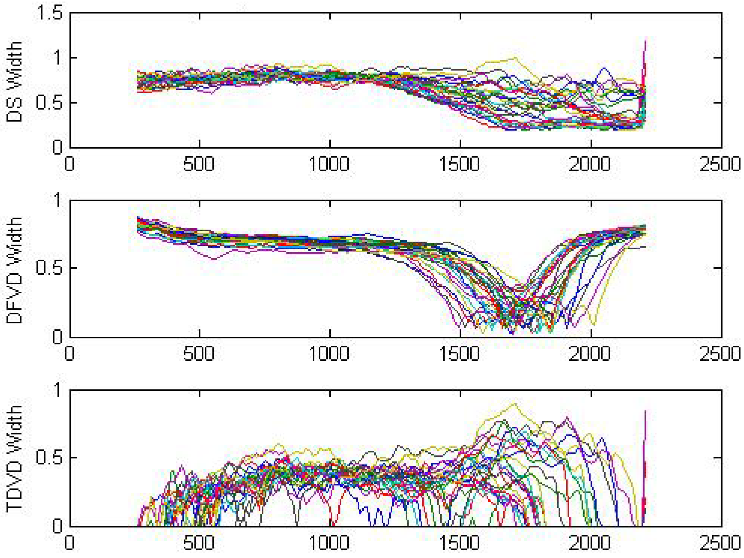

Fig. 7. Measured Doppler spectrum width and extracted turbulent and drop fall contributions versus range bin number for great number of realizations.

This figure shows the results of 15 minutes measurements that were processed to calculate the variance Q_f and W_{Turb}. The values of $\sqrt{Q_f}$ and $\sqrt{W_{Turb}}$ contributions are coded by the colour. Red colour corresponds to the highest values and blue corresponds to the smallest values.

The picture (Fig.8) represents the distributions of indicated parameters up to the heights of 500 m in rain zone. One can see that in this particular case, in upper heights the influence of drop fall velocities is predominant. In contrast to that, turbulence is predominant at the heights of about 350 m and lower.

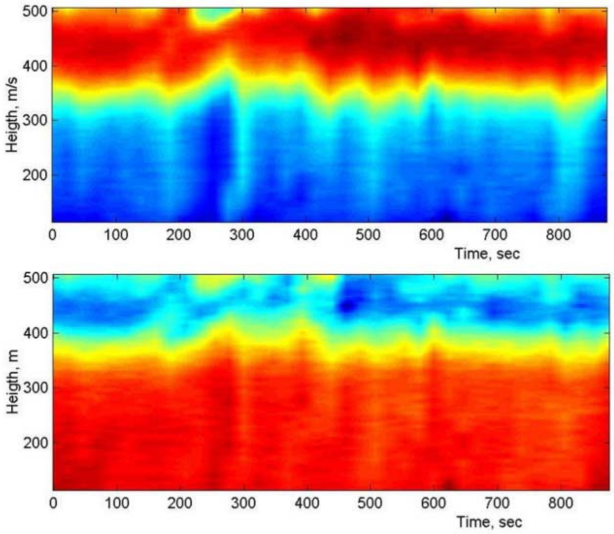

Fig. 8. Contribution of drop fall velocity (upper panel) and turbulence (lower panel) into the measured spectrum width in rain.

Conclusions

Doppler spectrum width is strongly dependent on turbulence intensity and rate. In contrast, it is weekly dependent on the shape of turbulence spectrum in the considered range of the spectrum shapes. Calculations have demonstrated that retrieval of information about turbulence intensity from Doppler spectrum is quite robust under the condition of changing turbulence energetic spectrum shape in rather broad range. Strong influence of turbulence intensity and rain rate has been confirmed by using experimental data. Further experimental validations of the developed models under the different conditions are extremely desirable. Results are necessary for radar, telecommunications and remote sensing.

Acknowledgment

The authors wish to acknowledge that experimental validation of the model was possible due to the data provided by the International Research Centre for Telecommunications and Radar at the Delft University of Technology.

References

1. F.J. Yanovsky, Modeling the processes of interaction between radar signal and turbulent weather object. *Visnyk of KIUCA* (*Letters of the Kiev International University of Civil Aviation*), Issue 1, pp. 125-136, 1998 (in Russian).
2. F.J. Yanovsky, Y. S. H. Khraisat, “Models of atmosphere turbulence in the tasks of remote sensing of clouds and precipitation”. *Visnyk of KIUCA* (*Letters of the Kiev International University of Civil Aviation*), Issue 1, pp. 154-160, 1999 (in Russian).
3. European Commission, COST 75, *Advanced Weather Radar Systems. International seminar*, Locano, Switzerland, 23 to 27 March 1998 / Edited by C.G. Collier, 858 pp., 1999.
4. Y. S. H. Khraisat, F.J. Yanovsky, “Influence of the shape of turbulence spectrum onto the Doppler spectrum of the radar returns from rain”. In *Proc. of the Workshop on Microwaves, Radar and Remote Sensing (MRRS 2005)*, pp. 134-137, Kiev, 2005.
5. Y. S. H. Khraisat, “Computational Model of Radar Signal Spectrum Reflected from Rain”, in *Proc. European Radar Conference EuRAD 2006*, pp. 166-169, Manchester, 2006.
6. R. Doviak and D. Zrnic, Doppler Radar and Weather Observations, 2nd ed., Academic Press, London, 1993.
7. F.J. Yanovsky, H.W.J. Russchenberg, and C.M.H. Unal. Retrieval of Information About Turbulence in Rain by Using Doppler-Polarimetric Radar. IEEE Transactions on Microwave Theory and Techniques, Feb., Vol. 53, No 2, 2005, pp. 444 – 450.

UDC 621.396.96

[*]**Felix J. Yanovsky**, Ph.D., D.Sc.
[*]**Vitaly V. Marchuk**
[*]**Yaroslav P. Ostrovsky**
[*]**Alexander A. Pitertsev**
[#] **Yahya S. H. Khraisat**, Ph.D.
[+]**Leo P. Ligthart,** Ph.D.

MICROWAVE SCATTERING FROM PARTICLES IN TURBULENT ATMOSPHERE AND ITS APPLICATION FOR HYDROMETEOR TYPE RECOGNITION AND TURBULENCE DETECTION

[*]National Aviation University, Prospect Komarova 1, Kiev, 03680, Ukraine, yanovsky@ieee.org
[#] Al_Balqa Applied University / Al-Huson University College, P.O.1375, Irbed 2110, Jordan, yahya114@hotmail.com
Delft University of Technology, IRCTR, P.O. Box 5031 2600GA Delft, The Netherlands, l.p.ligthart@irctr.tudelft.nl

The models of microwave scattering on atmospheric particles are presented. Shape, size, material, and turbulence influence of scatterers are taken into account at different wave polarizations. Results are important for remote recognition of hydrometeor types, radar and telecommunications..

Introduction

Operation of radar and telecommunications systems, especially those of microwave and shorter wavelength, is very much subjected by the influence of atmospheric formations, such as precipitation, clouds, fog. These formations consist of hydrometeors of different types. Hydrometeors damp out electromagnetic (EM) waves, what makes worse radar observability and quality of telecommunications. When EM waves propagate through areas of hydrometeors, attenuation takes place because of absorption and scattering. A part of EM wave energy is absorbed by hydrometeors and turns into a heat while another part is scattered by those hydrometeors in different directions including the direction back to the source of radiation (backscattering). Thus, the optimization of characteristics of an electronic system, which works in complicated weather conditions, as well as the development and selection of engineering solutions to lessen the influence of weather conditions onto the system, strongly depend on scattering properties of hydrometeors. This circumstance has stimulated extensive radio-meteorological research, which in turn has given extremely important knowledge on fundamental problems of aerophysics, meteorology, and on applied issues of weather forecast, measurements of rain rate, wind speed, etc. The importance of research on radar meteorology became even greater because of aviation needs. Aircraft flights with high speeds and flight intensity increase the probability to enter zones of dangerous hail and icing-in-flight, and the presence of powerful vertical airflows creates the possibility to collide with hailstones even in a cloudless atmosphere. That is why the problem of reliable hydrometeors detection and recognition of hydrometeor type becomes significant and gets attention by all experts in the field of radar meteorology, aviation and avionics. In this connection, the creation and improvement of radar and telecommunication systems is strongly related to the progress our knowledge on scattering properties of atmospheric formations. Till recently, the theory of scattering (and so radar reflectivity and radio-wave attenuation by hydrometeors) was based on the representation of such scattering object as an aggregate of randomly located separate spherical particles [1] which can differ only in size. However, quite obvious non-sphericity of hydrometeors in many cases plays an important role in their scattering properties especially taking into account the polarization of EM waves. This is very important also for the detection, identification and recognition of hydrometeor type.

Particles in atmosphere are also subjected to the influence of turbulence. This paper considers the developed model description and the calculation results of the joint influence that both rain intensity and turbulence produce on the spectrum width of the reflected signal in microwave frequency band. The model developed provides the possibility to calculate backscattered signal parameters at wide variety of the initial data.

A detailed analysis of hydrometeor scattering at dual-polarization radar measurements is considered in this paper. The polarization of the backscattered field depends on the shape, size, orientation and type of the particles. It is important for the development of a classification system to find a clear relation between the radar echo-signals and the hydrometeor properties, such as size, shape, phase state and fall behaviour. Extensive information about the microphysics of hydrometeors is contained in radar measurements with polarization diversity.

We shall analyze the case of different types and orientation of hydrometeors. Backscattering of microwaves on water droplets and ice crystals of different shapes is considered as function of polarization, antenna elevation, size distribution of scatterers and other factors. Details in the scattering results are necessary for recognition the type of hydrometeors, e.g. super-cooled water droplets remote detection. Methods of detecting zones where hazardous icing-in-flight is probable as suggested in [2], [3] were based on features of different behaviour of the polarimetric signal in water clouds and ice clouds. That is why this paper focuses on the calculation of backscattering and polarimetric variables in cases of water droplets and crystal clouds in turbulent conditions.

General models of scattering from particles

There are a number of different approximations known to describe EM scattering from separate particles. The most applicable and quite simple Rayleigh scattering is limited to the case in which particle size r is much less than wavelength λ. Normally this condition is expressed as $2\pi r/\lambda << 1$. Initially only dielectric particles were considered however later it was shown that Rayleigh formulas are applicable also at different complex refraction coefficients m , however for big $|m|$ an additional condition $|2\pi rm/\lambda| << 1$ should be satisfied. The last inequality gives even more stringent condition to possible sizes of scatterers for allowing the Rayleigh approximation [1]. Nevertheless Rayleigh approximation is widely used in case of analyzing microwave scattering on clouds and precipitation. However in case of large raindrops, where both r and $|m|$ for water can be rather big, a deviation of the real scattering and attenuation from the Rayleigh model can occur. Some other approximations can then be used for large particles, for example van de Hulst approximation for transparent particles comparable with wavelength, or even approximations of geometric optics for the case $2\pi r/\lambda >> 1$. Most accurate and universal approach is the well-known Mie solution, which was obtained from application of the Maxwell EM field theory to the problem of light scattering from a homogeneous spherical particle. Derivation of Mie formulas can be found in numerous books, for example in [1].

Kinds of particles

Real hydrometeors are not exactly spherical. However their non-sphericity becomes mainly apparent in their polarimetric properties while averaged scattering can still be estimated by using known approximations for spherical particles. Raindrops are generally oblate; the very small droplets are practically spherical ones, while the larger the dropsizes the more flatness becomes the droplets. In contrast to droplets, ice crystals are characterized by an extremely wide variety of shapes. The crystal shape depends on the conditions under which they were formed. However, there are three main types of ice crystals that are usually formed in clouds at temperature from 0 to -35^{o}□C, namely: columnar crystals, needles, and plates. There are many other kinds of hydrometeors, say, snowflakes and hailstones. Every type of hydrometeors is characterized by its features that can be used for the mathematical modeling and simulation.

Models of hydrometeors

The problem of simulation of scattering from hydrometeors is rather difficult because many different parameters of scatterers should be taken into account, at least their distributions on shape, size and orientation. The microstructure of precipitation can be characterized by physical and statistical properties of the individual particles. It will be shown that by modelling the shape of a hydrometeor by an ellipsoid we can simulate a wide variety of different shapes by changing ellipsoid parameters [4].

The average dropsize distribution in rain can be discribed by the gamma-distribution in the following form:

$$N(D) = N_0 D^{\mu}\, exp\left(-\frac{3.67+\mu}{D_0}D\right) \quad . \tag{1}$$

If $\mu = 0$ (Marshall-Palmer case) $N_0 = 8000$, and if $\mu \neq 0$, N_0 is derived from the Marshall-Palmer distribution by keeping the total volume of amount of water per m^3 constant for given D. If μ is an integer, this leads to the following formula [5]:

$$N_0 \approx \frac{264.59 \cdot (3.67+\mu)^{\mu+4}}{D_0^{\mu}(\mu+3)!} \tag{2}$$

with μ as spread parameter, and D_0 as median drop diameter.

The case of rain is the simplest one. It is much more difficult to find an adequate hydrometeor size distribution for clouds. According to [6] the gamma-distribution is good for description of the dropsize (radius r) distribution in a liquid cloud without rain; in this case the distribution is defined by two parameters α and β:

$$n(r) = \frac{N_0}{\Gamma(\alpha+1)\beta^{\alpha+1}} r^{\alpha} \exp\left(-\frac{r}{\beta}\right). \tag{3}$$

For clouds of given type (St, Sc, Ns, Ac, etc.) on average, the dropsize distribution is usually well described by the Hrgian-Mazin distribution:

$$n(r) = cr^2 \exp(-br), \tag{4}$$

where parameters b and c are constant for a given type of clouds, and $b = 3/\bar{r}$ with $\bar{r}$ as mean radius of droplets.

We considered clouds with median drop diameter in the range from 30 to 100 micron. Such values of this parameter in combination with negative cloud temperature and supercooled liquid water content more than 0.2 g/m^3 can lead to significant aircraft icing. The maximal droplet diameter in such type of cloud does not exceed 1 mm. The shape of such droplets is almost an ideal sphere. The crystal shape depends on the conditions under which they were formed. The percentage of columnar crystals, needles, and plates varies depending on cloud type, temperature and humidity of air, as well as on some other conditions. According to [4], a size distribution of ice crystals was described by the expression

$$N(L) = 1000\,L^{-2.3}, \tag{5}$$

where L is a characteristic size, e.g. length for columnar crystals and needles, and diameter for ice plates. The shape of columnar crystals and needles in this work was modelled by a spheroid with relation $d(L)$, approximated by the model $d(L) = BL^{\beta}$, where L is the length and d is the diameter for the column or needle, and with relation $h(d)$, approximated by model $h(d) = Ad^{\alpha}$, with h as thickness and d as diameter for the crystals of lamellar forms. The numerical values of model parameters were selected in accordance with data given in handbook [6], particularly:

1) for columnar crystals $B = 0.3\ldots0.6$ and $\beta = 0.9\ldots0.96$; 2) for needles $B = (0.03\ldots0.6)\cdot 10^{-2}$ and $\beta = 0.45\ldots0.6$; 3) for ice plates $A \approx 0.01$ and $\alpha \approx 0.42$.

Polarization models and polarimetric parameters

In this paper we consider dual-polarization illumination of an object in linear polarization basis. That means that a transmitting antenna radiates sounding waveforms by changing the linear polarization orthogonally from one modulation period to another. In the following we define that the polarization of the sounding waveform is changed from horizontal to vertical, to horizontal, etc. The polarization of the scattered signal depends on the shape and orientation of the scatterer. When an arbitrarily linearly polarized wave is incident on a target, the scattered field is then given by the expression

$$\begin{bmatrix} E_h^S \\ E_v^S \end{bmatrix} = [S]\begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix} = \begin{bmatrix} s_{hh} & s_{hv} \\ s_{vh} & s_{vv} \end{bmatrix}\begin{bmatrix} E_h^i \\ E_v^i \end{bmatrix}, \tag{6}$$

where E is the amplitude of the field (electric field strength), the superscripts i and s denote incident and scattered fields, and the subscripts H and V denote horizontal and vertical polarization. The quantities s_{kl} are in general complex. According to [7], for the most general case the second-order moments $\langle s_{kl} s_{nm}^{*} \rangle$ of constituents of scattering matrix (6) can be grouped in a four-by-four covariance matrix but, because of reciprocity ($s_{kl} = s_{lk}$) the covariance matrix reduces to a three-by-three dimensioned matrix

$$\begin{matrix} \left\langle |s_{hh}|^2 \right\rangle & \left\langle s_{hv}\, s_{hh}^* \right\rangle & \left\langle s_{vv}\, s_{hh}^* \right\rangle \\ \left\langle s_{hh}\, s_{hv}^* \right\rangle & \left\langle |s_{hv}|^2 \right\rangle & \left\langle s_{vv}\, s_{hv}^* \right\rangle \\ \left\langle s_{hh}\, s_{vv}^* \right\rangle & \left\langle s_{hv}\, s_{vv}^* \right\rangle & \left\langle |s_{vv}|^2 \right\rangle \end{matrix} \qquad (7)$$

By using covariance matrix (7) one can introduce a set of polarization parameters which can be measured. These parameters should then be related to physical characteristics that are observed and to properties of the scatterers (hydrometeors). As an example we use here only three parameters: differential reflectivity (DR) Z_{DR} and linear depolarization ratio (LDR) L_{DR}, and correlation coefficient at zero lag $\rho_{hv}(0)$:

$$Z_{DR} = 10\log|s_{hh}|^2 / |s_{vv}|^2\,; \qquad L_{DR} = 10\log|s_{hv}|^2 / |s_{vv}|^2\,; \qquad \rho_{hv}(0) = \left\langle s_{vv}s_{hh}^* \right\rangle \Big/ \left\langle |s_{hh}|^2 \right\rangle^{1/2} \left\langle |s_{vv}|^2 \right\rangle^{1/2}. \qquad (8)$$

Backscattering from a particle

The general approach to describe scattering of a particle is to calculate the scattering characteristics after substitution of a real particle by an ellipsoid with specific parameters. We consider an arbitrary oriented ellipsoid and spheroid. The RCS of a particle with equivolumetric diameter D can be described as $\sigma_{xy}(D) = \sigma(D,\lambda,\, m)Q_{xy}$, where $\sigma(D,\lambda,\, m)$ is independent on polarization component, and only a complex parameter $Q_{xy} = F_{xy}(\Lambda)\,\Phi_{xy}(\delta,\alpha,\theta)$ is responsible for the polarization properties of the particle. Here F_{xy} is a term that represents the shape of the particle (quantified with a vector of shape parameters Λ) [8], and Φ_{xy} takes into account the particle orientation (quantified be parameters of particle orientation in the vertical δ and horizontal α planes) and the antenna elevation angle θ.

Backscattering from droplets

For water droplets the problem can be solved if the relation between drop size and drop shape is taken into account [9]. Figure 1 shows the dependence of DR versus canting angle of raindrops of different diameters at horizontal sounding.

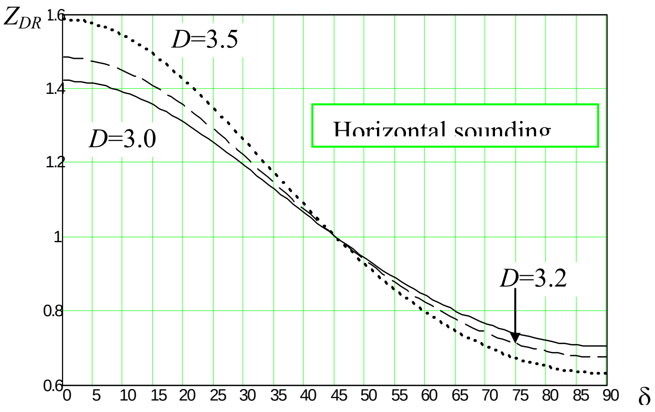

Figure 1. Differential reflectivity of droplets of diameter (mm) as function of particle canting angle (in degrees)

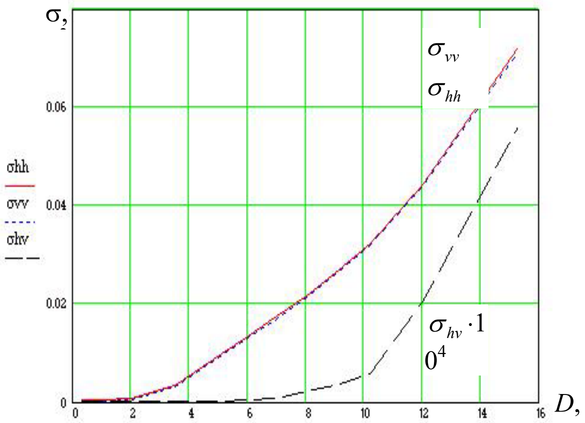

Figure 2. Radar cross section of hailstones versus equivolumetric diameter at different polarizations

Backscattering from ice crystals

Calculations of scattering from ice crystals were presented in [4]. Figure 2 shows an example of the RCS of hailstones at different polarizations, including the cross-polarization component as function of the equivolumetric diameter.

Ensemble of homogeneous hydrometeors

When calculating the scattering from the aggregate of particles we do not consider any possible mutual interaction of scatterers. The total RCS of a resolution volume filled with scatterers can be written as

$$\Sigma_{ri} = \iiint \sigma_{ri}(L,\delta,\alpha,\theta,\Lambda,m)\,p(L,\delta,\alpha,\theta,\Lambda,m)\,dL\,d\delta\,d\alpha\,d\theta\,d\Lambda\,dm \qquad (9)$$

with $\sigma_{ri}(L,\delta,\alpha,\theta,\Lambda,m)$ as RCS of a scatterer at the *ri* polarization, *r* and *i* denote polarization of received and incident wave correspondingly to [10]. The function $p(L,\delta,\alpha,\theta,\Lambda,m)$ is a joint probability density function of the scatterer equivalent length *L*, rotation angle α (around the vertical axis), canting angle δ of the scatterer vertical axis, vector of shape parameters Λ, and refraction coefficient *m*. Angle θ describes the antenna elevation. Modulation of backscattering has been performed for an ice crystal cloud with uniform distribution of crystal canting and azimuth, and with normal distribution around the vertical and horizontal axis. For canting angle of ice crystals in stagnant air we usually assume the normal distribution around the horizontal axis. Turbulence creates a uniform (or almost uniform) distribution, and crystal vertical orientation may be caused by electric forces. Now DR and LDR for the ensemble of scatterers can be expressed as $Z_{DR} = 10lg(\Sigma_{hh}/\Sigma_{vv})$ and $L_{DR} = 10lg(\Sigma_{hv}/\Sigma_{vv})$, where the first index means polarization of the receiving antenna while the second index means polarization of the transmitted waveform. Calculation results of DR and LDR for rain are shown in Figure 3 as function of antenna elevation angle.

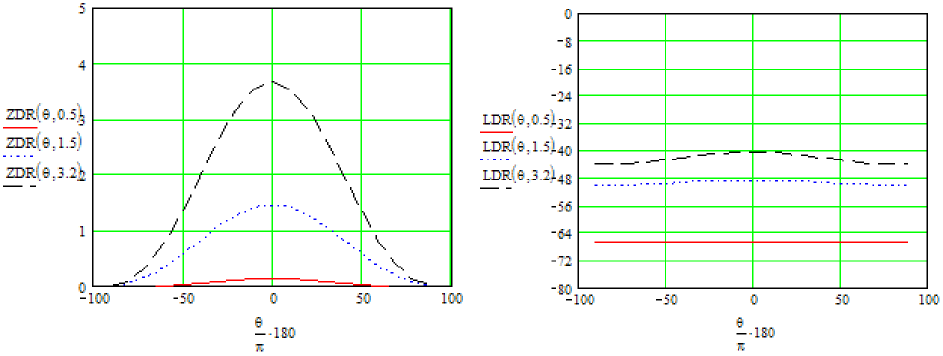

Figure 3. DR (left) and LDR (right) of rain versus elevation.

Rain is characterized by the ordered droplet orientation in the vertical plane. The polarization parameters were calculated assuming a Gaussian $p_\delta(\delta)$ distribution (with mean δ and rms σ_δ), uniform $p_\alpha(\alpha)$ distribution, and Marshall-Palmer dropsize distribution $p_D(D)$. Results for crystal clouds and analysis are presented in [4].

Ensemble of heterogeneous hydrometeors

Considering the mixture of different crystal types, we use a simple supposition that a uniform model of crystal orientation in both horizontal and vertical plane is valid; backscattering is incoherent; the total value of RCS is obtained by averaging of RCS values from various types of crystals in view of weight coefficients w. In this case the total RCS is $\Sigma_{mn_{total}} = w_{needles}\Sigma_{kl_{needles}} + w_{columnar}\Sigma_{kl_{columnar}} + w_{plates}\Sigma_{kl_{plates}}$, with $k = h;v$ and $l = h;v$.

Turbulence spectrum model

In this consideration we take into account only turbulent component of radial droplet velocity because we are interested by the influence of turbulence spectrum shape onto the Doppler spectrum width, and such influence is important for turbulence component only. Let us express analytically the turbulence spectrum as law

$$S(\Omega) = C_0\varepsilon^{2/3}\Omega^{-K}, \tag{10}$$

where C_0 is dimensionless factor of the order of unity, and the exponent of power K defines the shape of turbulence spectrum. The law of Kolmogorov is a partial case of the model (10), when K defines the shape of turbulence spectrum and equals $K = 5/3$. As it was done in [13], we again consider three partial cases of the model (10):

– Quadratic model $K = 2$ (later on, model *q*);
– Kolmogorov model $K = 5/3$ (model *k*);
– Four third models $K = 4/3$ (model *f*).

For each model S_q, S_k, and S_f one can find density of turbulent scales $w(L)$ if considering L and Ω as functionally related random values. In this case, the value $w(L,\varepsilon) = S(\Omega)/|dL/d\Omega|$ after the substitution $L = f(\Omega)$ and normalization can be interpreted as a probability density of scales for each of turbulence models:

$$w_q = \frac{1}{L_m};\ w_k = \frac{2}{3} L^{-1/3} L_m^{-2/3};\ w_f = \frac{1}{3} L^{-2/3} L_m^{-1/3}. \tag{11}$$

In expression (11) L_m is a maximal scale of turbulence that is taken into account. For calculation, it can be chosen from physic consideration; it should be in the limits of inertial range of turbulence where ε does not depend on turbulence scale. Movements of droplets cannot immediately follow to turbulent movements of air. Based on the results of [14], probability density function (PDF) of turbulent droplet velocity $p(v_T)$ can be written as:

$$p\left(\vec{v}_T\right) = \int_{L_{min(D)}}^{L_{max}} w_g\left(\vec{v}_T / L, \varepsilon\right) w(L) dL, \tag{12}$$

where $w_g(*)$ is Gaussian PDF with zero mean and the variance $\sigma_T^2 = C_0 \varepsilon^{2/3} L^{2/3}$. Upper limit of integration in formula (5) restricts the scale of turbulence $L_{max} \le L_m$. Lower limits of integration in formula (12) are important for taking into account inertia of droplets. Function $L_{min}(D)$ reflects the fact that the more the size (and mass) of a droplet the higher the inertia of the droplet [14].

By substituting values w_q, w_k or w_f from (11) to (12), after normalization one can get three expressions of PDF for turbulent velocity of droplet $p(v, \varepsilon, D)$ at each of three considered models: *q*, *k*, and *f*. Correspondent analytical expressions were obtained and analyzed in [13]. Let us designate them as $p_q(v, \varepsilon, D)$, $p_k(v, \varepsilon, D)$, and $p_f(v, \varepsilon, D)$ correspondingly. Doppler spectrum is defined as a weighted radial velocity distribution of scatterers in the reflected radar volume [7]. It can be written as

$$S(v, \varepsilon) = \int_{D_{\min}}^{D_{\max}} p(v, \varepsilon, D) \sigma(D) N(D) dD, \tag{13}$$

where $p(v, \varepsilon, D)$ is droplet radial velocity v probability distribution that depends on eddy dissipation rate ε as turbulence intensity parameter, and equivalent diameter D of droplet; $\sigma(D)$ is RCS of a droplet of given diameter; $N(D)$ is drop size distribution. By substituting models of $N(D)$ and $p_n(v, \varepsilon, D)$, $n = q; k; f$ to (13), we obtain expressions of Doppler spectra for three models: $S_q(v, \varepsilon)$, $S_k(v, \varepsilon)$, and $S_f(v, \varepsilon)$. Calculations show that PDF of droplet turbulent velocity $p_q(v, \varepsilon, D)$, $p_k(v, \varepsilon, D)$, and $p_f(v, \varepsilon, D)$ are rather different at three considered models *q*, *k*, and *f*. The results of calculating Doppler spectrum caused by turbulence were presented in [15]. Comparison of different turbulence spectrum models at different D_0 and ε shows that influence of the spectrum shape is rather weak in comparison with that of the parameters of turbulence intensity and rain rate.

Spectrum width calculations

Spectrum width is calculated as the rms W_K of the K-th spectrum (K =2; 5/3; 4/3) :

$$W_K^2 = \int_0^{v_m} v^2 S_K(v) dv - \left[\int_0^{v_m} v\ S_K(v) dv\right]^2. \tag{14}$$

Validation of the model at different rain rate and turbulence intensity was done with radar data provided by the Delft University of Technology. Figure 4 shows spectrum width as function of ε at two values of rain rate and different shapes of turbulence spectra. Analyzing the results, one can see the influence of both parameters: rain rate and eddy dissipation rate ε, that is, intensity of turbulence upon such important measurable variable of radar signal as spectrum width. These results can be useful for the interpretation of the data of atmosphere remote sensing with microwave Doppler radar. However further validation in different weather situations still is necessary. The developed model gives also the possibility to calculate Doppler spectra under the different conditions. Comparison of different turbulence spectrum models at different median drop diameter D_0 (strongly related with rain rate) and different eddy dissipation rate ε confirms that influence of the turbulence spectrum shape is negligible in comparison with influence of the parameters of turbulence intensity and rain rate. In contrast, both rain rate and turbulence significantly affect Doppler spectrum.

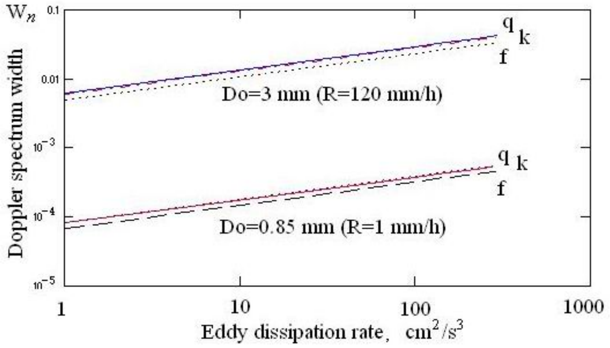

Figure 4 Spectrum width as function of eddy dissipation rate at two values of rain rate and different turbulence spectra

Dependence of Doppler spectrum width and other Doppler-polarimetric parameters on turbulence intensity under the different conditions can be used for better detection of turbulent zones by taking into account inertia of droplets and other kinds of particles.

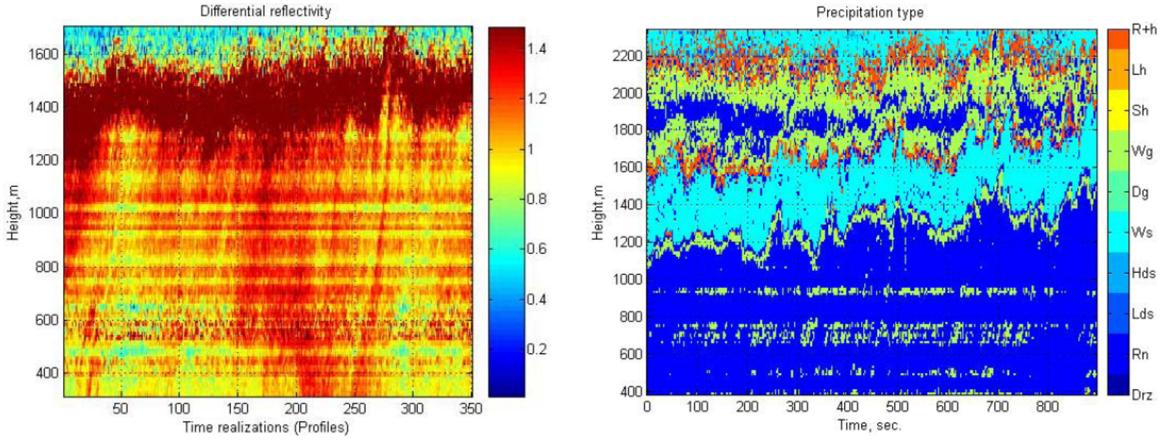

Figure 5. DR (left panel). Hydrometeor type recognition (right panel): Drz - drizzle; Rn - rain; Lds & Hds - low & high density snow; Ws - wet snow; Dg - dry graupel; Wg - wet graupel; Sh & Lh - small & large hail; R+h - rain+hail

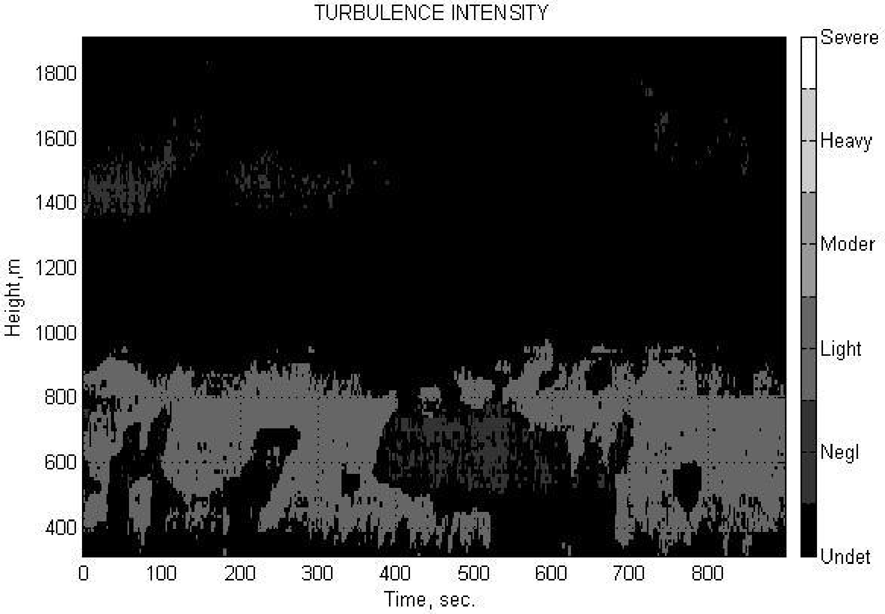

Figure 6. Turbulence detection in rain: turbulence intensity in time and height

Measurements

The Doppler-polarimetric S-band transportable atmospheric radar (TARA) which is operated by the TU-Delft [11] was used for measurements. Observations of precipitation and clouds were done on September 19, 2001 at the Cabauw Experimental Site for Atmospheric Research in the Netherlands. Numerous data were processed. For instance, Figure 5 shows examples of ZDR data and result of hydrometeor type recognition [12]. Figure 6 presents results of turbulence information extracting from radar returns from rain by using neural network technique [12].

Conclusion

The developed mathematical models of scattering from hydrometeors in turbulent atmosphere enable the calculation of polarimetric measurable variables, which are necessary to solving a number of important problems on remote sensing of clouds and precipitation. They are also useful in some tasks of wave propagation and telecommunications.

Acknowledgement

The authors thank H.W.J. Russchenberg and IRCTR sector of Remote Sensing at TU-Delft for data collection.

References

1. D. Deirmendjian, “Electromagnetic Scattering on Spherical Polydispersions,” American Elsevier Publishing Company, Inc. New York, 1969.
2. A. B. Shupiatsky, F. J. Yanovsky, "The influence of microphysical and electrical characteristics of troposphere non-homogeneity on transformation of polarization parameters of radar signals," 16 All-Union Conf. on Propagation of Radiowaves, Part 2. Kharkov, 1990, pp. 96-97 (in Russian).
3. A. B. Shupiatsky, F. J. Yanovsky, "Radar method of localization of aircraft icing zones," USSR Patent Application No 4898827, Priority 14 May 1990, positive decision, 1991.
4. A. Pitertsev, T. Sidorenko, F. Yanovsky, “Aircraft Icing Prevention Radar System: Models and Software for Calculation of Information Parameters,” Proc. International Radar Symposium, Berlin, Germany, 2005, pp. 489-492.
5. F. J. Yanovsky, “Doppler-Polarimetric Approach for Supercooled Water Detection in Clouds and Precipitation by Airborne Weather Radar,” Proc. International Radar Symposium, Warsaw, Poland, 2004, pp. 93-100.
6. I. P. Mazin, “Microstructure of clouds”, in the book “Clouds and Cloudy Atmosphere,” Leningrad, Gidrometeoizdat, 1989, 297-344 (in Russian).
7. R. Doviak, D. Zrnic, “Doppler Radar and Weather Observations,” Academic Press, Inc., London, 1993.
8. D. A. de Wolf, H. W. J. Russchenberg, L. P. Ligthart, “Effective permittivity of and scattering from wet snow and ice droplets at weather radar wavelengths,” IEEE Trans. Antennas and Propagation, Vol. 38, No 9, 1990.
9. F. J. Yanovsky, H.W.J. Russchenberg, L.P. Ligthart, “The Turbulence-Driven Relationship of Doppler and Polarimetric Radar Parameters of Rain: Introduction of the Spectral Differential Reflectivity,” IEEE Trans. Geoscience and Remote Sensing, submitted paper.
10. F. J. Yanovsky. “Polarimetric Technique for Aircraft Icing Alert Using Airborne Radar,” Proceedings of the European Radar Conference EuRAD 2004, Amsterdam, 2004, pp. 33-36.
11. A. Heldring, J. M. Rius, L. P. Ligthart, A. Cardama, “Accurate numerical modeling of the TARA reflector system”, IEEE Trans. Antennas and Propagation, Vol. 52, Issue 7, July 2004, pp. 1758-1766.
12. F. Yanovsky , V. Marchuk, Y. Ostrovsky, A. Pitertsev, “Neural Network Identification Algorithm for Weather Radar,” Proc. Int. Symposium on Tropospheric Profiling ISTP7, Boulder, CO, USA, June 11-17, 2006, CD ROM, 9 p. http://www.eol.ucar.edu/istp2006/istpprogram.html.
13. F.J. Yanovsky, Y. S. H. Khraisat, “Models of atmosphere turbulence in the tasks of remote sensing of clouds and precipitation”. Visnyk of KIUCA (Letters of the Kiev International University of Civil Aviation), Issue 1, pp. 154-160, 1999 (in Russian).
14. F.J. Yanovsky, Modeling the processes of interaction between radar signal and turbulent weather object. *Visnyk of KIUCA* (*Letters of the Kiev International University of Civil Aviation*), Issue 1, pp. 125-136, 1998 (in Russian).
15. Y. S. H. Khraisat, “Computational Model of Radar Signal Spectrum Reflected from Rain”, in *Proc. European Radar Conference EuRAD 2006*, pp. 166-169, Manchester, 2006.