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The influence of atmospheric precipitations on the operation of a ship's radar

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Abstract

The effects of precipitation of varying intensity on the operation of a ship's radar are considered. It is shown that during the propagation of the electromagnetic wave emitted by the antenna of a ship's radar, its energy is absorbed by precipitation. To determine the power loss of an electromagnetic wave due to its absorption by particles of precipitation, the effective absorption area, specific absorption coefficient, and specific effective total scattering area are used. The effective areas of absorption and total scattering depend on the shape of the precipitation particles, their size, state of aggregation, and the length of the electromagnetic wave emitted by the antenna of the ship's radar. The dependence of the effective absorption area on the particle size of precipitation is obtained at two wavelengths of 3 cm and 10 cm, on which the ship's radars operate. A decrease in the tracking range of an object tracked by a ship's radar in the case of rain falling is established compared with the tracking range of an object in clear weather. It is shown that a decrease in the tracking range of an object occurs only with moderate, strong, and very heavy rain. The attenuation of electromagnetic energy in rain with an intensity of 12.5 mm/h at a wavelength of 3 cm is obtained by calculation, which amounted to 24 dB with a length of the falling rain zone of 50 km, as well as with rain with an intensity of 100 mm/h with the same length of the precipitation zone.

Introduction: statement of the problem in general form and its connection with scientific and practical tasks

Currently, there is no data on the absorption of the power of an electromagnetic wave by precipitation particles, which means we are unable to determine with sufficient accuracy the distance to a navigation object using a ship's radar in the presence of precipitation. The existing theory of attenuation for the power of an electromagnetic wave is based on considering only the scattering of the power of the wave on the precipitation particles. When detecting precipitation zones, the ship's radars only use the effective backscatter area, even though (during power backscattering) its absorption also occurs. The amount of absorbed power by the radar space within the precipitation zone is obtained by multiplying the effective absorption area σ_A by the power flux density of the incident wave. The power loss during radar tracking of a navigation object of a ship's radar, located in the zone of precipitation along the entire path of propagation of an electromagnetic wave, is determined by its absorption and backscattering via the ratio:

$$dP_A = -N\,\sigma_A\,P_0\,dR \tag{1}$$

where P_A represents the power absorbed by precipitation particles, W, and N signifies the number of particles in the radar space, and P_0 is the power supplied to the receiver input due to backscattering by the precipitation particles.

The absorption and complete dissipation of the electromagnetic energy by the precipitation zone reduces both the range of the ship's radar and the probability of detecting a navigation object located in the precipitation zone.

Analysis of publications and recent results in which the solution to the considered problem has been started and the allocation of previously unsolved parts of the general problem

The weakening of electromagnetic energy in clouds and precipitation is considered in numerous articles (Odedina & Afullo, 2010; Grábner, Pechac & Valtr, 2018; Norouzian et al., 2019; Williams, 2022), in which the basic information about the effect of precipitation on the radar surveillance of objects is presented. In one paper (Grábner, Pechac & Valtr, 2018), an analysis of the attenuation of radio microwaves in the troposphere was performed. Another article (Norouzian et al., 2019) considers the attenuating property of the atmosphere and analyzes the intensity of the processes of scattering electromagnetic energy emitted by the ship's radar antenna. Recent research (Williams, 2022) considers the interaction of electromagnetic waves with the atmosphere. An analysis of the attenuation of electromagnetic energy by atmospheric gases, and in polydisperse hydrometeor formations, was also performed.

Research methods for calculating the radar characteristics of particles of hydrometeorological formations and the attenuation of the radar signal along its path are also considered (Odedina & Afullo, 2010). In addition, the influence of a homogeneous, turbulent medium and a medium with meteorological formations on the propagation of electromagnetic waves passing through these media during radar observation of navigation objects of a ship's radar was studied (Putyatin, Korban & Knyaz, 2018).

Other work (Korban, 2015) considered the use of the distribution laws of particles of various precipitation that accords to Litvinov and Shifrin, accounting for the nature of their formation, to estimate the decrease in the maximum detection range of navigation objects by the ship's radars operating at a wavelength of 3 cm. The analysis of the influence of precipitation of varying intensity on the reduction of the maximum range of detection of navigational objects by ship's radars was also considered. It was established in previous research (Korban, 2015) that, when there are sections of the atmosphere with precipitation and without precipitation along the path of propagation of electromagnetic energy emitted by the ship's radar, the total error in measuring the distance to the navigation object is determined by the values of the refractive indices of the pure atmosphere and precipitation.

Further research (Putyatin et al., 2017) considered the radio physical model of the reflective properties of the object navigation and meteorological formations, allowing navigation radar detection of an object in the presence of airborne moisture targets for the polarization differences of the reflected signals from a navigation object and meteorological formations. It is given a functional scheme of the radar layout that implements the process of radar recognition by separating them from a received signal of an electromagnetic wave of circular polarization reflected from the navigation object and an elliptically polarized electromagnetic wave reflected from a meteorological object.

In other work (Eremka et al., 2013), the features of radio wave propagation over the sea surface were considered both in the over-the-horizon region and in the line-of-sight zone. A technique and instrumental measuring systems were described for determining the distance dependences of the attenuation factor for VHF and microwave radio waves. Here, the effects of the real shape of the radiation pattern of antenna systems on the distance variation of the radio wave attenuation factor outside the radio horizon were considered. Moreover, the results of research on the altitude profile of the refractive index of the atmosphere over the Black Sea using microwave refractometers were presented. Examples of the influence of the vertical profile of the atmospheric refractive index on the radio wave propagation conditions were also offered.

Another paper (Knyaz, 2015) considered the methods and means of observing radar objects in difficult situations due to the atmospheric environment using a ship's radar. The development of a method and means of improving the information efficiency of ship's radars using polarization selection was also performed.

Formulation of the objectives of the paper (statement of the problem)

The presence of a navigation object in difficult atmospheric conditions predetermines the most unfavorable operating conditions for a ship's radar for radar surveillance of navigation objects on the ship's route. Under such conditions, the transmitted radar signal, when propagating to the navigation object, is the sum of the completely scattered and absorbed energy. The loss of power of the electromagnetic wave emitted by the ship's radar antenna leads to an increase in the absolute error of tracking the navigation object, whereas the backscatter of the signal power within the precipitation zone illuminates large areas of the indicator and completely masks the echo signals of the navigation object. The circumstances due to the possible influence of precipitation are much more numerous and variable. Therefore, it is necessary to introduce coefficients into the radar equation for point targets that consider the attenuation of the power of an electromagnetic wave within the precipitation zones, which is characterized by volumetric absorption and total power dissipation.

The purpose of this research is to establish the possibility of considering the influence of precipitation on the operation of a ship's radar during the radar surveillance of navigation objects.

Presentation of the research material with the substantiation of the obtained scientific results

One of the main factors limiting the range of radar surveillance of navigational objects during precipitation is the weakening of the electromagnetic energy emitted by the ship's radar antenna within the falling rain zone.

The simplest description of the effect of precipitation on the operation of a ship's radar is the radar range equation, one of the variants of which is given elsewhere (Odedina & Afullo, 2010; Grábner, Pechac & Valtr, 2018; Norouzian et al., 2019; Williams, 2022) and is written as:

$$P_{RC_{\min}} = \frac{P_e G^2 \theta^2 \lambda^2 \sigma_{no}}{(4\pi)^3 R^4} \alpha_{\text{att}} \tag{2}$$

where $P_{RC_{\min}}$ represents the minimum echo signal power supplied to the input of the ship's radar antenna, *W*, P_e signifies the emitted power, *W*, *G* is the directivity factor of the ship's radar antenna, λ is the length of the emitted wave in units of cm, σ_{no} is the effective scattering surface of a navigation object in m^2, *R* is maximum detection range of a navigation object in km, and α_{att} is the attenuation coefficient of the electromagnetic energy in the precipitation zone.

The magnitude of the echo signal decreases not only due to the distance (i.e., decreases in proportion to the square of the distance) but also because of the absorption and complete scattering by the particles of precipitation of varying intensity. The decrease in the power of the radar signals due to the absorption of total scattering occurs exponentially. Then the average power at the input of the ship's radar receiver is written as:

$$\overline{P}_{RC} = \overline{P}_0 e^{-0.2\alpha} \tag{3}$$

where $\overline{P}_0$ signifies the average power of the echo signal of the navigation object in the absence of precipitation weakening (i.e., clear weather) and α is the attenuation coefficient of the electromagnetic energy due to precipitation.

The attenuation coefficient, α, depends on the length of the precipitation zone and is determined in the direction of the passage of an electromagnetic wave from the ship's radar antenna through the precipitation zone and in the opposite direction of the wave (when it is scattered within the precipitation zone to the receiving antenna of the ship's radar). Then the attenuation coefficient is written as follows:

$$\alpha = 2\int_0^R \alpha'(R)\, dR \tag{4}$$

where $\alpha'(R)$ characterizes the change in the reflecting and absorbing properties of the precipitation zone along the direction of the beam. The factor "2" accounts for the passage of the electromagnetic energy of the distance *R* in two directions and is measured in neper/km.

Considering equation (4), the expression given by (3) can be represented as:

$$\overline{P}_{RC} = \overline{P}_0 e^{-2\int_0^R \alpha'(R) dR} \tag{5}$$

The transition from the unit "neper/km" to "decibels" is made by comparing the power in tenths of the logarithm of ten, while taking the unit of comparison in the decimal scale to increase or decrease the decimal logarithm by 0.1.

Next, equation (5) is rewritten for decibels in the form:

$$\overline{P}_{RC} = \overline{P}_0 10^{-0.2\int_0^R \alpha'(R) dR} \tag{6}$$

Here, we do not consider the attenuation of the electromagnetic energy by atmospheric gases since, at the wavelengths used in the ship's radar (i.e., $\lambda = 3$ cm and $\lambda = 10$ cm), the attenuation can be neglected.

If there is a zone of precipitation (liquid or solid) on the path of the propagation of the electromagnetic energy, we consider attenuation due to absorption and complete scattering of the precipitation by the particles. To complete this task, we establish a relationship between the attenuation coefficient and the effective areas of absorption and total scattering, i.e., σ_A and σ_{TS}. Based on previous work (Odedina & Afullo, 2010; Grábner, Pechac & Valtr, 2018; Norouzian et al., 2019; Williams, 2022), these areas are determined by the following dependencies:

$$\sigma_A = \frac{P_A}{\overline{P}_0}, \quad \sigma_{TS} = \frac{P_{TS}}{\overline{P}_0} \tag{7}$$

where P_A and P_{TS} are the power values of the electromagnetic wave lost during the passage through the precipitation zone due to absorption and total scattering, respectively.

From equation (7), the value of wave energy losses can be determined as:

$$P_A = \sigma_A \overline{P}_0, \quad P_{TS} = \sigma_{TS} \overline{P}_0 \tag{8}$$

When passing through the precipitation zone, an electromagnetic wave interacts with N particles of precipitation on an elementary path dR. We assume that, in an elementary radar space of precipitation limited by the width of the radiation pattern of the ship's radar antenna and the emitted spatial pulse length, there are N identical spherical liquid or solid particles of precipitation. Moreover, on an elementary section of the path dR, the following values of radiated power are, respectively, absorbed and totally scattered:

$$dP_A = -N\sigma_A \overline{P}_0 dR, \quad dP_{TS} = -N\sigma_{TS} \overline{P}_0 dR \tag{9}$$

where N is the number of particles in cm^3. The integration of equation (9) can obtain the power loss of the electromagnetic wave emitted by the ship's radar antenna when it passes through the precipitation zone so that:

$$\ln\left(\frac{P_A}{\overline{P}_0}\right) = -N\sigma_A R, \quad \ln\left(\frac{P_{TS}}{\overline{P}_0}\right) = -N\sigma_{TS} R \tag{10}$$

Considering equation (10), the attenuation coefficient from equation (3) can be written in terms of its components α_A and α_{TS}, which characterize the loss of radiated power on a one-kilometer path in the following form:

$$\alpha_{\Sigma_{att}} = \alpha_A + \alpha_{TS} \tag{11}$$

where

$$\alpha_A = 4.34 \cdot 10^3\, N\sigma_A, \quad \alpha_{TS} = 4.34 \cdot 10^3\, N\sigma_{TS} \tag{12}$$

The coefficients α_A and α_{TS} are, respectively, the specific coefficients of absorption and total scattering of electromagnetic energy in the precipitation zone on a one-kilometer path; they are measured in the unit dB/km. Then, considering equation (12), the total attenuation coefficient of the radiated electromagnetic energy of the ship's radar antenna as it passes through the precipitation zone is determined from the condition:

$$\alpha_{\Sigma_{att}} = 4.34 \cdot 10^3 N(\sigma_A + \sigma_{TS}) = 4.34 \cdot 10^3 N\sigma_\Sigma \tag{13}$$

To determine the total attenuation coefficient of equation (12), it is necessary to obtain information about the number of particles N (in a 1 cm^3) and the values of α_A and α_{TS}. The calculation of α_A and α_{TS} can be performed for a spherical particle according to the following dependencies:

$$\sigma_{A_i} = \frac{\pi^2 d^3}{\lambda} \operatorname{Im}\left(-\frac{m^2-1}{m^2+2}\right) \tag{14}$$

$$\sigma_{TS_i} = \frac{2}{3}\frac{\pi^5 d^6}{\lambda^4}\left|\frac{m^2-1}{m^2+2}\right|^2 \tag{15}$$

where d signifies the diameter of a spherical particle in units of cm, m corresponds to the complex refractive index of the particle substance, and Im denotes the imaginary part of the complex number in brackets.

The imaginary part and the squared absolute value in equations (14) and (15) characterize the influence of the aggregate state of the precipitation particles on the values of σ_A and σ_{TS}. The temperature dependence of the imaginary part of the ratio of the refractive index, and its absolute value, are presented in Tables 1 and 2 for water and ice, respectively.

Analysis of Tables 1 and 2 shows that the squared absolute value and the imaginary part of the ratio $(m^2-1)/(m^2+2)$ depend on the water particles of precipitation, both in terms of temperature and wavelength. For the ice particles of precipitation, there is no dependence of the value of the squared absolute value and the imaginary part of the ratio $(m^2-1)/(m^2+2)$ on the wavelength; there is only a dependence on the temperature.

Scattering in the direction of the ship's radar generates a signal reflected from the particles of the falling rain, which creates a mark on the indicator

Table 1. Temperature dependence of the squared absolute value and the imaginary part of the ratio (m^2–1)/(m^2+2) for water

Parameter	Temperature t, °C	λ, cm	
		3.0	10.0
$\left\lvert \frac{m^2-1}{m^2+2} \right\rvert^2$	20	0.9275	0.928
	10	0.9282	0.9313
	0	0.9300	0.9340
	–8	–	–
$\mathrm{Im}\left(-\frac{m^2-1}{m^2+2}\right)$	20	0.1883	0.00475
	10	0.0247	0.00688
	0	0.0335	0.01102
	–8	–	–

Table 2. As Table 1 but for ice

Parameter	Temperature t, °C	Parameter value
$\left\lvert \frac{m^2-1}{m^2+2} \right\rvert^2$	At all temperatures, if the density is 1 g/m^3	0.197
$\mathrm{Im}\left(-\frac{m^2-1}{m^2+2}\right)$	0	$9.6 \cdot 10^{-4}$
	–10	$3.2 \cdot 10^{-4}$
	–20	$2.2 \cdot 10^{-4}$

around the precipitation zone in which the navigation object is located. The effective backscattering area, σ_B, of a spherical particle is given by:

$$\sigma_B = \frac{\pi^5 d^6}{\lambda^4} \left\lvert \frac{m^2-1}{m^2+2} \right\rvert^2 \tag{16}$$

Here, the dimensions of a spherical particle satisfy the condition $\pi d/\lambda << 1$. Spherical particles found in fog and low-intensity rain (up to 1 mm/h) scatter and absorb electromagnetic energy depending on their size and phase state. Table 3 shows the effective areas of absorption σ_A, total scattering σ_{TS}, and backscattering σ_B towards the antenna of the ship radar of electromagnetic energy for two wavelengths (λ = 3 cm and λ = 10 cm) by the spherical water particles, the diameter of which varies from 0.05 cm to 0.5 cm.

During radar surveillance of a navigation object located in the zone of atmospheric formation or behind the zone of falling rain, electromagnetic energy is weakened by the entire extended zone of the precipitation. Therefore, to consider the complete attenuation of the energy of an electromagnetic wave, the absorption α_A and total scattering α_{TS} coefficients of equation (12) are used, which enable the obtaining of the magnitude of the attenuation of electromagnetic energy via precipitation of varying intensity.

Using the value of the total effective attenuation area of equation (13), considering the distribution of the precipitation particles according to Laws and Parsons (Laws & Parsons, 1943), in Table 4 we show the attenuation of radio waves (dB/km) in rain of varying intensity at 20°C.

Table 4. Value of the attenuation coefficient α (dB/km) of the electromagnetic waves in rain with different intensity I_r for λ = 3 cm and λ = 10 cm

I_r, mm/h	λ = 3 cm	λ = 10 cm
0.25	$0.172 \cdot 10^{-3}$	$0.780 \cdot 10^{-4}$
1.25	$0.116 \cdot 10^{-1}$	$0.350 \cdot 10^{-3}$
2.50	$0.284 \cdot 10^{-1}$	$0.678 \cdot 10^{-3}$
5.00	$0.718 \cdot 10^{-1}$	$0.133 \cdot 10^{-2}$
12.50	0.240	$0.330 \cdot 10^{-2}$
25.00	0.602	$0.678 \cdot 10^{-2}$
50.00	1.450	$0.142 \cdot 10^{-1}$
100.00	3.430	$0.309 \cdot 10^{-1}$
150.00	5.490	$0.492 \cdot 10^{-1}$

Table 3. Effective areas of absorption σ_A, total scattering σ_{TS}, and backscattering σ_B by spherical water particles at a temperature of 20°C

d, cm	Radiated wavelength λ, cm					
	λ = 3 cm			λ = 10 cm		
	σ_A	σ_{TS}	σ_B	σ_A	σ_{TS}	σ_B
0.05	$9.15 \cdot 10^{-6}$	$3.62 \cdot 10^{-8}$	$2.80 \cdot 10^{-9}$	$6.90 \cdot 10^{-7}$	$2.93 \cdot 10^{-10}$	10^{-16}
0.10	$1.5 \cdot 10^{-4}$	$2.35 \cdot 10^{-6}$	$3.2 \cdot 10^{-9}$	$5.82 \cdot 10^{-6}$	$1.88 \cdot 10^{-8}$	10^{-15}
0.15	$1.27 \cdot 10^{-3}$	$2.74 \cdot 10^{-5}$	$1.21 \cdot 10^{-8}$	$2.14 \cdot 10^{-5}$	$2.15 \cdot 10^{-7}$	10^{-15}
0.20	$5.37 \cdot 10^{-3}$	$1.58 \cdot 10^{-4}$	$1.84 \cdot 10^{-8}$	$5.64 \cdot 10^{-5}$	$1.21 \cdot 10^{-6}$	10^{-14}
0.25	$1.57 \cdot 10^{-2}$	$6.06 \cdot 10^{-4}$	$1.49 \cdot 10^{-8}$	$1.41 \cdot 10^{-4}$	$4.62 \cdot 10^{-6}$	10^{-13}
0.30	$3.53 \cdot 10^{-2}$	$1.98 \cdot 10^{-3}$	$1.62 \cdot 10^{-8}$	$2.46 \cdot 10^{-4}$	$1.38 \cdot 10^{-5}$	10^{-13}
0.35	$6.11 \cdot 10^{-2}$	$5.36 \cdot 10^{-3}$	$3.5 \cdot 10^{-8}$	$4.46 \cdot 10^{-4}$	$3.50 \cdot 10^{-5}$	10^{-12}
0.40	$9.49 \cdot 10^{-2}$	$1.31 \cdot 10^{-2}$	$3.8 \cdot 10^{-8}$	$7.66 \cdot 10^{-4}$	$7.85 \cdot 10^{-5}$	10^{-12}
0.45	0.1224	$2.96 \cdot 10^{-2}$	$3.9 \cdot 10^{-8}$	$1.24 \cdot 10^{-3}$	$1.59 \cdot 10^{-4}$	10^{-11}
0.50	0.1514	$6.36 \cdot 10^{-2}$	$4.5 \cdot 10^{-8}$	$1.95 \cdot 10^{-3}$	$3.01 \cdot 10^{-4}$	10^{-10}

The weakening of electromagnetic energy within the precipitation zone occurs in two directions. If the precipitation zone in which the navigation object is located occupies a distance of 50 km, and the intensity of precipitation is I_r = 12.5 mm/h, then the attenuation in the precipitation at a wavelength of λ = 3 cm is given by:

$$\alpha_{\text{att}} = 2 \cdot 50 \cdot 0.240 = 24 \text{ dB}.$$

With the intensity of precipitation equal to I_r = 100 mm/h (i.e., a tropical cyclone), with the same length of the precipitation zone, the attenuation coefficient will be:

$$\alpha_{\text{att}} = 2 \cdot 50 \cdot 3.43 = 343 \text{ dB}.$$

At a wavelength of 10 cm, the attenuation coefficient for precipitation intensity equal to I_r = 12.5 mm/h is:

$$\alpha_{\text{att}} = 2 \cdot 50 \cdot 0.330 \cdot 10^{-2} = 0.33 \text{ dB},$$

and, for the intensity of precipitation equal to I_r = 100 mm/h, we find:

$$\alpha_{\text{att}} = 2 \cdot 50 \cdot 0.309 \cdot 10^{-1} = 3.09 \text{ dB}.$$

The value of the electromagnetic energy reflected within the rain zone at the input of the ship's radar antenna is determined by the radar equation, on condition that the radio beam is completely filled with precipitation particles, so that:

$$\overline{P}_{RC} = \frac{\pi^4 P_e A h}{8\lambda^4 R^2} \left| \frac{m^2 - 1}{m^2 + 2} \right|^2 \Sigma N d^6 \tag{17}$$

where $\overline{P}_{RC}$ signifies the radiated power of the ship's radar antenna in units of kW, A is the antenna aperture area in m^2, h is the spatial emitted pulse length in m, R is the distance to the zone of falling rain in km, d is the diameter of precipitation particles in cm, and λ is the wavelength of the emitted wave in cm.

In equation (17), the values of P_e, A, h, and λ refer to the technical parameters of the ship's radar and are combined into the energy potential Π_E, i.e.:

$$\Pi_E = \frac{\pi^4 P_e A h}{8\lambda^4} \tag{18}$$

and the multiplier is written as:

$$\left| \frac{m^2 - 1}{m^2 + 2} \right|^2 \Sigma N d^6 = \eta_{\text{eff}} \tag{19}$$

which characterizes the effective reflection area of the rainfall zone. Considering equations (18) and (19), the radar equation for rain can be written as:

$$\overline{P}_{RC} = \Pi_E \frac{\eta_{\text{eff}}}{R^2} \tag{20}$$

or in decibels as:

$$10\lg \overline{P}_{RC} = 10\lg \Pi_E + 10\lg \eta_{\text{eff}} - 20\lg R \tag{21}$$

Let us denote the detection range of the navigation object in the presence of precipitation R_d and in the absence of precipitation R_c. Then, during radar surveillance of navigational objects in clear weather, the radar equation is written as:

$$\overline{P}_{RC} = \frac{\pi^4 P_e A h \sigma_{no}}{8\lambda^4 R_c^2} \tag{22}$$

where σ_{no} is the effective reflecting surface of the object in units of m^2.

Radar surveillance of an object in the presence of precipitation is characterized by the following radar equation:

$$\overline{P}_{RC} = \frac{\pi^4 P_e A h \sigma_{no}}{8\lambda^4 R_d^2} K_{\text{att}} \tag{23}$$

where K_{att} is the electromagnetic energy attenuation factor in rain. The latter is explicitly given by:

$$K_{\text{att}} = 10^{-0.2} \int_0^{R_d} \alpha(R_d)\, dR_d \tag{24}$$

where $\alpha(R_d)$ is the coefficient of absorption of the electromagnetic energy within the zone of falling rain, with a length of R_d (in units of dB/km), accounting for its scattering inside the rain zone by precipitation particles.

Let us denote the power of the electromagnetic wave entering the rainfall zone as P_{in}, and the power that passed through the rain zone and returned to the side of the ship's radar antenna as P_{out}. Then both powers are interconnected with the length of the rain zone by an exponential dependence, i.e.:

$$P_{\text{in}} = P_{\text{out}} e^{-2\alpha R_d} \tag{25}$$

This expression corresponds to the attenuation of the electromagnetic energy, expressed in decibels, proportional to the distance traveled in both directions equal to 8.68 dB per unit length of the rainfall zone.

The value of the attenuation coefficient is determined by the intensity of the falling rain and the physical properties of the rain particles (i.e., the size, shape, phase state, and distance between them) and by the length of the irradiating wave; it is approximately proportional to the density of the rain.

Table 5. Reducing the tracking range of an object on a 3 cm ship's radar during rain of varying intensity

Drizzle $I = 0.25$ mm/h		Light rain $I = 5$ mm/h		Rain of moderate intensity $I = 5$ mm/h		Heavy rain $I > 40$ mm/h		Rain of very heavy intensity $I = 100..150$ mm/h	
R_c, km	R_d, km	R_c, km	R_d, km	R_c, km	R_d, km	R_c, km	R_d, km	R_c, km	R_d, km
25.0	25.0	25.0	24.5	25.0	17.5	25.0	10.0	25.0	5.0
50.0	45.0	50.0	45.0	50.0	35.0	50.0	22.0	50.0	3.5
75.0	70.0	75.0	62.5	75.0	47.0	75.0	28.0	75.0	3.0

Attenuation is especially noticeable at high speeds for the falling rain particles and a large length of the rain zone. There are two options for radar observation of a ship's radar objects: tracking an object in clear weather at the maximum range R_c and tracking an object in the presence of rain, the particles of which fall at a speed of v_r (in units of mm/h).

Let us set the tracking range, R_r, of the object in the presence of rain. There are two possible occurrences here:

- rain wave attenuation of the electromagnetic wave $2\alpha v_r R_r$, with dB in the length of the rain observation zone ($2R_r$ is the distance traveled by the wave from the ship's radar antenna to the object in the presence of rain);
- decrease in the tracking range of an object from R_c to R_r, which introduces an increase in backscatter power received by the ship's radar antenna by a factor of $(R_c/R_r)^4$ or by $40\lg(R_c/R_r)$ in units of dB. This increase in received power (due to rain reflection) is accurately compensated by the attenuation endured by the rain. Thus, we obtain the following equality:

$$2\alpha v_r R_r = 40\lg\frac{R_c}{R_r} \tag{26}$$

From here, the maximum tracking range of the ship's radar object is determined in the presence of falling rain with the intensity available at a given time, i.e.:

$$R_r = \frac{20\lg\frac{R_c}{R_r}}{\alpha v_r} = \frac{20\lg\frac{R_c}{R_r}}{\alpha I_r} \tag{27}$$

where I_r is the intensity of rain in units of mm/h. Heavy rain produces intense backscattering of the electromagnetic energy of the wave irradiating within the rain zone. It is a potential source of interference for the indicator of the ship's radar and makes it difficult to track an object (even within range) via equation (27).

Given the known technical characteristics of the ship's radar, the intensity, and geometrical dimensions of the rain zone, as well as the range R_r for the ship's radar, equation (27) can be solved with respect to the tracking range of an object in clear weather, in the presence of rain, and within range R_r, i.e.:

$$R_c^4 = \frac{R_r^4}{\alpha} + 3.25\cdot 10^7\ I_r^{1.6} \tag{28}$$

The results of calculating the change in the range of a ship's radar, which has technical parameters $P_e = 60$ kW…29 dB, wavelengths $\lambda = 3$ cm, duration of the emitted pulse $\tau_e = 0.6$ µs, and receiver noise figure 16 dB, due to the influence of falling rain R_r (in comparison with the range in clear weather R_c) are listed in Table 5.

Analysis of Table 5 shows that only moderate, heavy, and very heavy rainfalls affect the reduction in the tracking range of the navigational objects of the ship's radar.

Conclusions and prospects for further research in this area

The following new scientific results were obtained in this paper:

1. The absorption of electromagnetic energy emitted by the ship's radar antenna within precipitation with a particle diameter from 0.05 cm to 0.5 cm (at a wavelength of 3 cm and 10 cm), and the backscatter of electromagnetic energy towards the ship's radar antenna, were considered.
2. A decrease in the tracking range of an object by a ship's radar was obtained during falling rain, with intensities from weak to very heavy, compared to the tracking range of an object in clear weather.

The results obtained in this paper can be used, in practice, to improve the radars of existing ships and the development of new radars in order to improve their characteristics when used in atmospheric precipitation conditions. Further research will be aimed at estimating the effect of attenuation and backscatter on the radar tracking range of a ship's radar object during precipitation of varying intensity.

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