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The frequency range selection for airborne weather radar with the search for areas with the visibility of landmarks for flight and landing

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A radar dome of a small aircraft can accommodate an antenna with a small aperture only. The energy potential and radiation parameters required for detection of hazardous weather events are thereby impaired. Mathematical modeling of the effect of wavelength change on the quality of radar meteorological forecast has been performed. Performance parameters of small-sized weather radars have been evaluated for enhancing the safety of the flights of small aircraft. Mathematics have been presented for comparing the efficiency of detecting dangerous thunderstorm areas with allowance for the signal reflection from the ground surface. The formula take into account the wavelength, the directional function of the antenna system, the radar reflectivity of the ground surface, the speed and altitude of flight. The efficiency of the weather radar with a small-sized antenna aperture operating in 3 cm and 8 mm wave lengths has been reviewed. The detection range of small aircraft radars with different wavelengths in different weather conditions has been determined. A flight envelope search mode is proposed with a possibility of visual orientation and landing in bad weather conditions. The mode is based on measuring the radar reflectivity of moisture targets.

Keywords: weather radar, ground clutters, detection of thunderstorms, visibility of ground objects

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Introduction

To date, the increasingly greater attention is devoted to the problem of air safety support under complicated meteorological conditions for flight vehicles of general aviation (small aircraft) [1]. Weather radars installed at the aircraft of civil aviation are used for the automatic identification of thunderstorm cloud zones (automatic detection of thunderstorms); these radars use the emission wavelengths in the 3.0–3.2 range ensuring the underdamping of electromagnetic waves in the atmosphere [2]. Whereby, the gross geometry of antenna systems located under the fairing of aircraft is too large in the case of small airplanes. The proliferation of small aircraft for general aviation requires the arrangement of smaller antennas in small-size compartments, which leads to the decrease in the antenna power gain and the extension of the aerial directivity function; this is accompanied both by the reduction of the detection range for areas of dangerous moisture targets and by the degradation of accuracy for the boundary delimitation of these areas.

In addition, small-size antennas are complicated in use for the generation of amplitude distributions ensuring the low level of side lobes. This provides the high power of signal radiation and reception reflected from the Earth's surface by the side lobes and leads to the appearance of false areas for dangerous thunderstorms at the display form for the pilot.

The analysis of weather radar efficiency in different frequency bands

It is necessary to study the differences in the effective use of millimeter (EHF) and centimeter (SHF) wavelength bands for the automatic detection of dangerous thunderstorms along the flight track; this is necessary for the reduction of the adverse effect of antenna size reduction. The 8-mm (EHF) and 3-cm (SHF) wavelength bands radar stations (RSs) typified by lower atmospheric attenuation were selected for such comparison [3].

The differences in weather radar operating efficiency were considered both in the context of the potential detection of dangerous thunderstorm areas and for the estimation of ground clutter reduction. These ground clutters have a strong adverse effect, since the flights of small aircraft are implemented at low altitudes. Let us consider further the way of estimation of the signal-to-interference from the Earth (signal-to-noise) ratio at the weather radar.

It is known that radar measurements in the mode for detection of dangerous thunderstorm cells are implemented with the estimation of Z radar reflectivity [3]. It should be noted that radar meteorology introduces the terms of specific radar cross-section (SRCS) for power, radar reflectivity of all cloud particles located in the volume unit and radar cross-section (RCS) of power [4].

The value of SRCS η, m^2/m^3 is calculated using the formula [4]:

$$\eta = \frac{\pi^5 Z}{\lambda^4}|K|^2, \tag{1}$$

where Z is radar reflectivity (mm^6/m^3); λ is the wavelength of the sounding signal (m); K is the coefficient which can be determined on the basis that [2]:

$$K = \frac{\varepsilon^* - 1}{\varepsilon^* + 2},$$

where ε^* is the complex dielectric constant of a water particle. The real and imaginary components for the complex dielectric constant of a water particle can be calculated by the formulas [2]:

$$\mathrm{Re}\,\varepsilon^* = n_0{}^2 + \frac{\varepsilon_0^{*2} - n_0{}^2}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2};$$

$$\mathrm{Im}\,\varepsilon^* = \frac{\lambda_s}{\lambda}\frac{\varepsilon_0^{*2} - n_0{}^2}{1 + \left(\frac{\lambda_s}{\lambda}\right)^2},$$

where $\varepsilon_0^* = 80.8$ is the static permittivity; $n_0 = 1.34$ is the optical index of refraction; $\lambda_s = 0.016$ is the wavelength for the hop.

The RCS value is calculated by the formula [4]:

$$\sigma_\text{м} = \eta V_\text{м}, \tag{2}$$

where $V_\text{м}$ is the volume of the moisture target (m^2).

Z is measured in dBZ [1] in the case of identification of a moisture target dangerous for flights:

$$Z[\text{дБ}Z] = 10\log Z\left[\text{мм}^6/\text{м}^3\right],$$

where the $x[y]$ record means the number of y units at the x physical value.

The term of a standard thunderstorm cell is used for the assessment of capability for detection of a dangerous thunderstorm in the specified range; one side of such cell (transversal to the radio-frequency signal propagating direction) is equal to 5.5 km, and another is equal to the length of the range resolution cell. The Z value is estimated by power reflected from the moisture target. The moisture targets with $Z \geq 40$ dBZ [1] are considered as dangerous for the flight of aircraft.

The comparison methods for the power of desired and interfering signals

The efficiency of minimizing the influence of rereflection from the Earth's surface on the moisture target threat evaluation can be determined as follows. One should correlate the signal power received by the basic beam (which is reflected from the bin with a dangerous moisture target) with the power of the interfering signal going by the side lobes after the reflection from the Earth's surface.

Let us consider the methods for comparison of these powers excluding the difference of attenuation losses inside the atmosphere in the flight line of the aircraft and in the segment of interfering signal propagation (aircraft – the Earth's surface). In other words, let us accept that the attenuation is the same, and the values characterizing the attenuation losses inside the atmosphere would be reduced during the determination of the interference power-to-signal power (from the moisture target) ratio. Let us determine the mathematical expectation for the power signal reflected from the Earth' surface at the discrete value of range and frequency filter where the parameters of the moisture target are estimated. This can be done as follows. Let us solve the special case of the task for sounding along the flight line of the aircraft. The geometrical formulation of the problem is presented in Fig. 1.

Let us select the random semiring of the range (marked with grey color in Fig. 1). This semiring corresponds to the bin along the flight line of the aircraft (marked with grey color at the X-axis) where the threat evaluation is implemented. The number of the range discrete value for this nd_1 bin can be determined by the formula:

$$nd_1 = \mathrm{round}\frac{R}{R},$$

where round is the function of rounding-off to the nearest integer; R is the present range, m; $\Delta R = 0.5ct_{imp}$ is the dimension of the range discrete value, m; c is the light velocity, m/sec; t_{imp} is the duration of the sounding pulse, sec.

The T_p pulse-repetition period will depend on the required unequivocal detection range for the dangerous moisture target. Let us select the maximum detection range for the dangerous thunderstorm cell equal to 100 km; this allows the flight with the speed about $V_{fv} = 200$ km/hours during 30 minutes, and the route for safe flying around the thunderstorm area or rightabout can be provided meanwhile. One can use the simulation case where the Earth's surface is located in the range

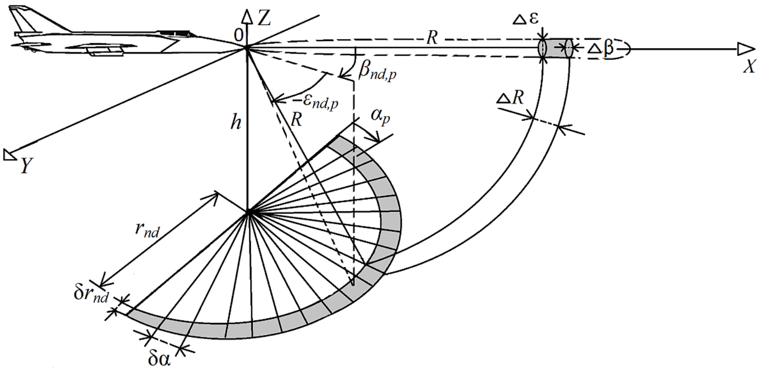

Fig. 1. Geometrical formulation of the problem for calculating interferences generated by the Earth's surface

from the flight altitude of the RS carrier h to the range of «damping of the Earth's background» ($x_{\max} = y_{\max} = R_b \approx 200$ km). Let us determine the numbers of range discrete values corresponding to these signals reflected from the Earth's surface by the formula:

$$nd = nd_1 + w\frac{0,5cT_{\text{п}}}{R}$$

subject to the condition $h \leqslant nd\Delta R \leqslant R_b$;

$$w = -\operatorname{round}\frac{R_{\text{ф}}}{R} \; ... \; \operatorname{round}\frac{R_{\text{ф}}}{R},$$

where w is the variable for enumeration of all range rings at the interval specified for modeling.

Let us determine the near boundary of range semirings which are located at the «Earth's» surface plane for nd selected numbers using the formula:

$$r_{nd} = \sqrt{(nd \quad R)^2 - h^2}.$$

The length of range «semiring» at the Earth's surface is

$$\delta r_{nd} = \quad R / \cos\left(\operatorname{arctg}\frac{h}{r_{nd}}\right),$$

and the distance to the centers of range «semirings» will be

$$R_{nd} = r_{nd} + 0,5\delta r_{nd}.$$

Let us split all range «semirings» at the horizontal Earth's surface into sectors (see Fig. 1). For this purpose, each semiring can be divided by beams (the number of beams is equal to M) which begin at the projection point of aircraft to the Earth's surface and are located at the same angular distance δα. Each area of the semiring confined by the beams has its feed angles in the antenna coordinate system: azimuth – the tilt angle (β and ε, respectively). When the flight of the aircraft is provided without the roll and pitch, the areas located symmetrically to the flight line generate the returned signals with the same F_d Doppler frequency because $F_d = 2Vf_v\cos\beta\cos\varepsilon/\lambda$.

If the modeling of interferences from the Earth's surface areas rightward to the flight line (X-axis projection to the plane at the Earth's surface) would be provided, the power value received for the concrete discrete and filter should be multiplied by two – this can allow taking into account the signal reflection from the Earth areas leftward to the flight line. The coordinates of sector centers in the coordinate system connected with the antenna suspension point are recorded in the form of:

$$X_{nd,p} = R_{nd}\cos\alpha_p;$$
$$Y_{nd,p} = R_{nd}\sin\alpha_p; \; Z = -h;$$
$$\alpha_p = 0,5\pi - p\delta\alpha; \; \delta\alpha = 0,5\pi/M;$$
$$p = 0, 1 ... M,$$

where p are the sector numbers at the range semiring.

The azimuths and tilts in the antenna coordinate system above the Earth's surface areas can be calculated using these coordinates:

$$\beta_{nd,p} = \operatorname{arctg}\frac{Y_{nd,p}}{X_{nd,p}};$$
$$\varepsilon_{nd,p} = \operatorname{arctg}\frac{Z}{R_{nd}}.$$

The area lateral length across the direction of radius-vector beginning from the point of the aircraft location projection to the Earth's surface and going through the area center is $R_{nd}\delta\alpha$, and the lateral length of this area along the direction of the radius-vector is δr_{nd}. The desired S_{nd} area square is equal to their intersection. One can calculate the RCS of the area knowing the area square in the horizontal plane and specifying the SRCS; the area of RCS is the projection of the horizontal area to the direction for the weather radar. It is known from the exploratory tests [5] that the dependence of specific RSC on the θ angle of incidence can be different due to the type of surface, but ranges from the law of diffused scattering for radio waves $\gamma(\theta) = \gamma\sin(\theta)$ to the independent model from the incident angle $\gamma(\theta) = \gamma$. Let us select the averaged model of clutter return (geometric mean). Then the RCS at the direction to the meteorological and navigational radar is determined as follows:

$$\Omega_{nd} = \gamma \sin\left(\operatorname{arctg}\frac{h}{R_{nd}}\right)^{1,5} S_{nd}.$$

The power received from one area of the Earth's surface can be estimated by the formula:

$$P_{nd,p} = \frac{P_{\text{имп}} G^2 D_\Sigma^2\left(\beta_{nd,p};\varepsilon_{nd,p}\right)\lambda^2\Omega_{nd}}{(4\pi)^3 R_{nd}{}^4},$$

where P_{imp} is the pulse power of the signal from the RS transmitter output, W; G is the RS antenna power gain for radiation (reception); $D_\Sigma(\beta_{nd,\,p};\ \varepsilon_{nd,\,p})$ is the function forming the value of antenna normalized pattern in the direction to Earth's surface area.

The returned signal frequency depends on the relation between the F_d Doppler returned signal frequency and the F_p pulse-recurrence frequency. Considering the fact that Doppler frequency for the resolved area would be:

$$F_{\text{Д}_{nd,p}} = 2\frac{V_{\text{ла}}}{\lambda}\cos\beta_{nd,p}\cos\varepsilon_{nd,p},$$

the returned signal frequency after the fast Fourier transform can be calculated by the formula:

$$F_{nd,p} = F_{\text{Д}_{nd,p}} - F_{\text{П}}\,\text{round}\frac{F_{\text{Д}_{nd,p}}}{F_{\text{П}}}.$$

Therefore, searching through all nd discrete numbers multiple of the range period and the areas p, one can calculate the power values at each filter for the discrete nd_1, using the test for entering of $F_{nd,p}$ frequency into the filter with nf number

$$P_{nf,nd_1} = \sum_{nd}\sum_{p} P_{nd,p},$$

if

$$\delta F nf \le F_{nf} < \delta F(nf+1),$$

where δF is the width of one filter $\delta F = F_p/N_{fft}$, Hz; N_{fft} is the base of fast Fourier transform.

The mathematical expectation of Earth interference power at one filter is calculated by the formula:

$$\bar{P}_{\text{З}}(nd_1) = \frac{1}{nf_{\text{макс}}+1}\sum_{nf=1}^{nf_{\text{макс}}} P_{nf,nd_1}, \qquad (3)$$

where nf_{max} is the maximum number of the filter which is filled by the interference from the Earth's surface during the sighting along the flight line. Then it is possible to calculate the power reflected by the bin on assumption that the entire volume of the bin is filled by the moisture target with the targeted value of radar reflectivity, i.e. by the formula (1). Then one can present the radar equation for the meteorological target as follows:

$$P_{\text{м}}(nd_1) = \left(\frac{P_{\text{имп}}\lambda^2}{(4\pi)^3 R_{nd_1}^4} G^2\right)\eta V_{\text{м}} = \frac{\pi^2 P_{\text{имп}}}{64 R_{nd_1}^4 \lambda^2} G^2 |K|^2 Z V_{\text{м}}. \quad (4)$$

Let us calculate the volume of the reflecting moisture target by the formula:

$$V_{\text{м}} = S \quad R = S_{\text{м}}\frac{ct_{\text{имп}}}{2},$$

where S is the cross-section of the basic beam of the directional diagram by half power (m^2); S_m is the cross-section of the reflecting part (m^2).

The standard thunderstorm cell in the space presents a cylinder with a circular base (cross-section towards the radial direction of radiation lying in the horizontal plane) with the diameter d_{obl} = 5556 m and the length equal to the range bin. Therefore, if it is necessary to calculate the input power by the formula (2), one should calculate the S cross-section incorporated by the detected standard thunderstorm cell in the bin.

Let us introduce the angular dimension of a standard thunderstorm cell for this purpose:

$$\alpha(R) = 2\operatorname{arctg}\frac{0{,}5 d_{\text{обл}}}{R_{nd}}.$$

Then the values of the angles incorporating the cross-section of the moisture target in the azimuth resolution cell and tilt can be determined by the following formulas:

$$\beta_{\text{м}} = \begin{cases} \beta, \text{ если } \alpha(R_{nd}) \ge \quad \beta \\ \alpha(R), \text{ если } \alpha(R_{nd}) < \quad \beta \end{cases};$$

$$\varepsilon_{\text{м}} = \begin{cases} \varepsilon, \text{ если } \alpha(R_{nd}) \ge \quad \varepsilon \\ \alpha(R), \text{ если } \alpha(R_{nd}) < \quad \varepsilon \end{cases},$$

where $\Delta\beta$ and $\Delta\varepsilon$ are the values equal to the width of the directional diagram in azimuth and tilt, respectively.

The cross-section of the meteorological object is

$$S_{\text{м}} = \frac{\pi}{4}\quad \beta_{\text{м}}\quad \varepsilon_{\text{м}} R_{nd}^2.$$

At the same time, the power of the signal reflected from the moisture target would be distributed at the filters number that corresponds to the width of the Doppler spectrum for radial velocities at the detected meteorological object. If one detects the thunderstorm areas with turbulence having the mean-square deviation of wind speeds at the bin up to $\varsigma_{\text{в}}$ = 5 m/sec, the number of Doppler filters where the incoming power would be distributed would achieve at least:

$$N_{\text{ф.м}} = \text{ceil}\frac{2\sigma_{\text{в}} N_{\text{бпф}}}{\lambda F_{\text{п}}},$$

where ceil is the function of rounding to the nearest integer.

Let us determine the C/S (clutter/signal) ratio which is equal to the ratio between the total power (3) and total powers (4) for all range discrete values in the period; this is required for taking account of signal rereflected from the Earth's surface:

$$C / S = \sum_{nd_1=1}^{Nd} \frac{\bar{P}_{\text{з}}(nd_1)}{P_{\text{м}}(nd_1) / N_{\text{ф.м}}}, \tag{5}$$

where

$$Nd = \mathrm{floor}\frac{T_{\text{п}}}{t_{\text{имп}}}.$$

It should be taken into account during the calculations that $|K|^2$ value for λ = 3.2 cm in formula (4) is approximately equal to 0.93, which is in agreement with results presented in [4], and for λ = 8 mm $|K|^2$ takes on the value 0.92. The SRSC of summertime prairie was used as an example; it is (–15) dB at λ = 8 mm, and (–23) dB at λ = 3.2 cm [6].

The above-mentioned formulas for the specified maximum dimensions of the antenna equal to 0.4 m were used for calculations of antenna parameter coefficients and the formed Dolph-Chebyshev amplitude distribution which ensured that the C/S ratio for λ = 8 mm would be no worse than for λ = 3.2 cm. The investigation showed that equal amplitude distribution ensured the –30 dB side-lobe level, and the C/S ratio for λ = 8 mm in the range bracket from 1 to 80 km was higher by the factor of 5.5 than for λ = 3.2 mm. Whereby, the following parameters for the weather radar with λ = 3.2 cm wavelength were obtained: G = 800; $\Delta\beta = \Delta\varepsilon$ = 7.2°; for the weather radar with λ = 8 mm: G = 6600; $\Delta\beta = \Delta\varepsilon$ = 2.5°.

The methods of comparison for potentials of centimetric and millimetric wavelength ranges radars

The comparison of energy potentials for weather radars with different wavelengths should be implemented on the condition of identity of the energetic and temporal parameters of the sounding signal (at the output of the transmitter), noise power at the receive path and the loss factor considering the hardware/software losses of the RS. Then, the differences during the automatic detection of dangerous moisture targets will be determined in comparison of reflected powers at the input of the receive path with the number of accumulated pulses with allowance for the propagation path attenuation. When the pulses have been accumulated, the correlation of the resulting power values (radar energy potentials) can be determined at a first approximation by the formula:

$$Э_{1\_2} = \frac{\lambda_2^2}{\lambda_1^2} \frac{\beta_1 \;\; \varepsilon_1 |K_1|^2 (G_1)^2 \sqrt{N_{\text{имп}1}}}{\beta_2 \;\; \varepsilon_2 |K_2|^2 (G_2)^2 \sqrt{N_{\text{имп}2}}} \cdot 10^{0,2(l_1 - l_2)R}, \tag{6}$$

where N_{imp1} and N_{imp2} are the numbers of pulses accumulated from one direction; l_1 and l_2 are the power-loss ratios for signals at the propagation path (dB/km); R is the distance between the RS and the thunderstorm cloud. All indicated parameters with the indices 1 and 2 correspond to the parameters of weather radars operating at λ_1 and λ_2.

Let us use by comparison the following initial data:

- the ΔB = 90° scan sector specified by azimuth should be studied concerning the presence of dangerous moisture targets over the T_{surv} = 4 sec;
- the flight is implemented in the real atmosphere in the conditions of possible stratocumulus clouds or rain at the radiofrequency signal propagation path; and the radar and climatic parameters of these objects can be determined by [7].

The number of directions required for the survey of the specified azimuth coverage will be the following: $Q = \Delta B/\Delta\beta$. One should take into account that the specified coverage sector must be surveyed during the T_{surv}; so, the time that can be used for the accumulation of the desired returned signal from each separate direction, $T_{beam} = T_{surv}/Q$. Let us select the range period equal to R_{unam} = 100 km for the unambiguous determination of the distance to dangerous moisture targets; then the corresponding period for pulse repetition $T_r = 2R_{unam}/$ sec.

The maximum number of pulses which can be accumulated by the weather radar from one angular direction (with the rounding downward) is equal: $N_{imp} = T_{beam}/T_r$.

The determination of flight areas with the capability of visual orientation and landing under bad weather conditions

The standards for the danger of moisture targets are not determined for flights of small airplanes. Indeed, the pilot should agree only the time and direction of the flight before the takeoff, and the decision of danger for meteorological conditions he makes by himself. On the other hand, the flights of small aircraft were considered formerly as acceptable during daylight – if the visibility of nonluminous objects at the background of Earth's surface (forest, grassland) at a height to 3 km was provided [8]. If the meteorological range of visibility for safe flight is S_M = 5 km, one can estimate the allowable rate of rain as $I \approx$ 1 mm/hour in accordance with the formulas presented in [7, 8]. The allowable rate of rain I, mm/hour is connected with the radar reflectivity of the meteorological object [1] by the empirical relationship:

$$Z = 200 I^{1,6}. \tag{7}$$

Then, the radar reflectivity would be $Z \approx$ 23 dBZ at the rate $I \approx$ 1 mm/hour. So, the 23 dBZ threshold for the danger of moisture targets can be established for small aircraft. Two cases of detection were used for the comparison of weather radar energetic potentials; these radars were operated at different wavelengths. In the first case, the stratocumulus clouds with 0.1 mm/hour rate were located between the weather radar and the dangerous thunderstorm cloud; and in the second case, the rain with 1 mm/hour rate was between them. The attenuation coefficients in the atmosphere with different rates of precipitation are presented in [2].

The dependences of power on the range (taking into account the accumulation per pulse packet) for $\lambda = 8$ mm (curve 1), $\lambda = 3.2$ cm (curve 2), as well the power of internal noises at the receiver (curve 3) at $I = 0.1$ mm/hour are presented in Fig. 2.

The dependencies for $I = 1$ mm/hour are presented in Fig. 3.

It can be seen from these figures that the mode for detection of dangerous thunderstorm clouds at cloudy and clear weather using the $\lambda = 8$ mm wavelength has the best energetic potential which decreases sharply during the flying in rain to 12 km detection range. Indeed, it has the best resolution and stronger spatial selectivity of the antenna system in relation to ground clutters.

However, the detection range of 8 mm range weather radar during the flights in inclement weather is way below the 3.2 mm wavelength radar. So, the use of 2.8–3.2 cm wavelengths even with small antenna dimensions is expedient for the all-weather warning about the dangerous moisture targets.

The following mode can be realized in weather radars for small aircraft: the mode providing the imaging of flight areas at the indicator with capabilities of visual orientation and landing in bad weather conditions.

It is known that the visibility depends on the meteorological conditions. The meteorological range of visibility should be determined for its estimation – the visible range for a blackbody with sufficient angular dimensions (at least 0.5°) projected to the cloudless sky background near the horizon in the daytime. The dependence between the meteorological range of visibility (S_M km) and the transmission coefficient τ is expressed by the formula [8]

$$S_{\text{M}} = \frac{\ln \alpha}{\ln \tau},$$

where α is the contrast threshold for the sensitivity of the eye (%).

Taking into account that the transmission coefficient is connected with the attenuation index ξ [7] $\tau = \varepsilon^{-\xi}$, one can obtain

$$S_{\text{M}} = \frac{\ln \alpha}{-\xi}.$$

According to [9], when the pilot knows the flight area well, the character of observation comes down to the search for the object (reference point) in the known direction (if this object is at the extreme limit of perception). The brightness-difference threshold $\alpha = 3\%$ corresponds to this case. However, it should be taken into account that the pilot observes the objects (reference points) through the glass of the cockpit which introduces the distortions into the perception of the observed picture. The cockpit glass distorting effect gives the just cause to increase the value from 3 to 4%. Herewith, it should be noted that this parameter is higher during the rain and snow shower ($\alpha = 7\%$). When the glass

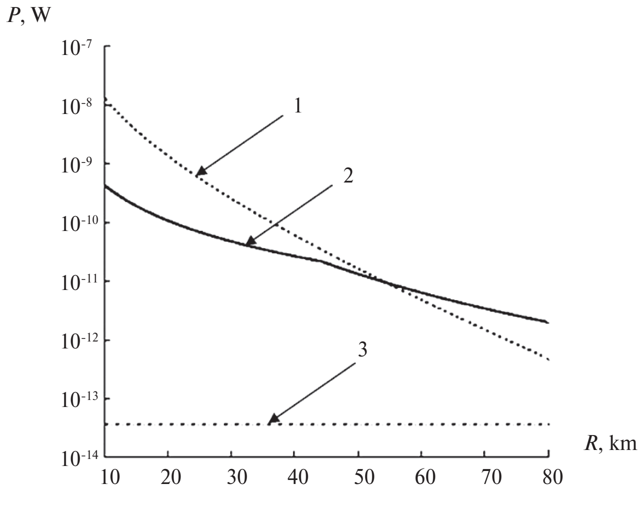

Fig. 2. Dependences on the power range of the input signal reflected from a dangerous thunderstorm cell at different wavelengths, received against the background of the internal noise of the receiver at $I = 0.1$ mm/h: 1 – $\lambda = 8$ mm; 2 – $\lambda = 3.2$ cm; 3 – internal noise of the receiver

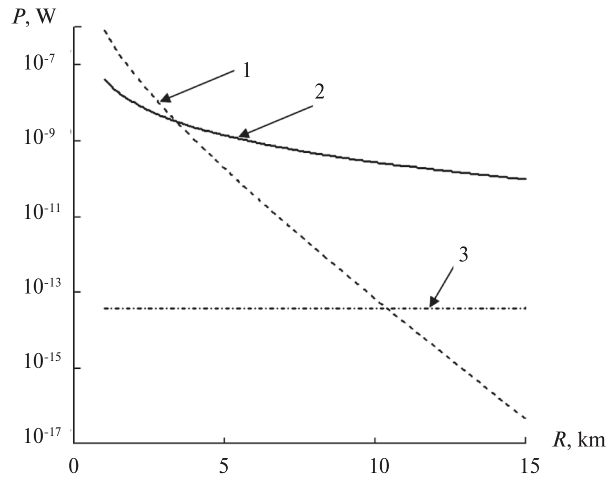

Fig. 3. Dependence on the power range of the input signal reflected from a dangerous thunderstorm cell at different wavelengths, received against the background of the internal noise of the receiver at $I = 1$ mm/h: 1 – $\lambda = 8$ mm; 2 – $\lambda = 3.2$ cm; 3 – internal noise of the receiver

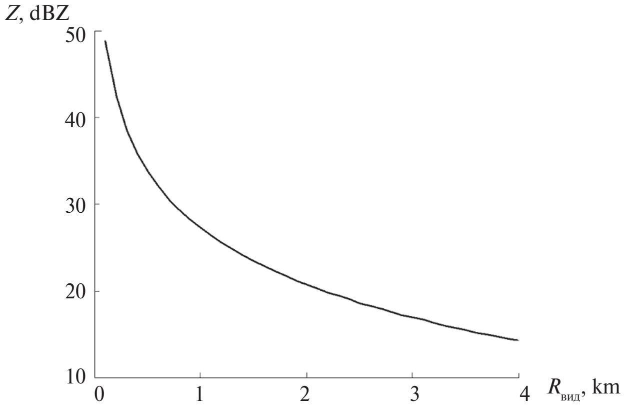

Fig. 4. The relationship between the radar echoes of precipitation and the actual range of visibility of terrestrial objects

of the cockpit is covered with the polarization coating, $\alpha = 14\%$, and

According to [9], when the low visibility conditions take place, the flight crew members should estimate the correspondence of meteorological conditions to the minimum characteristics, and they need information not only on the meteorological range of visibility. Primarily, the slant visual range (S_{sl}, km) should be taken into account. The first parameter must not be identified with the slant visual range, since S_{sl} is 25–50% of the S_m value during the low cloud ceiling and different weather phenomena. Let us assume S_{sl} = 25% of S_m under bad weather conditions; one can obtain the required slant visual range (km):

$$S_{нак} = \frac{0{,}66}{\xi}.$$

Now one should estimate the visibility of ground objects with the specified S_{sl}. The matter is that both parameters are calculated for the condition of observability of the blackbody against the sky background. According to [8], if one needs to obtain the real value for the object, it is necessary to multiply only the value of the visible range by the k_{vis}, coefficient characterizing the visibility of this object (km):

$$R_{вид} = k_{вид} S_{нак}.$$

In accordance with the data represented in [8], the visibility factor varies from 0.50 to 0.97 during the observation of real buildings against the background of the forest, grassland, and snow. Taking the minimum value as a basis, it can be obtained that the real visibility range of different objects against the background of the Earth's surface depends on the attenuation rate ξ:

$$R_{вид} = \frac{0{,}33}{\xi}. \quad (8)$$

The attenuation index for visible electromagnetic radiation is connected with the I rainfall rate by the empirical relationship [8]

$$\xi = 0{,}21 I^{0{,}74}. \quad (9)$$

Let us determine the interrelation between the radar reflectivity of the meteorological object (dBZ) and the real visibility range for objects taking into account formulas (7)-(9):

$$Z = 10 \lg \frac{531}{R_{вид}^{2{,}162}}\ . \quad (10)$$

The result of calculation by formula (10) is presented in Fig. 4.

The visible range of objects for visual orientation in flight and whilst landing thus defined is connected with the radar reflectivity displayed at the scan of the weather radar. According to [9], the safe landing and navigation by the observed terrestrial references can be provided when the distance between the pilot and visually observable objects at the Earth is at least 1 km. The level of radar reflectivity not above 27 dBZ corresponds to the specified range. The weather radar estimates the radar reflectivity taking into account the established threshold; it would allow the automatic detection of spatial areas where the safe flight and landing without use of additional aviation equipment can be provided.

Conclusion

It was demonstrated that the weather radar designed to ensure safety for small aircraft with 8 mm range can be used for the detection of thunderstorm areas only during the slight rain. Its energetic potential decreases strongly due to the attenuation during the wave propagation at the precipitation with higher intensity. Nevertheless, the signal to noise ratio in fine weather (during the detection of a standard thunderstorm cell at a distance of up to 55 km) is higher than for operation at 3.2 cm wavelength. It also has the best resolution (3 times higher) and has advantages for the rejection of clutters from the Earth's surface (5.5 times better). The correlations for the estimation of visually observable objects range depending on the level of precipitation radar reflectivity have been obtained, and the level of 27 dBZ has been determined, when the air staff can implement the flights with the provision of visual navigation and landing.

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