Improving the effectiveness of monitoring of dangerous meteorological phenomena

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Abstract. Three approaches to improving the effectiveness of monitoring of dangerous meteorological phenomena are considered. The first one is based on the modernization of incoherent weather radar on the example of MRL-5 for the possibility of estimating the width of the doppler spectrum by implementing algorithms for pseudo-coherent frequency signal processing with subsampling. Mathematical modeling is carried out, confirming the technical feasibility of the algorithms. On the basis of mathematical analysis, expressions are obtained and graphs of the suppression coefficient of the moving target selection system are presented. The second approach offers a way to improve the efficiency of monitoring for turbulence. An algorithm for detecting zones of increased turbulence and estimating their parameters is proposed. Equations are obtained, on the basis of which algorithms for detecting and estimating the normalized width of the doppler spectrum of zones of increased turbulence, as well as determining the power level of the reflected signals, are synthesized. The third approach describes a way to improve the efficiency of thunderstorm detection and the accuracy of their localization by supplementing the MRL-5 with magnetometric equipment. An example of the implementation and brief technical specifications are given.

1. Introduction
In recent decades, there has been a significant increase in the need to obtain timely information about atmospheric hazards in order to take timely measures to protect human health and ensure reliable and safe operation of industrial and agricultural enterprises, transport, communications, etc. Dangerous phenomena in the atmosphere include, in particular, the areas of formation of thunderstorms, turbulence, heavy rain, and snowstorms.

In order to obtain such information, meteorological (MRL) radars are widely used, which are integrated into multifunctional networks and allow monitoring the weather situation in real time [1]. Thus, one MRL processes information from an area of more than 40 thousand square kilometers.

Currently, the MRL-storm broadcasting network operates 28 sets of MRL-5 type weather radars [2]. To date, they have fully developed their technical resource. In this regard, the question often arises on the agenda: is it advisable to modernize the existing MRL network? The transition to the use of solid-state modulators and amplifiers, digital receivers and coherent signal processing in the design of the MRL is undoubtedly a significant step in improving the functionality of the MRL. However, this is accompanied by a significant complication of circuitry, design, and, most importantly, a significant increase in the cost of the locator.

In addition, the MRL-5 included in the MRL-storm warning network operate in the S (10 cm) range, which is especially effective when observing low cloud cover both in winter conditions and
conditions of a dense cloud wall, an approaching storm or hail. Modern radars that operate only in the C-wave range (5.3 cm), or X (3.2 cm) in conditions of significant signal attenuation in clouds and precipitation, including in the subtropics and tropics, where powerful thunderstorm clouds, hurricanes, tornadoes and precipitation are noted, are ineffective. In connection with the above, the modernization of the MRL-5 with a simultaneous increase in the effectiveness of monitoring of dangerous meteorological phenomena in conditions of limited funding is relevant.

2. **The first approach to improving the effectiveness of monitoring dangerous weather events is the introduction of a doppler mode with pseudo-coherent frequency processing into the MRL-5.**

One of the key tasks in the modernization of incoherent weather radar on the example of MRL-5 is to obtain the ability to estimate the width of the doppler spectrum and, on the basis of this, significantly expand the amount of information received about weather events. When the doppler mode is introduced into the MRL-5, the frequency of radar signals reflected from moving objects (clouds, precipitation) differs from the frequency of the radiated signal by an amount proportional to the radial component of the speed of movement. In addition to the reflectance, data on the average radial component of the velocity and the width of the doppler spectrum of radial velocities appear. The introduction of the Doppler mode in the MRL-5 will allow to obtain doppler information:

- the radial component of the speed of hydrometeors
- detect wind shifts in the troposphere and its surface layer, creating a significant danger during take-off and landing of aircraft;
- determine the local rotations (turbulence) of the air masses.

The use of real-time digital signal processing on modern ADCs, signal processors, and FPGAs makes it possible to implement in MRL-5 algorithms for pseudo-coherent frequency signal processing with subsampling, based on storing the phase of the emitted high-frequency signal and comparing the phase of the received signal with it, followed by single-channel digitization at an intermediate frequency. This makes it possible to obtain an estimate of the width of the doppler spectrum and, based on it, significantly expand the amount of information obtained about weather events. The implementation of single-channel digital signal processing allows you to reduce the volume of equipment, increase its reliability and eliminate the influence of non-identity of quadrature channels on the efficiency of digital processing systems.

The proposed upgrade of the MRL-5 for pseudo-coherent frequency processing does not present significant difficulties and is implemented at low financial costs (significantly lower than for the new DMRL).

To test the proposed solutions, a simulation and further mock-up of the coupler-attenuator necessary for transmitting the signal emitted by the magnetron to the DSP system in order to remember its phase was carried out. The coupler is made in the form of a segment of a waveguide with a length of 800 mm. It provided a signal attenuation factor of more than 60 dB. Figures 1-3 shows the appearance of the directional coupler layout and graphs that reflect the standing wave ratio (SWR) and the attenuation coefficient for its ports, respectively.

![Figure 1. Mathematical model and appearance of the directional coupler layout](image-url)
Figure 2. SWR of the directional coupler by its ports
The figure shows: blue-SWR in the forward channel (0 dB), red-in the tap channel on the ADC (more than 60 dB), green-attenuation on the matched internal load

Figure 3. Attenuation coefficient of the directional coupler along its ports

At the second stage, single-channel signal processing was implemented to evaluate its effectiveness in the operation of the moving target selection system (MTSS).

We assume that when taking samples from a signal with a time difference $\Delta$ equal to the sum of an integer and a quarter of the period, there is a phase shift between the samples of the signal $\pi/2$. It is obvious that in this case, the signals represented by these samples will be conjugated by Hilbert and they can be considered as quadrature components of a single signal. This representation of the signal is called subsampling.

In the proposed version of digital processing of discrete signals (figure 4) with a repetition period of $T$, the signal from the UPF output with a frequency of $f = 1/T$ and synchronization pulses with an interval are fed to the ADC. From the resulting signal samples at time $t = iT$ and $t_i + \Delta$, where
In this case, one sample forms the cosine, and the other − the delayed sine components of the complex signal. The sampling frequency is selected above twice the signal spectrum width, but significantly (by an order of magnitude) below the intermediate frequency. The information about the phase structure of the input signal is completely preserved.

After forming the samples of the complex envelope, the usual quadrature signal processing is performed, which consists in calculating the interperiod correlation coefficient $\hat{K}_v$, and then, using its argument, estimating the speed.

**Figure 4.** Block diagram of doppler processing at an intermediate frequency with subsampling

To analyze the pseudocoherent signal processing algorithm, we present the sampled signals at moments $t_i$ and $t_{i+1}$ in an analytical form:

$$
\hat{Y}(t_i) = Y(t_i) + jY(t_i + \Delta), \quad \hat{Y}(t_{i+1}) = Y(t_{i+1}) + jY(t_{i+1} + \Delta).
$$

We assume that in the period $T$ the number of samples is taken $N$: $T = N\Delta$,

where $\Delta = mT_0 + T_0/4 = T_0(m+1/4), m = 0...N$ − the number of integer periods between samples.

To calculate the speed estimate, we find the cross-correlation function of the samples $Y(t_i)$ and $\hat{Y}(t_{i+1})$:

$$
\hat{K}_v = \frac{1}{2} M\{\hat{V}(t_i)\hat{V}^*(t_{i+1})\} = \frac{1}{2} M\{(V(t_i) + jV(t_i + \Delta))\{(V(t_{i+1}) - jV(t_{i+1} + \Delta))\}
$$

(1)

Then the estimate of the average speed, according to [2], will be described by the relation:

$$
\hat{v} = -\left(\frac{\lambda}{4\pi T}\right) \arg \hat{K}_v(T),
$$

(2)

where $\lambda$ is the wavelength of the carrier oscillation.

Function argument $\hat{K}_v(T)$ it is expressed in radians, and the minus sign indicates that positive Doppler frequency shifts correspond to negative velocities. For a specific analysis, the signal at the ADC output at time points $t_i$ it can be represented as $Y(t_i) = A(t_i) \cos (\omega_0 t_i + \Omega_d t_i + \varphi)$.

Then for the count delayed by $\Delta$, $\omega_0 \Delta = \omega_0 k T_0 + \omega_0 T_0/4 = 2k \pi + 2\pi/4 = \pi/2$, and the signal at the moment $t_i + \Delta$ will take the form $\hat{Y}(t_i + \Delta) = A(t_i + \Delta) \sin (\omega_0 t_i + \Omega_d t_i + \varphi + \Omega_d \Delta)$. Similarly, the quadrature components of the sample are found at the moment of time $t_i + 1 + \Delta$. Based on the assumption that the functions describing the signals are ergodic, their average value over time coincides with the average value over the set. With this in mind, the expression (1) is reduced to the form:
\[ \dot{K}_v = \frac{1}{2} K(T) \cos(\Omega_d T) + j \frac{1}{4} K(T-\Delta) \left[ \sin(\Omega_d T-\Omega_d \Delta) + \sin(\Omega_d T+\Omega_d \Delta) \right]. \]

Provided that the correlation function of the signal has a gaussian form, we get:
\[ K(T+\Delta) = K(T-\Delta) = K(T) \exp(-\alpha\Delta^2). \]

Using the sine sum formula, we obtain the following expression for the cross-correlation function:
\[ \dot{K}_v = \frac{1}{2} K_A(T) \left[ \cos(\Omega_d T) + j \sin(\Omega_d T) \cos(\Omega_d \Delta) \exp(-\alpha\Delta^2) \right]^{0.5}, \]

substituting which in the expression (2) we get an estimate of the average speed. To assess the quality of measuring the signal parameters against the background of powerful passive interference, it is necessary to consider the impact of the introduction of subsampling on the operation of the MTSS system.

One of the parameters that characterize the efficiency of the MTSS system is the coefficient of suppression of the passive interference of the notch filter. We will analyze the dependence of the suppression coefficient on the example of a single and two-time the interperiodic subtraction system (ISS) for different parameters of the sampling period.

The suppression coefficients normalized for the single and two-time ISS are described by the relations [3] \( K_1 = \frac{1}{1-\rho_1}, \quad K_2 = \frac{1}{1-\frac{1}{2}\rho_1 + \frac{1}{2}\rho_2}, \)

where \( \rho = \rho(\Omega_d, iT, \Delta) \) – interperiodic signal correlation coefficients associated with the cross-correlation function by the ratio \( \rho = \frac{|\dot{K}_v|}{\frac{1}{2}K(T)}. \)

From formula (3) it follows:
\[ |\dot{K}_v| = \frac{1}{2} K_A(T) [\cos^2(\Omega_d T) + \sin^2(\Omega_d T) \cos^2(\Omega_d \Delta) \exp(-2\alpha\Delta^2)]^{0.5}. \]

Then
\[ \rho(\Omega_d, iT, \Delta) = [\cos^2(\Omega_d iT) + \sin^2(\Omega_d iT) \cos^2(\Omega_d \Delta) \exp(-2\alpha\Delta^2)]^{0.5}. \]

As mentioned above, the sampling period \( \Delta \) is determined by the number of integer periods \( m \), so the analysis of the effect of the sampling period on the suppression coefficient will be carried out at different values of \( m \).

The calculations were carried out using the software product MathCad.

When \( m = 0, T_0 = 1 \) (s), \( F_d = 0...0.35 \) (Hz), \( \Omega_d(F_d) = 2\pi F_d (\text{rad/s}), \Delta(k) = mT_0+ T_0/4 \) (s), \( \Phi(F_d)=\Omega_d(F_d)T \) (rad), \( E(m)=\exp(-2\Delta(m)^2) \) graphs of the dependence of the suppression coefficient for single and two-time ISS are shown in figure 5.

**Figure 5.** Suppression coefficients of the single and two-time ISS at \( m = 0 \).
As can be seen from the graphs above, with an increase in \( m \) and a decrease in the sampling rate of the signal, the suppression coefficient drops quite quickly. An increase in the phase shift also leads to a decrease in it. Therefore, to reduce energy losses due to subsampling, it is necessary that the sampling period is significantly less than the duration of the probing pulse, that is \( \Delta \ll \tau_{\alpha} \).

The use of non-equidistant pulse sequences in MRL-5 will expand the limits of unambiguous measurement of the doppler frequency and reduce the values of the maximum dips in the frequency response of ISS.

3. The second approach to improving the effectiveness of monitoring dangerous weather events is the implementation of an algorithm for detecting zones of increased turbulence and evaluating their parameters.

Zones of high turbulence are a factor determining the formation and development of clouds of various shapes, atmospheric fronts, and cyclones [4]. In addition, they pose a particular danger to the flights of various aircraft, disrupt communication, form tornadoes, etc. [5], therefore, obtaining information about the intensity of turbulence, its spatial and spectral structure in clouds of various shapes, and evaluating the parameters of zones of increased turbulence is an important task.

When analyzing and systematizing radar studies of areas of increased turbulence in clouds and precipitation, it is necessary to take into account the features of meteorological objects and the influence of the parameters of meteorological radars, as well as to analyze and more fully use the signs of the appearance of zones of increased turbulence in clouds and precipitation.

It is known that clouds and precipitation are a system of many suspended (or falling) spatially distributed hydrometeors (drops, crystals, etc.). If their size is less than the size of the wavelengths, they scatter in the so-called Rayleigh region. For distributed targets, the effective scattering surface (ESR) is determined by the ratio [4]:

\[
\mathcal{G} = V_{\tau} \eta,
\]

where \( \eta \) – specific reflectivity of clouds per unit volume; \( V_{\tau} \) – pulse volume;

\[
\eta = \sum_{i=1}^{N} \bar{6}_i
\]

where \( N \) – number of point reflectors per unit volume; \( \bar{6}_i \) – specific gravity value ESR \( i \)-th point reflector;

\[
V_{\tau} = \frac{c t_{\tau}}{2} \frac{\theta_\alpha \theta_\beta R^2}{\pi},
\]

where \( c = 3 \times 10^8 \text{м/сек} \) – speed of light propagation; \( t_{\tau} \) – duration of the signal at the output of the matched filter; \( \theta_\alpha, \theta_\beta \) – antenna radiation patterns by azimuth and elevation angle; \( R \) – distance to the cloud.

In accordance with the relation (4), when analyzing the reflected signals from clouds, the dependence of the change in the pulse volume should be taken into account \( V_{\tau} \), and, consequently, the effective reflecting surface of the distance \( R \) between the radar and the cloud.

The influence of the parameters of meteorological radars on the accuracy of the estimation of the spatial and spectral structure of clouds of various shapes follows from the ratio for the specific reflectivity \( \eta \) of clouds [2,4]:
where \( q \) – threshold signal-to-noise ratio at the radar receiver input; \( R \) – distance to the cloud; \( C_\lambda \) – a constant that characterizes the potential of a weather radar and is determined by

\[
\lg C_\lambda = \lg P_n + 2\lg G + 2\lg \lambda + \lg \tau_n + \lg \theta_a + \lg \theta_B - \lg P_w - 0.1\xi + 6.63,
\]

where \( P_n \) – pulse radiation power (W); \( G \) – antenna gain; \( \tau_n \) – pulse duration, (s); \( \xi \) – total attenuation introduced by the microwave path, (dB); \( \lambda \) – wavelength, (cm); \( \theta_a, \theta_B \) – the width of the antenna radiation pattern in the azimuthal and vertical planes, (rad); \( R \) – distance to the weather object, (cm).

As can be seen from the presented expressions, the accuracy of measuring the reflectance from meteorological objects significantly depends on the magnitude and stability of the potential \( C_\lambda \), therefore, it is necessary to ensure:

- the operation of the meteorological radar with operational control of its main parameters before conducting meteorological observations using the built-in automated control and measuring equipment, for example, the energy potential of the radar with an accuracy of up to 3 dB relative to the nominal value;
- automation of the process of measuring the radar reflectance of meteorological objects with the introduction of signal correction at a distance according to the law \( 1/R^2 \) in the range of at least 36 dB with a step of 6 dB and an accuracy of \( \pm 1.5 \) dB using a step microwave attenuator;

We will conduct research on the main signs of increased turbulence in clouds and precipitation.

Existing empirical models of atmospheric turbulence are based on experimental data obtained during aircraft flights and radar measurements. At the same time, it is necessary to note the variety of causes of atmospheric turbulence, as a result of which thermal, dynamic and mechanical atmospheric turbulence are distinguished [5]. Their common features are more than an order of magnitude increase in the intensity of reflections and pulsations of wind speed, as well as the appearance of a temperature contrast. Turbulent wind gusts involve particles of clouds and precipitation in their movement, which are scatterers of the energy emitted by the weather radar, so an increase in the intensity of turbulence leads to a decrease in the mutual correlation function of reflected signals from the pulsed volumes of clouds that are spaced apart.

Using the direct Fourier transform of the cross-correlation function, the width of the spectra of the reflected signals is estimated, which are associated with the root-mean-square deviation of the wind speed as follows [4]:

\[
\Delta F_d = \frac{\sqrt{2}\sigma_v}{\lambda},
\]

where \( \Delta F_d \) – width of the spectrum of reflected signals; \( \sigma_v \) – standard deviation of wind speed; \( \lambda \) – working length of the weather radar.

This relationship between the wind speed and the width of the reflected signal spectrum is used to detect areas in clouds and precipitation with a high level of turbulence. The accuracy of estimating the width of the spectrum of reflected signals is largely determined by the frequency of the radar's probing pulses, the speed of the antenna, the level of coherence of the receiving and transmitting equipment, etc.

The second important feature of zones of high turbulence in clouds is a significant increase in the reflectivity of signals due to the formation of large droplets when they merge as a result of collisions (the so-called coagulation) in the presence of ascending air flows. For example, an increase in the diameter of a drop by 2 times leads to an increase in reflectivity by 64 times.

Thus, ascending air flows and turbulence contribute to condensation and coagulation, which means an increase in the size of the drop and an increase in radar reflectivity, so high radar reflectivity is an important sign of a zone of increased turbulence.

There are a number of techniques for detecting areas of increased turbulence in clouds and precipitation based on the above relationships between turbulence and the characteristics of reflected radar signals, which are practical applications. The basis of the algorithms for radar detection of zones of increased turbulence in clouds and precipitation is the estimation of the spectrum width and radar reflectivity of signals from two pulse volumes spaced in space in accordance with the turbulence scale.
In [6], a device and a method for solving the problem of detecting and evaluating the parameters of dangerous turbulence zones by pre-converting the reflected signals in two orthogonal channels were developed, which allowed us to form algorithms containing sufficiently complete information about the zones of dangerous turbulence. The device contains three channels: signal sum channel, doppler signal channel, channel of difference signals.

The signal sum channel is designed to generate the total power of the reflected signals from the pulse volumes of clouds and precipitation spaced in space. The Doppler signal channel is designed to determine the parameters of the signals reflected from the zone of increased turbulence, in terms of estimating the width of the spectra of the reflected signals. The channel of difference signals is designed to estimate the change in the intensity of reflected signals from two pulsed volumes of clouds separated in space.

The proposed method of converting the reflected signals makes it possible to obtain sufficiently complete information about the zones of dangerous turbulence, which makes it possible to synthesize general algorithms for estimating the normalized width of the doppler spectrum, the intensity of reflection, to ensure their reliable detection and informative indication.

4. The third approach to improving the effectiveness of monitoring dangerous weather events is the use of magnetometric equipment for assessing geophysical phenomena.

Current trends in the development and modernization of systems for locating thunderstorms, as one of the most dangerous weather events, are associated with the use of magnetometric equipment for assessing geophysical phenomena. Table 1 shows a number of dangerous meteorological phenomena and the types of informative fields in which they occur.

**Table 1. Relationship of dangerous meteorological phenomena and informative fields**

| Dangerous meteorological phenomenon | Display in informative fields |
|-------------------------------------|-------------------------------|
|                                     | E-field variations | H-field variations |
| Atmospherics                        | +                   | +                     |
| Magnetic storms                     | +                   | +                     |
| Electromagnetic Schumann resonances | +                   | +                     |
| Lightning discharges                | +                   | +                     |
| Heavy fog                           | +                   | -                     |
| Heavy precipitation                 | +                   | +                     |

The above confirms the feasibility of supplementing the MRL-5 with magnetometric equipment for assessing geophysical phenomena to improve the effectiveness of monitoring dangerous meteorological phenomena, for example, thunderstorms.

Magnetometric equipment should include passive channels for assessing the variation of electric and magnetic fields in the range from kilohertz units to megahertz units, accompanying lightning discharges. At the same time, to obtain the full vector of electric and magnetic fields (EMF), it is necessary to provide receiving equipment in a three-channel design (X, Y, Z components).

Within the framework of the Federal Target Program, equipment and algorithms for evaluating the energy characteristics of such EMFs, as well as locating their sources, have been developed.

Brief characteristics of the equipment:
- Operating frequency range 1 kHz-1 MHz;
The dynamic range of the evaluation of the magnetic and electrical EMF components is not less than 128 dB:

- Sensitivity (in the smallest analysis band) - no worse than 0.6 fTl (0.5 nA/m);
- The limits of the basic error of the EMF intensity estimation – no more than 2 dB;
- Limits of the basic error of frequency estimation-no more than \( \Delta f = \pm (f \Delta f_0 + \Delta F) \) Hz, where \( f_0 \) – the value of the frequency at which the measurement is performed, Hz; \( \Delta f_0 \) – relative frequency instability of the reference oscillator \( (5\times10^{-6} \) in internal synchronization mode) in the operating temperature range; \( \Delta F \) – analysis band from the list of fixed values, Hz;
- Signal analysis bands – \((19\times2^m)\) Hz, where \( 0 \leq m \leq 4 \);
- The limits of the permissible basic error of marking the edges of the signals-no more than \( \Delta t = \frac{1}{f_a} + \Delta t_{PPS} + \frac{1}{[1/[f_a] - 1/(f_a \pm \Delta f)]^* N} \) c, where \( f_a \) – calculated value of the sample rate; \( \Delta t_{PPS} \) – time reference error of the front of the PPS signal of the GPS-GLONASS receiver \( (\Delta t_{PPS} = \pm 100 \) ns for embedded devices GPS-GLONASS systems); \( \Delta f \) - offset \( f_a \) due to the discreteness of tuning the quartz oscillator according to the PPS signal in the internal synchronization mode; \([f_a]\) – the integer part of the calculated sample rate value.

- Type of data transmission channel – fiber-optic communication line/Ethernet.
- Resistance to climatic factors: UHL1 GOST 15150.

The appearance of the magnetometric equipment for assessing geophysical phenomena and the result of time-frequency signal processing are shown in figure 7.

**Figure 7.** The appearance of the magnetometric equipment for assessing geophysical phenomena and the result of the time-frequency processing of electrical component EMF (atmospherics).

It should be noted that this equipment allows you to record the wave forms and the EMF spectrum in real time. Taking into account the presence of a built-in high-precision unified time system (GPS/Glonass), the ability to connect an external rubidium frequency and time standard, the ability to work as part of a spatially separated network and synchronize data over the Ethernet network with other equipment, it, in addition to the MRL-5, will provide an increase in the effectiveness of thunderstorm hazard monitoring. At the same time, the equipment allows the use of difference-ranging, direction-finding (angle-measuring) and interferometric algorithms for estimating the location of thunderstorms.

Taking into account the significant increase in the completeness of data, the accuracy of forecasts of the location of thunderstorms, as well as its low cost, with the help of the specified equipment for monitoring electromagnetic fields, it is advisable to add the specified equipment to each position placing the MRL-5.
5. Conclusions

The following conclusions can be drawn from the study.

The approaches to improving the effectiveness of monitoring of dangerous meteorological phenomena are considered. The results of mathematical modeling and modeling are presented, confirming the fundamental possibility of a significant increase in the effectiveness of monitoring of dangerous weather events.

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