Radar turbulence detection: statistical synthesis and experimental check of adaptive algorithms

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ABSTRACT

In this paper the adaptive algorithms for radar signals processing are developed and applied to the detection of turbulent zones in rain. Efficiency of the algorithms is analyzed by statistical modeling. Simulation of weather radar signals and testing of the processing algorithms are performed for comparative analysis of the developed algorithms and known pulse-pair algorithm. The results demonstrate a significant superiority of adaptive algorithms in comparison with the known one. The main emphasis is done to the two-sample algorithm. Algorithms are tested by using the data of Doppler-polarimetric remote sensing of rain. Two-sample algorithm is checked by using radar measurements. Experimental check confirms high efficiency of the two-sample adaptive algorithm. It is recommended for practical use in weather radars.

Keywords: Radar, turbulence detection, adaptive algorithm, statistical synthesis, remote sensing of atmosphere

1. INTRODUCTION

Flight safety, regularity, and efficiency significantly depend on weather conditions. Remote detection of dangerous turbulence still is a task of great importance. Weather radar is necessary as well as obligatory standard equipment of any modern aircraft. A major aspect of the operational efficiency of airborne weather radar is the reliability of turbulence detection. Detecting turbulence is difficult, because the reflectivity involved sometimes can be rather weak. Hence, noise and interference can essentially influence the reliability of the wanted information, resulting in quite short detection ranges. At the same time, one of the major applications of turbulence detection is during cruise flight, at maximum airspeed. Finally, for aircraft in controlled airspace, often a significant lead-time is required before turbulence avoidance manoeuvres can be initiated. All these factors require large detection ranges if the turbulence detector is to be of any practical use. Available airborne radars still do not enable us to accurately detect zones of dangerous turbulence in clouds and precipitation. Therefore, at present it is necessary to use an excessively cautious decision-making strategy in order to ensure an acceptable flight safety level. This leads to an essential decrease in flight regularity, an increase in flight time, unproductive fuel expenditure, and deterioration of other air transport economic parameters.

The turbulence detection algorithms proposed in the paper have been synthesized as optimal ones. The synthesis has been based on a new mathematical model for radar signals reflected from turbulent zones[1]. The model developed takes into account two important kinds of signal modifications caused by turbulence: changes in signal power and in the spectral structure of the pattern after the envelope detector. The change in the spectral composition appears as a spectrum widening and therefore as a decrease in the inter-period correlation coefficient. Ultimately, the signal is described as a Markovian narrow-band random process with exponential autocorrelation function. Multi-dimensional probability density function of samples $x_1,...,x_n$ of the envelope readings of reflections from a turbulent zone:

$$\omega(x_1,...,x_n;r,\sigma^2)=\frac{x_1}{\sigma^2}e^{-\frac{x_1^2}{2\sigma^2}}\prod_{i=2}^{n}\frac{x_i}{\sigma^2(1-r^2)}e^{-\frac{r^2x_{i-1}{}^2+x_i^2}{2\sigma^2(1-r^2)}}I_0\left[\frac{rx_ix_{i-1}}{\sigma^2(1-r^2)}\right], \tag{1}$$

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$$x_i > 0, \quad i = 1,...,n, \tag{2}$$

where r is the correlation coefficient of adjacent readings, σ^2 is variance of the signal.

The use of this convenient mathematical model together with a statistical synthesis technique of optimum decision rules has led to new adaptive algorithms for the detection of radar reflections from turbulent zones. Three algorithms were developed [1]: the parametrical algorithm, which assumes all statistical information known; the algorithm invariant to noise power; and the adaptive two-sample algorithm, which is invariant to the intensity of background scattering. However the developed algorithms must be checked experimentally before final assessment of their efficiency can be done.

This paper describes the algorithms developed and shows the results of modeling and experimental test of the most powerful two-sample adaptive algorithm. Applications of the results are suggested for increasing flight safety, flight path optimization and improvement of economic parameters of air transport.

2. PARAMETRICAL ALGORITHM

A limiting factor in practice of radar detection is always the time of observation. The statistical characteristics of samples estimations essentially depend on the number of samples. An insufficient samples number, which are used for deriving consistent estimations of informative parameters, abridges the reliability of turbulence detection by any algorithms. Besides, noise and interference, which may change during the measurement time interval, can essentially influence the reliability of the wanted information. Therefore on the one hand the heuristic algorithms, constructed on the basis of physical reasons, do not always appear as the best in real-life situations. On the other hand, during the algorithms development we are mainly interested into information which is derived from the statistical relation of signal parameters and weather object characteristics. In case of the synthesis of parametrical algorithm we suppose known statistical models of signals and interferences. Only parameters of the models can be different.

The problem of detecting dangerous turbulent zones can be formulated as testing the parametrical hypothesis H_1: "dangerous turbulence is present" against the parametrical alternative H_0: "dangerous turbulence is absent". The parametrical algorithm [1] can be written as

$$\lambda(x_1,...,x_n) = \sum_{i=2}^{n-1} C_1 x_i^2 + C_2 x_{i-1}^2 + C_3 x_i x_{i+1} > V_p\,, \tag{3}$$

where V_p is the threshold, $\lambda(x_1,...,x_n)$ is likelihood ratio of the sample $(x_1,...,x_n)$, $C_1 = C_{21} r_0^2 - C_{22} r_1^2$, $C_2 = C_{21} - C_{22}$, $C_3 = 2(C_{21} r_1 - C_{22} r_0)$, $C_{21} = 2\sigma_1^2(1 - r_1^2)$, $C_{22} = 2\sigma_0^2(1 - r_0^2)$, r_0 & r_1 are correlation coefficients and σ_0 & σ_1 are rms in amplitude of adjacent readings of weather echoes for non-dangerous and dangerous zones correspondingly. This algorithm was developed under the condition that probability density

Parametrical algorithm is the best under the condition of accepted criteria and adequate mathematical models. However if real process is different from the model, reliability of detection can drop significantly. That is why the parametrical algorithm can be used as the reference point for the comparison of different algorithms.

3. INVARIANT ALGORITHM

For a given reflectivity of clouds or precipitation, the power of the echo-signal depends on the distance from the radar to the reflecting volume. In order to assure a constant false alarm probability, the threshold of decision-making Vp in the parametrical algorithm (3) should be changed with the distance.

An algorithm for the turbulence detection, which is invariant to the echo-signal power, has been synthesized considering the likelihood ratio for the competing hypotheses averaged over all possible power values of the power parameter. Invariant to noise power algorithm is given as

$$\lambda(x_1,...,x_n) = (1+r_0)\sum_{i=1}^{n} x_i^2 - 2r_0\sum_{i=2}^{n} x_i x_{i-1} \bigg/ \frac{1+r_1}{2(1-r_1^2)}\sum_{i=1}^{n} x_i^2 - \frac{r_1}{(1-r_1^2)}\sum_{i=2}^{n} x_i x_{i-1} > V_p\,. \tag{4}$$

Therefore, algorithm (4) is also satisfying when we introduce the decision rule

$$\sum_{i=1}^{n} x_i^2 \bigg/ \sum_{i=1}^{n} x_i\, x_{i-1} > V_p', \tag{5}$$

which is easier to use in applications. The invariant one-sample algorithm (4) or (5) is not sensitive to the echo-signal power and only depends on the correlation coefficient during turbulence measurements. Note that here we are discussing turbulence detection but not just a signal detection on the background of receiver noise. That means that echo-signal has been for sure detected before the turbulence detection procedure (5) is applied.

4. TWO-SAMPLE ALGORITHM

Additional information originating from background (earth surface) scattering or from other fixed reflectors in the radar volume can be used to construct the two-sample decision rule. Such an algorithm uses two samples: a signal sample $x_1, ...x_n$ and a learning sample $y_1, ...y_n$, containing the background echo signal only.

The hypothesis H_0 specifies the situation in which both the signal sample and the learning sample belongs to the distribution with unknown variance σ^2 and correlation coefficient $r = r_0$. The hypothesis H_1 still assumes the same distribution to be valid, however, now with the variance $\sigma_c^2 = \sigma^2(1+\gamma)$ and the correlation coefficient $r = r_1(\gamma) < r_0$. Factor $\gamma \geq 0$ determines the change in the distribution resulting from the change from hypothesis H_0 to H_1. In accordance with the generalized empirical Bayesian technique[1] the structure of the two-sample decision rule may be derived from:

$$\lambda(x_1,..., x_n, y_1,..., y_n) = \frac{\int_0^\infty \omega_1(x_1,..., x_n,\psi, r_1)\omega_0(y_1,..., y_n,\psi, r_0)d\psi}{\int_0^\infty \omega_0(x_1,..., x_n,\psi, r_0)\omega_0(y_1,..., y_n,\psi, r_0)d\psi}, \tag{6}$$

where $\Psi = \sigma^2$ corresponds with the reflected signal power; ω_o and ω_1 are the density distributions at the H_0 and H_1 hypotheses respectively.

After substitutions, integration and identical transformations we may obtain the expression for the two-sample algorithm $\lambda(x_1,...,x_n, y_1,..., y_n) > V_p$ with V_p as threshold level.

Substituting multi-dimensional probability density function (1) into equation (6), considering the values of informative parameters σ_c and r at the corresponding hypotheses H_0 and H_1, using the approximation $I_0(z) \approx e^z / \sqrt{2\pi z}$, after the integration we finally find the two-sample algorithm as

$$\lambda(x_1,...,x_n, y_1,..., y_n) > V_p, \tag{7}$$

with

$$\lambda(x_1,...,x_n, y_1,..., y_n) = \frac{(1+r_0)(\sum_{i=1}^{n} x_i^2 + \sum_{i=1}^{n} y_i^2) - 2r_0(\sum_{i=2}^{n} x_i x_{i-1} + \sum_{i=2}^{n} y_i y_{i-1})}{C_1\sum_{i=1}^{n} x_i^2 + C_2\sum_{i=1}^{n} y_i^2 + C_3\sum_{i=2}^{n} x_i x_{i-1} + C_4\sum_{i=2}^{n} y_i y_{i-1}}, \tag{8}$$

where $C_1 = \dfrac{1+r_1}{2(1-r_1^2)(1+\gamma)}$, $C_2 = \dfrac{1+r_0}{2(1-r_0^2)}$, $C_3 = -\dfrac{r_1}{(1-r_1^2)(1+\gamma)}$, $C_4 = \dfrac{r_0}{(1-r_0^2)}$, with γ as SNR.

The turbulent zone can now be detected by comparing the statistics $\lambda(x_1,..., x_n, y_1,..., y_n)$ determined by expression (5) with the decision threshold V_p. Thus, the two-sample algorithm is synthesized as invariant to the intensity of background scattering.

5. SIMULATION

The developed mathematical models and software enable us to analyze the synthesized turbulence detection algorithms and compare them with each other and with the known pulse-pair algorithm, which is widely applied in weather radars [2]. For the evaluation of pulse-to-pulse correlation, we use a sample correlation coefficient calculated as

$$r^* = \frac{1}{n}\sum_{i=1}^{n-1} x_i x_{i+1} - \frac{\left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2}{\frac{1}{n}\sum_{i=1}^{n} x_i^2 - \left(\frac{1}{n}\sum_{i=1}^{n} x_i\right)^2}.$$

For the analysis of the algorithm efficiency, the Monte-Carlo method was used. The sequence of readings of the envelope of the narrow-band Gaussian random process that was simulated corresponds well to experimental data. Fig. 1 shows turbulence detection probability *D* for sample size *N*=16, false alarm probability *F*=0.1 and SNR=10 dB. Test results for 4 different algorithms are indicated: pulse-pair algorithm (curve 1), invariant to noise algorithm (curve 2), two-sample algorithm (curve 3), and parametrical algorithm (curve 4). Fig. 2 shows the similar curves at SNR = 20 dB.

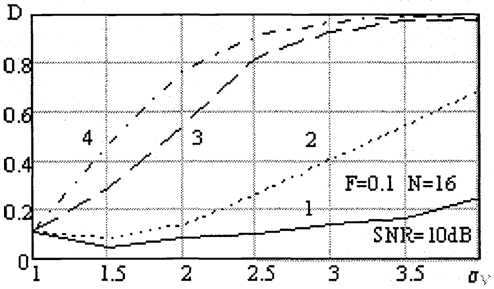

Fig. 1. Probability of turbulence detection D at SNR=10 dB.

An important task of the analysis was to compare all algorithms in the case when real characteristics of the signal differ from the models accepted in the synthesis.

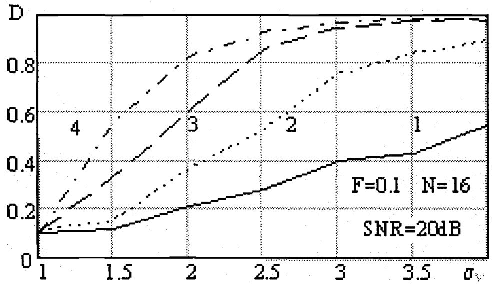

Fig. 2. Probability of turbulence detection D at SNR=20 dB.

The analysis was done under the following conditions: 1) various SNR levels were used, including for the cases when the condition of large SNR was not valid; 2) exponential amplitude distribution was used instead of Rayleigh distribution accepted in the synthesis; 3) the power of the echo signal was determined independent of the turbulence intensity, that is, the power feature accepted in the synthesis did not work. The results of simulation assure that the proposed invariant algorithms are always superior to the pulse-pair algorithm. It is important to note that the synthesized algorithms are also highly efficient when the statistical model of the input signal is modified. This has been confirmed by simulating the data with Rayleigh or exponential distributions. Another positive aspect of the new algorithms is that they are more efficient than the pulse-pair algorithm even if the power of the echo-signal is completely independent of the turbulence intensity. The details of simulation were discussed in the previous paper [1]. Here we are concentrated on the measurements.

6. MEASUREMENTS

The data were acquired by the Transportable Atmospheric Radar TARA on September 19, 2001 in Cabauw (the Netherlands). The weather of that day was characterized by steady rainfall, amounting to a total of 100 mm. It was widespread rain. TARA is an FM CW Doppler full polarization high spatial resolution radar system. Basic specifications of TARA are: carrier frequency 3.315 GHz; frequency sweep 2 ... 50 MHz computer controlled (range resolution 75 ... 3 m); Doppler resolution 8.9 cm/s; dynamic range 90 dB; receiver noise figure 1 dB; antenna parameters: beam width 2.2°, cross polarization ≤-30 dB, first side lobe level ≤-25 dB.

The data set which was taken for the processing is the sequence of complex Doppler spectra for each of 134 range bins recorded during 351 profiles that correspond to observation during about 15 min. During the measurements of rain the range resolution was set 15 m. We chose for processing the data got at slant sounding (antenna elevation of 45 degree).

As an example, in Fig. 3 the curve of radar reflectivity for 6th time (profile) over all 134 range bins (upper panel) and the Doppler spectrum for 121-th range bin (lower panel) are presented.

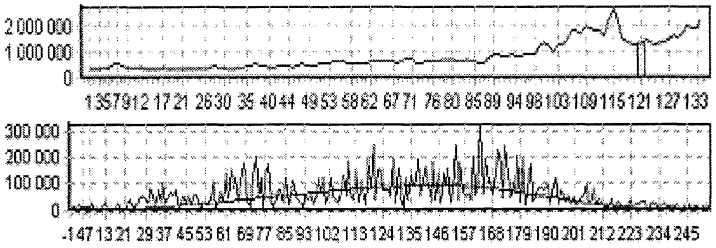

Fig. 3. Radar reflectivity versus range bin number and Doppler spectrum for 121-th range bin.

7. DATA PROCESSING

The data were transformed from spectrum sequence to time sequence, that is, from frequency domain to time domain. Then the obtained sequence of readings of the envelope (in time domain) was processed in running window. Algorithm (7) was applied to the data processing. The processing was done to each of 134 range bins and 351 profiles. The results of the processing are shown in Fig. 4 as a spatial-time field. Range bin number can be easily recalculated to the range, which is proportional to the height (taking into account the antenna elevation). One can see the sandwich-type structure of the investigated object. Increased turbulence is seen at the layers that correspond to range bin numbers of about 10th, 40th, 60th, and 110th. The threshold for the decision making was chosen by the experience to have a clear image. For the comparison, the similar image that was obtained using lower threshold is shown in Fig. 5, where the scales are presented as height versus time.

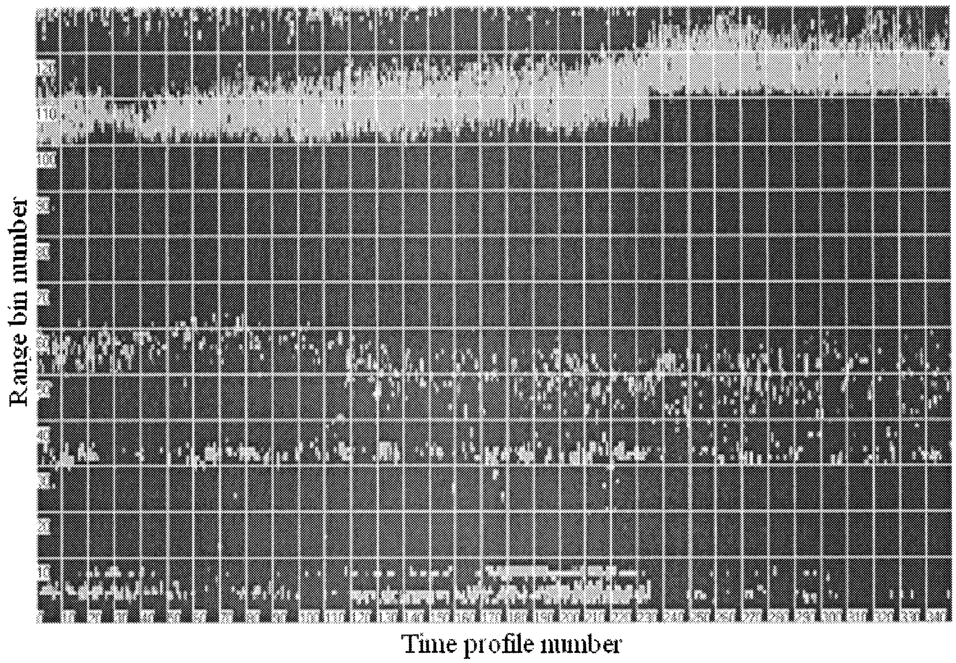

Fig. 4. Spatial-time field of the processed data.

Thus, experimental test allows to conclude the efficiency of the proposed algorithm of turbulence detection on the envelope of the reflected signal.

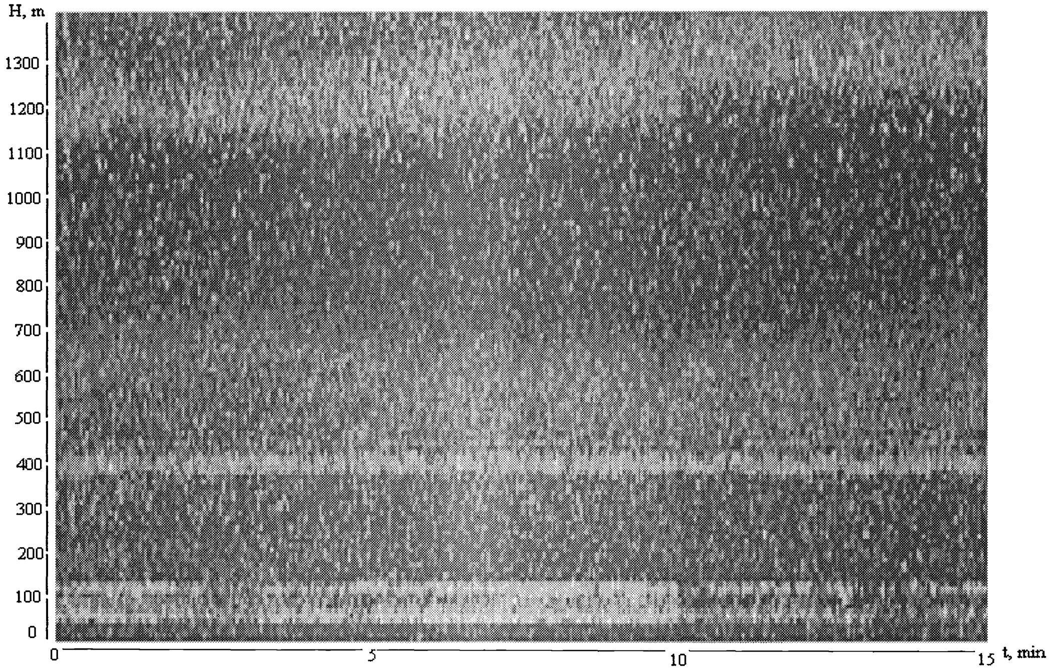

Fig. 5. The same data as in Fig. 4 but processed with lower threshold.

In order to estimate the quality of the algorithm for turbulence detection we used Doppler-polarimetric data that were processed as non-coherent by two-sample algorithm. However, neither coherence nor polarization properties of the data were taken into account during this processing. The same data were also processed with much more sophisticated Doppler-polarimetric algorithm [3] that gives considerably more information to be interpreted. The results are presented in Fig. 6.

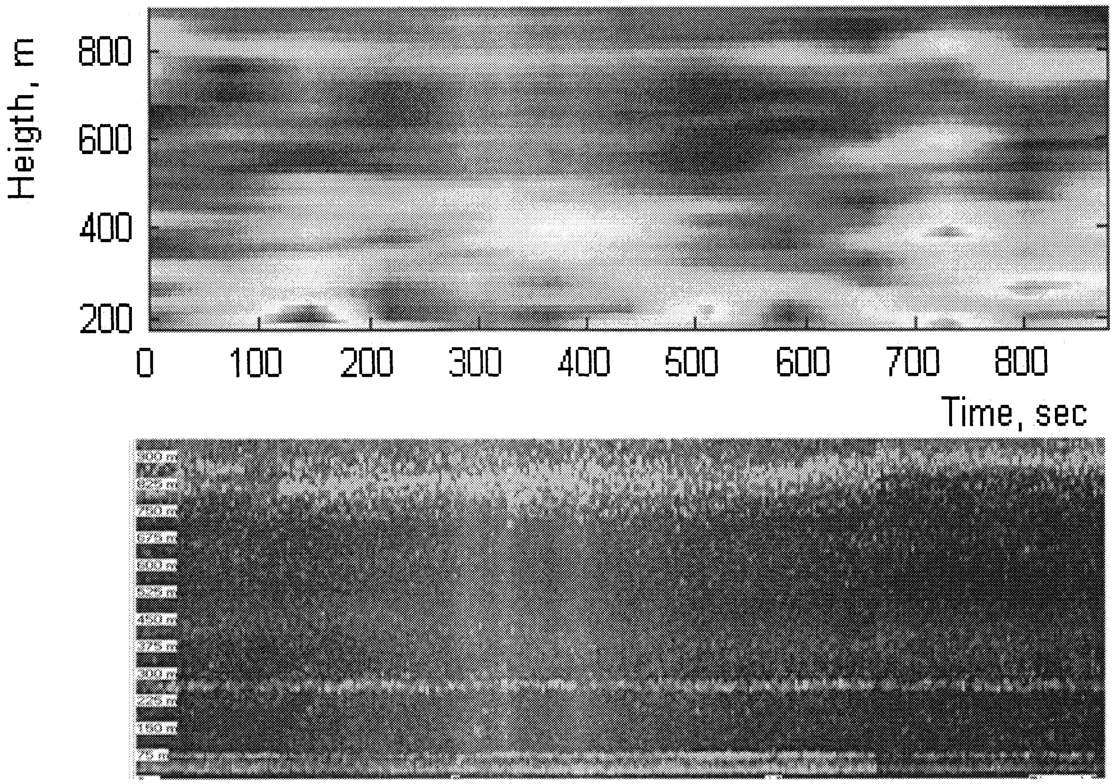

Fig. 6. Comparison of the results of Doppler-polarimetric processing (upper panel) and non-coherent detection algorithm (lower panel).

The upper panel presents Doppler-polarimetric processed data while the lower panel shows the same data processed by non-coherent two-sample algorithm. One can see the turbulent layers detected by the adaptive two-sample algorithm.

8. DISCUSSION

The turbulence detection algorithms presented in this paper have been synthesized as optimal ones. The synthesis has been based on a new mathematical model for radar signals reflected from turbulent zones. The model developed takes into account two important kinds of signal modifications caused by turbulence: changes in signal power and in the spectral structure of the pattern after the envelope detector. The change in the spectral composition appears as a spectrum widening and therefore as a decrease in the inter-period correlation coefficient.

The signal was described as a Markovian narrow-band random process with exponential autocorrelation function. The use of this convenient mathematical model together with a statistical synthesis technique of optimum decision rules has led to new adaptive algorithms for the detection of radar reflections from turbulent zones.

Three algorithms have been developed: the parametrical algorithm, which assumes all statistical information known; the algorithm invariant to noise power; and the adaptive two-sample algorithm, which is invariant to the intensity of background scattering. The synthesized turbulence detection algorithms were analyzed and compare with each other and with the known pulse-pair algorithm. For the analysis of the algorithm efficiency, the Monte-Carlo method was used. The sequence of readings of the envelope of the narrow-band Gaussian random process that was simulated corresponds well to experimental data.

This paper for the first time has presented the results of experimental test of the most sophisticated two-sample algorithm. The proposed new algorithms take into account two features of the signal: power and correlation factor. The pulse-pair algorithm uses a non-parametric estimation of the inter-period correlation coefficient and leaves out amplitude characteristics of the radio echo. The sample correlation coefficient, which is practically measured to implement the pulse-pair algorithm, is not an optimal correlation factor estimate of the envelope of the mix of weather signal and receiver noise. The wide application of such an estimate is based mostly on tradition and heuristics. Thus, it is natural that the efficiency of the synthesized algorithms exceeds that of the non-optimum pulse-pair algorithm.

The advantage of the new algorithm is especially apparent at low SNR levels because the pulse-pair algorithm detects a decrease of correlation factor, and uncorrelated noise causes strong decorrelation of the received signal. It means that the detection threshold must be increased in order to get the same false-alarm probability. That is why the efficiency of the pulse-pair algorithm is reduced sharply if SNR equals 10 dB or less.

A similar phenomenon is characteristic for some moving target indication algorithms, which are efficient only for large SNR (at comparatively small distances). Thus, the outcome of this analysis shows the high efficiency of the new algorithms. Each of them ensures a higher efficiency in comparison with known algorithm used already in weather radars, especially for a small number of samples, which is usual in practical circumstances.

9. CONCLUSION

Existing methods and tools for radar detection of dangerous turbulence zones in the atmosphere show insufficient performance. The reason of this is the incomplete use of information contained in the echo signal.

Proposed algorithm are researched by modeling and checked by measurements. Its advantage has been ahown.

Simplicity of engineering realization, potentials of high efficiency and improved noise stability of the algorithm developed here promise wide applicability in modern airborne and airport weather radars.

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