Signal Modeling for the Efficient Target Detection Tasks

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Abstract: *The statistical simulation systems which are created for the efficient solving of target detection tasks need to have special signal simulation complex. The simulation methods that can be used as the base of such complex for the pulse radar signals and clutters simulation are considered. The system that uses such algorithms is realized and demonstrates the efficiency of described methods.*

1. Introduction

Nowadays, radar systems are widely used in various fields of science and technology: from CNS/ATM and weapon control systems to medical and geophysical applications. Modern radar systems are closely associated with digital signal processing. So it is very important to improve and develop the hardware and software for signal processing channels.

Modern radars must be able to operate in extreme environment. There are many types of clutters that can heavily complicate functioning of radar systems. In the CNS/ATM systems sources of such clutters are the radio equipment, natural phenomenons, reflections from the meteorological objects etc. Therefore, the signal processing channel must be capable to detect targets in high-noise environment with various clutters.

The development of such systems needs to use complex computer models. Such models must include models of radar signals and clutters, models of processing algorithms (for detection, filtering, tracking etc.), tools for estimation of target detection efficiency and for data visualization (including oscilloscope or radar screen).

Issues of modeling of different radar subsystems are widely discussed in literature [1-4]. In this article we consider mathematical and computer models of the radar signal processing channels with complex signals.

2. Criteria of radar signal processing channels efficiency

The radar system provides the survey of the environment in a particular area. In this area a large number of clutters can be found depending on the position of the radar, structure of the space (terrain, sea surface, weather conditions) etc. Besides, the signal to noise ratio at different points of radar coverage are quite irregular.

The signal detection efficiency can be described by two characteristics: the probability of false alarm α (error of the first kind) and the probability of signal missing β (error of the second kind). Since the power of interference in different parts of radar coverage is different, these probabilities depend on the coordinates of analysing point (R, ϕ), where R is a range; ϕ is an azimuth. Thus, there is a need of the simulation system which allowes to create a map of interference and to evaluate the average efficiency characteristics of a signal processing channel:

$$\begin{aligned} \mathrm{A} &= \int_0^{R_{\max}} \int_0^{2\pi} \alpha(R,\phi)\, d\phi\, dR, \\ \mathrm{B} &= \int_0^{R_{\max}} \int_0^{2\pi} \beta(R,\phi)\, d\phi\, dR. \end{aligned} \tag{1}$$

The generalized performance criteria of the signal detection efficiency is then

$$\Sigma = C_1 \mathrm{A} + C_2 \mathrm{B},$$

where C_1, C_2 are costs of errors. In the case when there is a need to compare two different signal processing channels the minimal value of Σ indicates the better signal detection efficiency.

3. Gaussian noise

The main source of the Gaussian noise (Fig. 1) is an internal noise in the receiver and noise from the environment. With a computer system such noise sequence can be simulated according to the next equation:

$$\dot{\eta}_{m,n} = \sigma_\eta \sqrt{-2 \cdot \ln(rnd1_{m,n})}\exp(j \cdot 2\pi \cdot rnd2_{m,n}),\ m = \overline{0, M-1},\ n = \overline{0, N-1}, \qquad (2)$$

where σ_η is a standard deviation of Gaussian noise; $rnd1_{m,n}$ is a set of uniformly distributed in the interval $(0,1]$ random values; $rnd2_{m,n}$ is a set of uniformly distributed in the interval $[0,1)$ random values; $n = \overline{0, N-1}$ is an azimuth indicator; $m = \overline{0, M-1}$ is a range indicator; N is a soundings per survey number; M is a range circle number.

The computer random number generator provides uniform distribution within the interval $[0,1]$. While simulating $rnd1$ every zero-valued sample must be excluded from the final sequence. While simulating $rnd2$ every one-valued sample must be excluded from the final sequence.

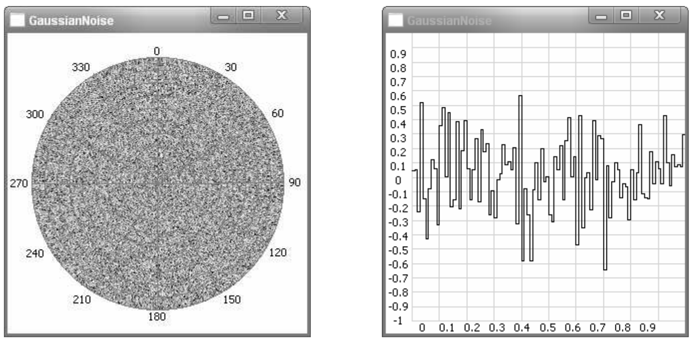


Figure 1. The Gaussian noise

4. Correlated Gaussian noise

Correlated clutters (Fig. 2) are the result of signal reflection from the terrain or sea surface and from the atmospheric phenomena. These clutters can be simulated in two steps.

At first step a random sequence with range correlation is simulated according to:

$$\dot{\xi}'_{0,n} = \dot{\eta}_{0,n},\ \dot{\xi}'_{m,n} = \dot{\xi}'_{m-1,n} \cdot r_r + \dot{\eta}_{m,n}\sqrt{1 - r_r^2},\ m = \overline{1, M-1},\ n = \overline{0, N-1}, \qquad (3)$$

where $\dot{\xi}'_{m,n}$ is a set of range correlated random values; r_r is a range correlation coefficient; $\dot{\eta}_{m,n}$ is a random Gaussian values; $n = \overline{0, N-1}$ is an azimuth indicator; $m = \overline{1, M-1}$ is a range indicator; N is a soundings per survey number; M is a range circle number.

At the second step a two-dimensional azimuth-range correlated set $\dot{\xi}_{m,n}$ is formed from $\dot{\xi}'_{m,n}$ in the following way:

$$\dot{\xi}_{m,0} = \dot{\xi}'_{m,0},\ \dot{\xi}_{m,n} = \xi_{m,n-1} \cdot r_a + \dot{\xi}'_{m,n}\sqrt{1 - r_a^2},\ m = \overline{0, M-1},\ n = \overline{1, N-1}, \qquad (4)$$

where r_a is an azimuth correlation coefficient.

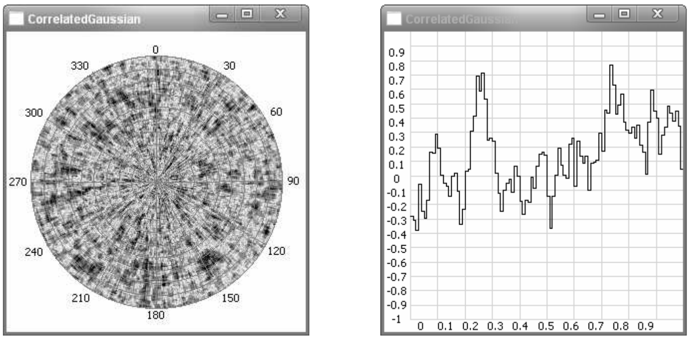


Figure 2. The correlated Gaussian noise

5. Asynchronous impulse interference

Impulse interference appears when impulse signals from other transmitter are received by examined radar receiver. This inference can be either synchronous or asynchronous.

The source of asynchronous interference (Fig. 3) is a transmitter of radio pulses with inconstant sounding period. For the simulation of an asynchronous interference the next equation can be used:

$$\dot{y}_{m,n} = \begin{cases} \dot{\eta}_{m,n}, rnd_{m,n} < P; \\ 0, \quad rnd_{m,n} \geq P. \end{cases}, \; m = \overline{0, M-1}, \; n = \overline{0, N-1}, \tag{5}$$

where $rnd_{m,n}$ is a set of uniformly distributed in the interval [0, 1) random values; P is a probability of asynchronous impulse appearing (from the interval [0, 1]).

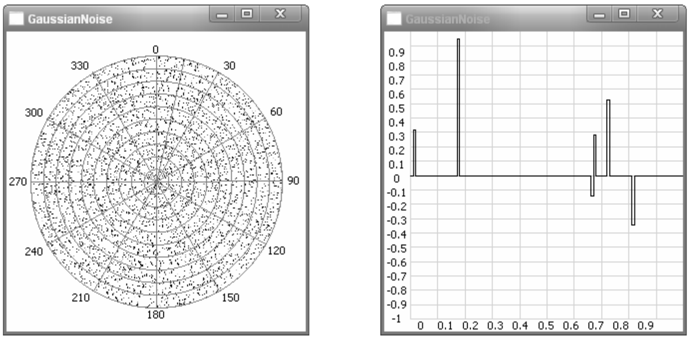


Figure 3. The asynchronous impulse interference

6. Synchronous impulse interference

Synchronous interference (Fig. 4) are usually appears by the reason of other radar impact. Both radars must have fixed scanning periods. Such interference can be simulated in two steps.

At the first step the values of the counter $k_{m,n}$ that indicates the impulse placement position are calculated as:

$$k_{0,0} = rnd \cdot K; \; k_{0,n} = (k_{M-1,n-1} + L) - \left\lfloor \frac{k_{M-1,n-1} + L}{K} \right\rfloor K; \; k_{m,n} = \begin{cases} k_{m-1,n} - K, k_{m-1,n} + 1 \geq K, \\ k_{m-1,n} + 1, \quad k_{m-1,n} + 1 < K; \end{cases} \tag{6}$$
$$m = \overline{1, M-1}; \; n = \overline{1, N-1},$$

where rnd is a random value from uniform distribution on the interval [0, 1); K is a normalized impulse appearing period; L is an additional compensator (is equal 0 in the simplest case); operator $\lfloor x \rfloor$ returns the largest integer lower or equal x.

At the second step the output sequence is generated:

$$\dot{y}_{m,n} = \begin{cases} \dot{\eta}_{m,n}, \ k_{m,n}+1 \geq K; \\ 0, \quad\ k_{m,n}+1 < K. \end{cases}, \ m=\overline{0, M-1}, \ n=\overline{0, N-1}. \tag{7}$$

If parameters of the radar (T is a scanning period of the examined radar; T' is a scanning period of the affecting radar; ΔR is a range resolution) are defined it is possible to calculate coefficients K and L:

$$K = \frac{c \cdot T'}{2\Delta R}, \quad L = \frac{c \cdot T}{2\Delta R} - M \ , \tag{8}$$

where c is the speed of light.

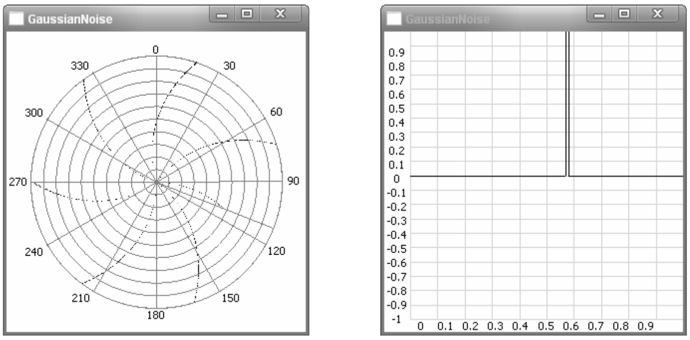


Figure 4. The synchronous impulse interference

7. Moving target

The signal received from a target, which is simulated for the efficient target detection tasks, has square envelop (Fig. 5). Such signal is simulated using the next equation:

$$\dot{s}_{m,n} = \begin{cases} S_{\max} \exp(j(\gamma_s \cdot n + \Phi_{s0})), m = m_{s0}, n \in [n_{s0}, n_{s0}+N_s-1]; \\ 0, (m \neq m_{s0}) \cup (n \notin [n_{s0}, n_{s0}+N_s-1]); \end{cases}, \tag{9}$$

$$m=\overline{0, M-1}, \ n=\overline{0, N-1},$$

where m_{s0} is a range circle where target is located; $S_{\max}$ is a target signal amplitude; $\Phi_{s0} = rnd \cdot 2\pi$ is an initial phase of the target signal; rnd is a random value from the uniform distribution in the interval [0, 1); γ_s is a normalized signal frequency fluctuation; N_s is a pulse number in the signal pack; n_{s0} is an index of the first pulse from the target pack.

To simulate the radar operating space with defined parameters the following equation should be used:

$$m_{s0} = round(R_{s0} / \Delta R); \quad \Phi_{s0} = 4\pi R_{s0} / \lambda;$$
$$\gamma_{\mathrm{s}} = 4\pi \cdot \mathrm{V_{sR}} T / \lambda; \quad S_{\max} = K \frac{\sqrt{\sigma}}{R_{s0}{}^2}, \tag{10}$$

where λ is a radar signal wavelength; $\mathrm{V_{sR}}$ is a radial velocity of the target; T is a scanning period; R_{s0} is a target range; ΔR is a range resolution; σ is a radar cross section; K is a signal attenuation coefficient. Coefficient K involves radar transmitter and receiver parameters and some environmental parameters.

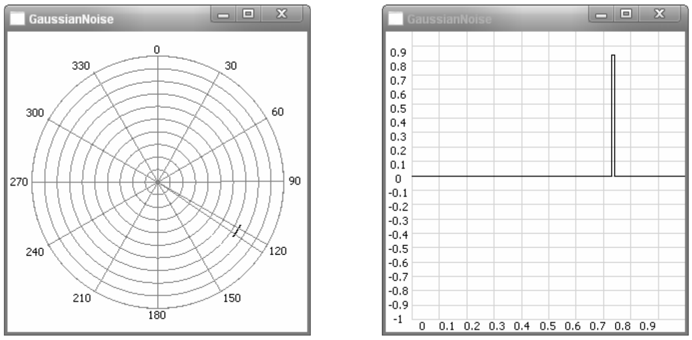


Figure 5. The signal representation from the targets

8. The full received radar signal

The full signal received by the radar (Fig. 6) can be simulated as the mixture of various clutters:

$$\dot{U}_{m,n} = \dot{s}_{m,n} + \dot{\eta}_{m,n} + \dot{\xi}_{m,n} + \dot{y}_{m,n}, \; m = \overline{0, M-1}, \; n = \overline{0, N-1}, \qquad (11)$$

where $\dot{s}_{m,n}$ is a signal backscattered from the target; $\dot{\eta}_{m,n}$ is a Gaussian noise; $\dot{\xi}_{m,n}$ is a correlated Gaussian noise; $\dot{y}_{m,n}$ is an impulse interference.

The particular components of (11) can be modeled as an additive components. Their physical nature is different and independent.

Usage of such simulating method requires considering the clutters coverage, clutters space activity, target and radar parameters. It also requires taking into account the changes of the signal to noise ratio depending on their range.

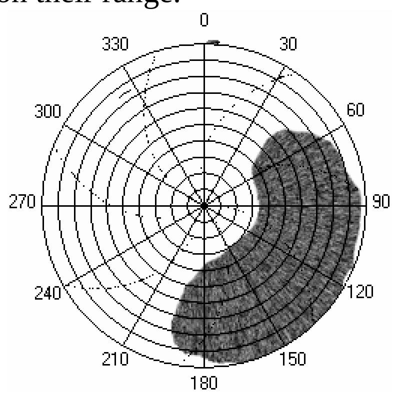


Figure 6. The full received radar signal

9. Main processing algorithms testing

The computer simulations are used to estimate the target detection efficiency. The scheme of the computer program which is designed for such purposes is shown on the Fig. 7. This program simulates the uniform field of clutters and disposes the targets inside clutters coverage. Then program provides signal processing process using some algorithms. The resulting signal is compared with target signal and the program calculates the target detection characteristics. The detection characteristics which this program can calculate are: $\mathrm{A} = N_{\alpha} / N_{\bar{s}}$ is probability of false alarm and $\mathrm{B} = N_{\beta} / N_{s}$ is probability of target missing. In these equations N_s is target discrete number; N_{β} is target discrete number where target is not detected; $N_{\bar{s}}$ is discrete number without target; N_{α} is discrete number with false target detection.

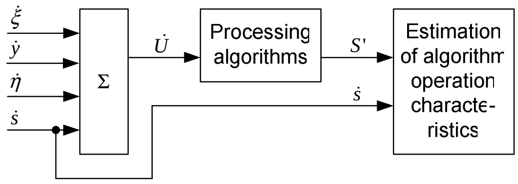
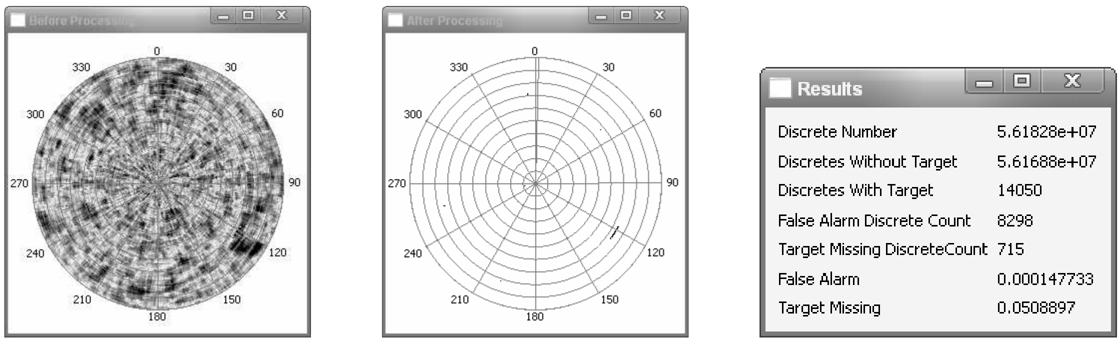


Figure 7. Structure of a computer program for the target detection efficiency estimation

10. The demonstration of target detection efficiency estimation

The software for estimating target detection efficiency has been designed (Fig. 8). This program uses the methods described above in practice. It creates a digital model of radar coverage with a single target. There is correlated Gaussian noise within radar coverage. The moving target indicator is used for target detection. The program simulates a large number of surveys and counts the statistical indicators based on all surveys. The modeling parameters are:

- radar parameters: $N = 1000$, $M = 100$;
- target parameters: $S_{\max} = 0.6$, $m_{s0} = 73$, $n_{s0} = 325$, $\mathrm{N_s} = 25$, $\gamma_s = 0.85$;
- clutter parameters (correlated Gaussian noise): $\sigma_\eta = 0.3$, $r_r = 0.85$, $r_a = 0.95$;
- processing algorithm: digital moving target indicator;
- threshold level: 0.4;
- modeling parameters: number of surveys = 562.



a) b) c)

Figure 8. Software for target detection efficiency estimation:
a) pure radar signal; b) radar signal after moving target detection; c) window with statistical results

11. Conclusions

Each radar simulation system should be able to read signals from the real radar or simulate it by itself. This article demonstrates the principles and algorithms of radar simulation systems that can be useful for target detection efficiency estimation. Methods described above allow us to compare any digital radar signal processing algorithms.

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