Enhancing capabilities methods of the model of reflected radio altimeter signal based on Monte Carlo statistical modeling

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Abstract

When designing various on-board navigation equipment to perform a qualitative analysis of the characteristics of the developed devices, there is a need to have models of signals or responses entering the developed device. Therefore, creating and improving models of such signals is an actual design task. The paper proposes ways to improve a previously developed model of a radio altimeter reflected signal, which was obtained using statistical Monte Carlo simulation. The developed method involves expanding the capabilities of the model through the use of specific customizable pseudo-random number generators, a wide range of which are offered by free mathematical extension programs. A simple pseudo-random number generator format has been proposed for the needs of this model. The disadvantages of using only a sequence of pseudo-random numbers generated by generators as weight functions without a series of Monte Carlo runs for the base signal are also shown by comparing their time domain performances.

Keywords

air navigation, statistical simulation, Monte Carlo, pseudo-random number generator, electronic design

1. Introduction

The development of new and improvement of existing aviation on-board and ground equipment is an actual scientific and technical problem today. The development of new on-board equipment has become especially relevant due to the active development of unmanned aerial systems. This fact does not mean a reduction in the demand to improve existing systems. Some states are trying to develop their aircraft manufacturing and also aircraft instrument making. The emergence of new manufacturers and developers of

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aviation equipment is due to several factors. The basic factor, in our opinion, is the high cost of aircraft and their equipment. At the same time, a couple of dozen well-known aircraft manufacturers carefully guard their technological secrets and limit the issuance of licenses for the production of aircraft equipment to other companies. On the other hand, we can identify trends that, in turn, can stimulate the development of aviation technology for startups – beginner developers. For the development of both new aircraft designs and aviation equipment and instruments, an important stimulating factor is the availability of modeling and design software – mathematical extension software packages and computer-aided design systems. Also, for the development of devices specifically for aviation instrumentation, the incentive is the availability of modern radio-electronic devices, microcircuits, and microprocessors. Another stimulating trend is the expansion of scientific research, which became possible thanks to the development of a network of international and government programs for the allocation of grants for research, like the Horizon 2020 program, the simplification of communications among scientists in different parts of the globe, which made it possible to increase the number of conferences and seminars held, conducted especially in online format.

2. Related works

The study of various aspects related to the development and improvement of onboard and ground-based aircraft equipment affects the scientific interests of researchers who are specialists in various branches of knowledge. As is known, either onboard or ground aviation radio-electronic equipment mainly belongs to one of three types of equipment: navigation, communication, or surveillance equipment. A large number of publications related to the development of this type of equipment are devoted to the study of a wide class of problems arising during the development and operation of aviation electronic devices. Plenty of publications link the tasks of improving equipment with the requirements of increasing flight safety. For example, an onboard aviation weather radar operates while an aircraft is flying a route.

The authors of article [1] propose a solution to the problem of increasing information awareness about meteorological phenomena through the developed algorithm for identifying turbulences of varying intensity. Automatic dependent surveillance equipment plays an important role in ensuring flight safety and improves situational awareness. The authors of the publication [2] proposed a simplified, from the point of view of computing power, a method for minimizing the errors of trajectory measurements obtained from automatic dependent observation equipment or an aerometric altimeter, based on a probabilistic approach. To prove the hypothesis about increasing the probability of making the right decision, it is proposed to use a hierarchical monitoring system [3] developed to support the life cycle of aviation equipment. Important tasks in equipment maintenance are reliability and durability, as well as high-quality informative monitoring. The use of the regression model proposed in [4] will improve the accuracy of diagnosing the degree of deterioration of aircraft devices. Navigation equipment plays a basic role in ensuring the safety of flights. Therefore, naturally, a large number of publications are devoted to solving problems of navigation services and improving navigation equipment.

The authors of the publication [5] propose a solution to the problem of relative navigation of mobile objects by implementing signals from mobile communication equipment into the process of navigation calculations. An algorithmic solution involving the use of signals from sources of powerful electromagnetic interference for a local orientation system based on inertial and magnetometric converters was proposed in [6]. A particular direction in the development of navigation equipment is developments related to hardware. In publication [7], to determine the course of both aircraft and other moving objects, the structure of an inductive magnetometric sensor with a non-orthogonal arrangement of the axes of its structure was developed. In connection with the emerging transition of civil aviation to electric energy sources, publications are increasingly appearing that cover various aspects of the implementation and operation of autonomous electric energy sources - rechargeable batteries built on the basis of different charge storage technologies. Thus, to assess and develop a forecast of the current charge level of a battery built on the basis of lithium-polymer technology, a charge assessment method has been developed that takes into account the indicators of on-board navigation devices of the UAV by developing a solution using the mathematical apparatus of fuzzy logic [8].

Measuring the altitude of an aircraft, despite the fact that radio altimeters have been used in aviation since 1938, continues to be an actual development task. [9]. The authors of the article [10] proposed a new solution for the CRW-13 radio altimeter, which provides for the integration of the antenna module with an intelligent signal processing unit. Attention is also paid to solving specific issues in the development and improvement of radio altimeters. Often, when solving problems of developing on-board equipment or assessing its performance, a statistical approach is used. In [11], a method is proposed for constructing a model of the reflected radio altimeter signal obtained as a result of statistical modeling using the Monte Carlo method of the characteristics of the noise signal source. This model is convenient in that it was obtained using the built-in mathematical apparatus of the electronic design automation software environment and, accordingly, can be directly used by developers for operational testing of improved radio altimeter units, which are usually developed using EDA programs. The authors of the publication [12] performed statistical modeling using the Monte Carlo method to assess the errors in the indicators of the Doppler velocity and drift angle meter and noted the effectiveness of this method with known instrumental errors of other on-board devices that emit radio signals, in particular from radio altimeters.

3. Problem statement

As is known [13], the model of the downward radio altimeter signal can be considered as a reference or test model since it does not contain a spurious component. Such a signal contains only mandatory components – a high-frequency carrier of 4.4 GHz and a low-frequency component of the signal frequency of a triangular or sawtooth shape, which forms the law of changes in the carrier within no more than 10%.

The transmitted radio altimeter signal is reflected from the earth's surface and a small part of the energy of this reflected signal is returned to the receiving antenna of the radio altimeter. The model of the received signal, in addition to the high-frequency component, will also contain spurious components [14, 15].

The radio altimeter accuracy is ±1 ft or ±3% of the indicated altitude, whichever is greater. Traditional radio altimeter errors include errors due to reflections from parts of the aircraft structure (for example, landing gear), due to signal leakage between the transmitting and receiving antennas, and other factors [16]. Some prototype radio altimeters are equipped with radio receivers provided with improved filter circuits to protect against spurious and back-reflected signals, while others are affected by signals coming from outside the 4.2 to 4.4 GHz frequency range.

However, the development of technology has posed new challenges for radio altimetry. In [17], the need to assess the influence of signals of the new 5G telecommunication standard on the accuracy of radio altimeter readings is indicated. The conducted simulation modeling of the influence of 5G standard signals using the worst-case method on different prototypes of radio altimeters showed that the magnitude of reading errors in some examples of radio altimeters generated by such a spurious signal can be significant [18]. The results of this study showed an increased level of generated interference from 5G mobile networks. The base station of this standard generates spurious 5G radiation in the 3.7-3.98 GHz frequency band and spurious radiation in the 4.2-4.4 frequency band. GHz, which just overlaps the carrier frequencies of radio altimeters, which does not meet the requirements of the International Telecommunication Union [19]. The danger of underestimating these factors can be confirmed by plane crashes that have already occurred due to errors in radio altimeter indicators [20].

This article shows a study of the advantages of the previously proposed radio altimeter signal reflected model, developed on the basis of statistical modeling using the Monte Carlo method, and also proposes a way to improve this model using flexible settings of a pseudo-random number generator.

4. Fundamental for building a model using the statistical modeling method using the Monte Carlo method

As known, using the Monte Carlo method we can calculate integrals by replacing them with summation [21]

$$\langle g(X)\rangle = \int_{-\infty}^{\infty} g(x)f(x)\,\partial x = E\left(\frac{1}{N}\sum_{i=1}^{N} g(X_i)\right). \qquad (1)$$

To use the relationship given in equation (1), we need to select a sequence of random variables X_i from the probability distribution function $f(x)$; estimate the real function $g(x)$ for each X_i. The arithmetic mean of all $g(X_i)$ values is an estimate of the integral, and the variance of this estimate decreases as the number of terms increases. Assume that an estimator G, its mean $\langle G\rangle$, and variance $var\{G\}$ can be determined. Then the Chebychev inequality is

$$P\left\{|G-\langle G\rangle| \geq \left[\frac{var\{G\}}{\delta}\right]^{\frac{1}{2}}\right\} \leq \delta, \qquad (2)$$

where δ is any positive number. This inequality is often called the first fundamental theorem of Monte Carlo because it provides an estimate of the probability of a large deviation occurring in a Monte Carlo calculation. To be specific, let $\delta = 0.01$. Then formula (2) can be written

$$P\{(G - \langle G \rangle)^2 \geq 100 var\{G\}\} \leq \frac{1}{100}.$$

Or using the equation $var\{G\} = \left(\frac{1}{N}\right) var\{g\}$, we can rewrite

$$P\left\{(G - \langle G \rangle)^2 \geq \frac{100}{N} var\{g\}\right\} \leq \frac{1}{100}.$$

Since for a sufficiently large N the variance of G becomes very small, the probability of obtaining a large deviation with respect to δ between the estimate of the integral and the actual value also becomes very small. For a large sample size (i.e. large N), the range of observed G values with some fixed probability will be in the region of decreasing size near $\langle G \rangle$. This is the essence of the Monte Carlo method for calculating integrals [22].

Thus, when applying the Monte Carlo method, random numbers are extracted from a continuous distribution function and used to approximate the integral. Similar procedures are used to calculate sums using this method. This technique is effective when many indexes are involved.

For the Monte Carlo method, it is assumed that the base random variable is uniformly distributed in the range from 0 to 1. Below is an example of using this random variable in an integration operation

$$\int_0^1 \sqrt{1 - x^2} \partial x = \frac{\pi}{4},$$

which can also be written as

$$\int_0^1 f_u(x) \sqrt{1 - x^2} \partial x = \frac{\pi}{4}.$$

The integral now has the form in which we can apply the method of calculating integrals described above. Homogeneous random variable ξ_i selected from $f_u(x)$

$$g(\xi_i) = \sqrt{1 - \xi_i^2}$$

calculated, and this process is repeated N times to form

$$G_1 = \frac{1}{N} \sum g(\xi_i) = \frac{1}{N} \sum \sqrt{1 - \xi_i^2}.$$

It is easy to develop program code to calculate G_1. To generate ξ_i, we can use the pseudo-random variable generation functions built into the kernel of modern programming environments [23].

5. Capabilities of electronic design automation software environments for carrying out statistical modeling

For the last couple of decades, the design of radio-electronic devices has been carried out using special software that belongs to the type of electronic design automation programs. This software has different levels of integration. These software environments are designed to support end-to-end electronic design technology. This technology supports a chain of development stages from creating a virtual model of the circuit's principal diagram to developing a printed circuit board wiring diagram. The most important stage of development is the simulation of a virtual project, which, as a rule, includes several types of analysis. The vast majority of EDA programs use the reference system for describing electronic circuits SPICE as the core of the modeling environment [24]. Statistical modeling using the Monte Carlo method is a mandatory part of programs for both industrial, professional circuit design shells, as well as semi-professional or even amateur programs of this class.

As examples, we will consider the possibilities of conducting statistical analysis in three software environments of EDA – Design Lab 8 vers., NI Multisim 14 vers. and Electronic Workbench 5 version. The first two programs listed can be classified as professional software shells, the third program is an amateur program that uses a single-display graphical interface and is often used for educational purposes. Since statistical modeling is a secondary type of analysis in EDA programs, it is imperative to choose one of the three main types of simulation for which it can be used – AC Sweep, DC Sweep, and Transient analysis. Users of Electronic Workbench can enter in the text boxes: a number of runs; tolerance value (in global value); seed; distribution type (two types only available – Gaussian or Uniform); collating function with a threshold value. We can immediately note the impossibility of setting up changes in various parameters of device models or signals.

The NI Multisim 14 design environment allows for a more precise setup for Monte Carlo analysis. On the tab "Model Tolerance List" the user can select the required component (or model) of a scheme; its parameter to be analyzed; tolerance value; distribution type (two types only available too – Gaussian or Uniform). On the tab "Analysis parameters" the user must select basic analysis on the basis of which simulating will be performed using the Monte-Carlo method; number of runs; output variable; collating function with a threshold value. Additionally, user can add except output variable some mathematical expression. Such expression must contain math symbols or special functions defined in XSPICE (used as a core in Multisim).

In our opinion, the most advanced possibility of performing statistical modeling is provided by the Design Lab's electronic design environment. In the settings that can be specified, the user can also enter number of runs; tolerance value (in global value); seed; collating function with a threshold value. Additionally, in the "MC Options" of "Output" groupBox user can select one of RadioButton elements to be output on the screen of demonstrating results of simulation of selected runs.

When editing a component model, the user can specify the number of the random number generator – the program has a built-in ability to select one of ten generators, as well as specify the law of distribution of the random variable. Two distribution laws are built into the core of the simulation – Gaussian and Uniform. However, when creating a description of a circuit in the SPICE language, the user is allowed to set the parameters of the required distribution law of a random variable, if it differs from the normal or uniform law. This feature can be used by using the directive "Distribution". In this case, the format of this directive provides for assigning a name to the distribution law and entering the coordinates of the graph of points depending on the probability of a random variable. This capability undoubtedly allows developers of devices whose performance testing requires statistical modeling to perform more informative studies of the characteristics of their device models.

6. Checking the possibility of using pseudo-random number generation functions built into EDA software environments to build a model

The basic component in Monte Carlo calculations is a random number generator, more precisely a pseudo-random number generator in the case of a software implementation of the statistical modeling methodology. As we have seen from the above material, developers of EDA software environments offer the user already complete interfaces with which he only enters the necessary data and variables. Only the Design Lab environment allows you to choose one of ten PNG generators. However, the user is not provided with any information even about the type of generators that are implemented in the mathematical core of the modeling software unit. In fairly detailed reference materials from the developers of the Design Lab environment and its later release called OrCAD, which is based on Spice, information about the types of PNG generators is not indicated.

The Multisim program contains rnd() in the list of mathematical functions, which is a software PNG generator [25]. At the same time, it is used as a separate mathematical functional. Nowhere in the descriptions or reference documents is it explicitly stated that the rnd() function is used in statistical modeling. However, the user can check the functionality of this function in a simple way. In the Monte Carlo analysis settings window, instead of simply specifying the name of the output variable, you can enter an expression using built-in mathematical functions. To do this, you need to install the CheckBox "Expression", create an expression in the dialog box and confirm its entry into the output variable line. Below in Figure 1 is a fragment of the window where an expression is written in the output variable field – the operation of multiplying the potential value of the output node by the rnd() function with an argument 5.

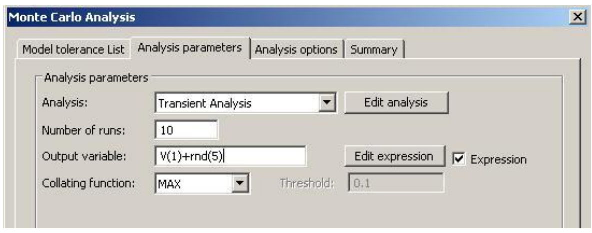

Figure 1: Adding of an expression in the Output Variable textbox.

After performing the analysis, the result of this action is displayed on the screen, shown in the figure below.

The result of the operation is shown in green. The sine wave signal of the carrier frequency is displayed in red. Without using signal processing methods, we can say from the results of visual observation that as a result of multiplying the output voltage (with an amplitude value of 3 mV) by pseudo-random numbers generated by the rnd() function with argument 5, a distorted signal with peak values of approximately 18 mV and minus 16 mV is obtained. However, a certain pattern is clearly visible – all signal fluctuations on the positive half-wave have a positive sign (or are equal to zero), but all signal fluctuations on the negative half-wave have a minus sign. On the runs presented below in Figure 2, and Figure 3, this pattern is also clearly visible.

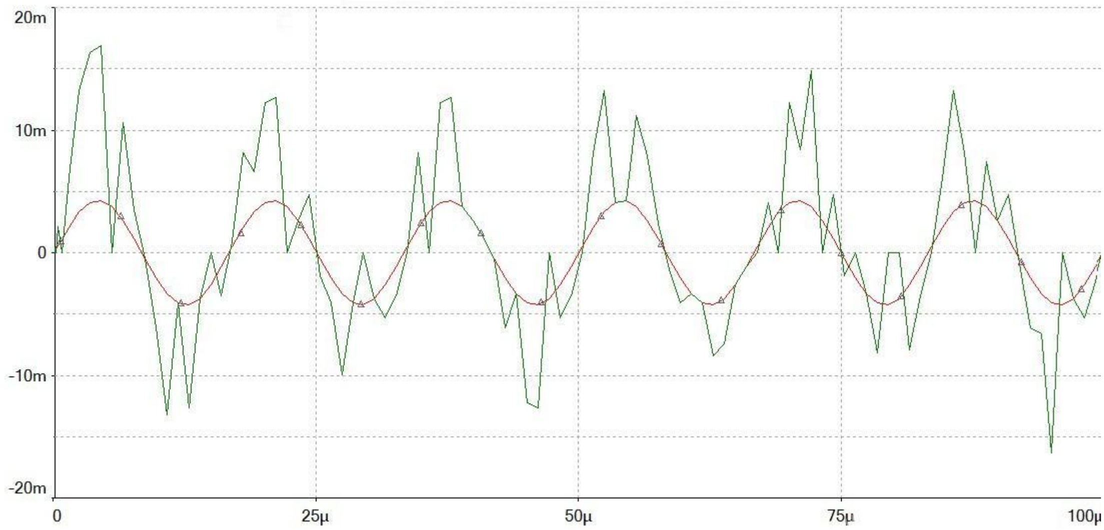

Figure 2: Result of a rnd() action with a sin trace of carrier signal.

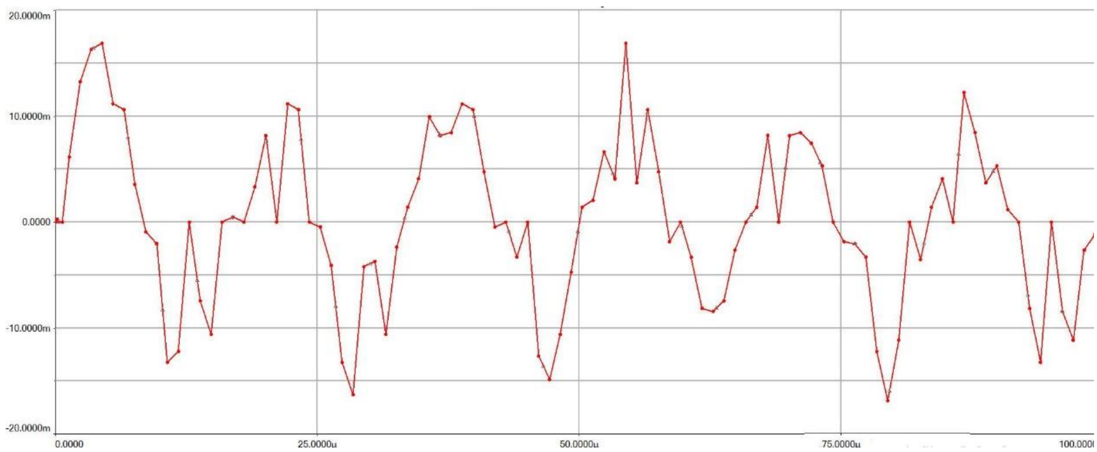

Figure 3: Result of rnd() action.

Considering that the radio altimeter measurement unit records precisely the fact of the signal passing through zero (and not reaching a zero value), such a model of the received signal will not adequately reproduce interference that simulates a false “phase” of the signal causing the radio altimeter counter to trigger.

7. Advantages of the signal model obtained from statistical modeling of the reflected signal model

The model proposed in [11] does not have this drawback. Signal fluctuations are clearly visible when the characteristic moves from a negative domain to a positive one and vice versa (Figure 4).

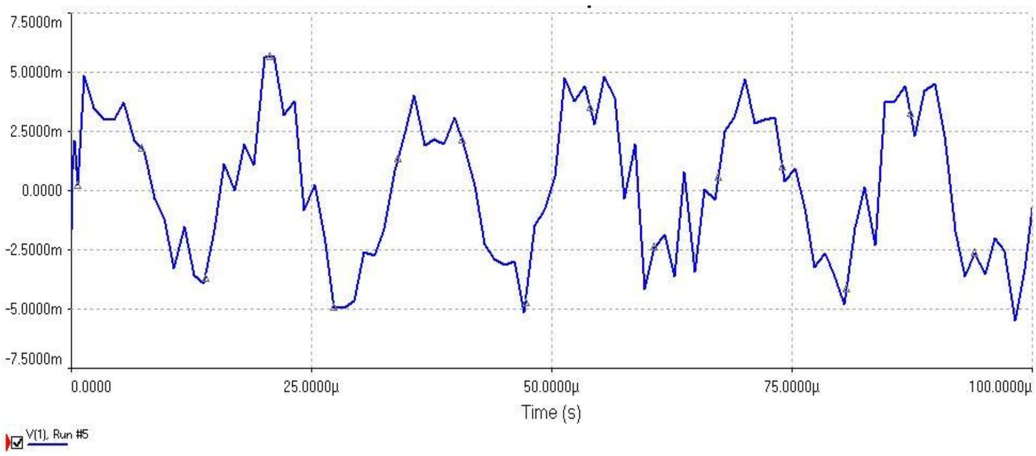

Figure 4: Result of MRRAS action.

A developer who wants to use such a model according to the method proposed in the article [11] will be faced with the task of choosing the most optimal rub from the set that offers the result of the Monte Carlo simulation. Of course, the authors do not propose to make such a choice by visually selecting each characteristic. The developer needs to take advantage of the opportunity to convert the simulation results file into an ASCII file or an Excel spreadsheet file. Then the developer or programming specialist will have to create a script to analyze the numerical characteristics data according to the criterion of the maximum number of false positives or possibly other criterion.

8. A method for expanding the capabilities of the model by intelligently tuning the required PNG generator

Since a sufficient number of scientists and specialists have mastered programming skills, the capabilities of modern integrated software development environments are at their disposal to solve the problem of constructing PNG generators. One of the popular software environments designed for data processing is the R environment. Among the functions of this environment, there is a function for generating uniformly distributed random numbers

– randu without arguments. This function provides a data frame with 400 observations on three variables named x, y, and z that produce the first, second, and third random number in the triple. The disadvantage of using this generator to build a model of the reflected signal, as well as other built-in functions like RNGkind(), is that they give a uniform distribution of the random variable. However, it is obvious that the errors of the reflected signal obey the normal distribution law. Of course, there are techniques that allow one to convert uniformly distributed sequences into a normal distribution law like the Ziggurat Method [26].

Another solution to this problem is the use of software products of another class – mathematical extension programs. The use of these programs will allow one to design the required PNG generator and/or the required version of the Monte Carlo method. The first program of this type of programs can immediately be called MatLab. Of course, the capabilities of this program are beyond doubt. However, nowadays programs from the free software group are becoming increasingly popular. One of such programs is GNU Octave, which has been successfully used by scientists and specialists from various branches of knowledge for quite a long time. This mathematical extension software environment has significant computing capabilities, a good visual representation of calculation results, and in addition, has an interface with the MatLab program implemented through the use of m-files. This modeling system contains a whole set of PNG generators:

- Function rande – generates PNGs distributed according to exponential law.
- Function randg – generates gamma law distributed PNG.
- Function randp – generates random numbers distributed according to Poisson's law.
- Function randn – generates random numbers distributed according to the normal law.
- Function rand – generates random numbers distributed according to a uniform law.
- Function randi – generates integer PNGs random numbers distributed according to a uniform law.
- The discrete_rnd function generates distributed univariate discrete numbers.

The empirical _rnd function determines the empirical distribution.

In this case, the integer type is converted without complex transformations into a real type, which is needed in the reflected signal model. Here is an example of setting up such a generator to suit the needs of the problem being solved:

$$x = randi([-1000,1000], 10,10)/1000.$$

This generator format allows to retreat from the positive bias of standard generators, which generate numbers in the range [0,1]. As a result of the proposed generation scheme, we will obtain the following set of numbers (Figure 5). As we can see, a set of one hundred randomly distributed positive and negative values in the range [-1, 1], which is used in EDA programs has been received. Accuracy to the third number after the point, in our opinion, is quite sufficient to solve the problem.

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-0.2860000   0.2970000   0.2610000   0.5980000  -0.0590000   0.9210000  -0.7710000   0.8730000  -0.5770000   0.8170000
-0.7190000   0.2910000  -0.6500000  -0.6070000   0.8690000   0.5800000  -0.9200000   0.2890000  -0.7530000  -0.5020000
 0.7620000  -1.0000000   0.6690000  -0.8840000  -0.7890000   0.5540000   0.4020000  -0.9110000  -0.3150000  -0.9780000
 0.3800000   0.7570000   0.8270000  -0.2580000   0.5740000  -0.9560000   0.7160000   0.5040000  -0.3130000   0.4880000
-0.8080000   0.2950000  -0.8310000   0.7860000   0.4120000   0.3040000  -0.3300000  -0.5530000   0.9210000   0.1270000
-0.9700000   0.6300000  -0.1690000   0.6140000  -0.5630000  -0.1050000   0.0040000  -0.9710000   0.5480000  -0.4290000
 0.7620000  -0.0150000   0.3620000  -0.6610000  -0.5260000  -0.6240000  -0.5230000  -0.8050000  -0.2340000   0.0770000
-0.5150000  -0.6410000   0.3600000  -0.9930000  -0.5180000  -0.9920000   0.0690000  -0.7890000   0.0100000   0.2220000
-0.6580000   0.7450000  -0.6290000   0.5490000  -0.1980000  -0.7310000  -0.6350000  -0.9240000  -0.9090000   0.5390000
-0.4230000   0.9950000   0.2600000  -0.8600000   0.2570000  -0.1960000  -0.6150000   0.9320000   0.7120000  -0.4440000
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Figure 5: Pseudorandom set generation result.

9. Conclusions

In the paper, through comparative studies, a higher degree of compliance with the model of the reflected signal of the radio altimeter, which is obtained when conducting statistical tests of a circuit with a noise signal source using the Monte Carlo method, is confirmed. It is shown that using only the function of generating pseudo-random signal sequences as weighting functions of the source of the reference signal does not accurately reproduce the noise processes in the signal at the input of the radio altimeter receiver, since in this case all components of the signal on the positive half-wave have a positive sign (or are equal to zero), but all signal fluctuations on the negative half-wave have a minus sign, while there are no continuous transitions from the positive to the negative region and vice versa, which does not correspond to the real state of affairs.

On the contrary, the results of tests of a model with a noise signal source carried out by statistical modeling using the Monte Carlo method do not have this drawback. In order to expand the properties of the developed model, it is proposed to perform a more flexible configuration of the pseudorandom number generator by selecting a generator with the required distribution law of random variables and redesigning it to generate pseudorandom sequences in the required range.

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