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**CREATION AND DEVELOPMENT OF THE FUNDAMENTAL AREA
"FRACTAL RADIOPHYSICS AND FRACTAL RADIO ELECTRONICS:
DEVELOPMENT OF FRACTAL RADIO SYSTEMS".
Part 2. SELECTED RESULTS AND PERSPECTIVE TRENDS.**

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In the second part of the article, the main results on the creation of new information technologies based on textures, fractals, fractional operators and nonlinear dynamics methods obtained over 40 years by the author and the team under his leadership are presented. The investigation has been conducted within the framework of the research area "Fractal Radio physics and Fractal Radio electronics: Designing Fractal Radio Systems", initiated and developed by the author in the V. A. Kotelnikov Institute of Radio Technologies and Electronics of the Russian Academy of Sciences from 1979 until the present day. Introduction of the above-mentioned radiolocation terms to the scientific use enabled the author for the first time in the world to propose and then apply new dimensional and topological (but not energy!) features or invariants that are combined under the generalized concept of "sampling topology" ~ "fractal signature".

Keywords: radio physics; radiolocation; nonlinear dynamics; dimension theory; textures; fractals; scaling; fractional operators.

INTRODUCTION

The paper discusses the main areas of the implementation of textures, fractals, fractional operators and methods of nonlinear dynamics into the fundamental problems of radio physics, radiolocation and a wide range of radio engineering to create new information technologies. The investigation is conducted within the framework of the research area "Fractal Radio physics and Fractal Radio electronics: Designing Fractal Radio Systems", initiated and developed by the author in the V. A. Kotelnikov IRTE of the Russian Academy of Sciences from 1979 until the present day [1-50].

1. Main results

As a result of joint long-term natural experiments with leading industry research institutes and design departments of the USSR and Russia, a statistical analysis of large amounts of new data on the spatiotemporal dispersion characteristics of land covers within MMW and SHF ranges was carried out. It took into account their seasonal and angular variations in various weather conditions in order to define the boundaries of radar contrasts, the distribution laws of the specific RCS, the spectral width, the time and the fluctuation correlation interval of the intensity of reflected simple and complex phase-shift keyed signals within MMW range and the structure of the reflected pulse signals that made it possible to consider the terrain features when developing various imaging systems.

A theory of millimeter radio waves scattering by chaotic covers was developed. It used the first introduced functionals of stochastic backscattered fields and frequency coherence functions with regard to the antenna directivity diagram and the correlation of unevenness slopes. The results of

this theory make it possible to determine the coherence zones of space-time radio channels with variable parameters for optimal selection of the sounding signal bandwidth, frequency spacing in multi-frequency systems and values of complex sounding signal base, reflected signal characteristics, generalized uncertainty functions, potential accuracy of aircraft over flight height estimates, characteristic dimension of unevenness. Theoretical and experimental results were used in preparation of reference digital radar maps.

For the first time, a new class of informative features, based on the fine structure of the reflected radar signals of millimeter range radio waves has been proposed. It makes for improving the identification of land covers.

For the first time, *complete* assemblies of textural and spatial spectral-correlation features of optical and radar images of real land covers have been studied, followed by clustering and determination of the most informative features for certain texture classes. It has been proved that the existence domain of textural features of radar images within the MMW range is completely determined by the corresponding domains of optical image features. The performed experiments demonstrated the effectiveness and generality of the proposed approach in the problems of land cover classification when integrating images on optical and millimeter waves. The integration of images increases the efficiency of detection, identification and classification based on an extended vector of informative and stable features. The results of image processing are detailed digital radar maps. Such maps make it possible to present radar information in a form suitable for further use in the radio navigation of aircraft and the identification of various types of ground objects. [Note that these studies had no analogues, neither in the USSR nor in Russia, and have not lost their relevance at the present time].

For the first time, the author has developed a number of textural methods for detecting various objects and their contours in real optical and radar images of the ground surface at small signal / background ratios. A relationship between the dimensions of the object and the analyzed fragment of optical and radar images of a wide class of land covers in the case of optimal detection has been established.

The possibility of stochastic autoregressive synthesis of optical and radar images of land covers with transformation of intensity bar graphs has been theoretically substantiated and experimentally confirmed. The optimal dimensions of the intensity domain and the order of the autoregressive series involved in the forecasting for adequate image synthesis have been determined. With an increase in the correlation order, the domain for determining the textural features of the synthesized images is narrowed. When comparing parts of the original optical or radar image with a synthesized reference standard, it is shown that the resulting two-dimensional binary field of cross-correlation coefficients directly detects the location of the object in the original image. It makes for obtaining a circulation a map and dynamics of the detected object. Using various combination algorithms (classical correlation, the method of pair functions, and the method of absolute difference) it has been established that the physical accuracy of stochastic autoregressive synthesis reaches 90%

On the base of the above mentioned radio physical studies, a system approach to developing an axiomatic information model of radar maps of non-uniform terrain has been developed and implemented. A generalized radio physical model for generating radar maps of non-uniform terrain has been developed. It involves both methods of stochastic autoregressive image synthesis and the information about the field of specific RCS of land covers. The characteristic gradation number of the specific RCS of the ground surface has been defined. Based on the analysis of the system architecture for obtaining the reference standard, an algorithm for synthesizing in the radio range of contour and halftone radar maps of non-uniform terrain is implemented. It is shown that the destruction of the correlation maximum takes place for a contour radar map of the terrain at a wavelength of 8.6 mm at an angle of relative turn of $5^0 \dots 7^0$, and for a halftone radar map – at an angle of $14^0 \dots 17^0$. Then, the fractal parameters have been first introduced into the generalized radio

physical model for developing radar maps of non-uniform terrain. This fact has increased the information content of the synthesis.

The existence of a strange attractor controlling radar scattering from vegetation covers was predicted. Later on, the effect was experimentally detected at a wavelength of 2.2 mm (2002). The obtained results confirmed the theoretical ideas about the existence of chaos in a dynamic system that described the nature of the scattering of electromagnetic waves by vegetation covers. The reconstruction of the attractor made it possible to determine its fractal dimension D , the maximum Lyapunov exponent, embedding dimension, the prediction interval (time). The experimental characteristics of the strange attractor formed the basis of a fundamentally new non-Gaussian model of radar scattering of MMW by vegetation cover based on the theory of dynamical systems and stable distributions. It was shown that the interval (time) of predicting the intensity of the reflected radar signal is approximately by an order of magnitude longer than the classical correlation time. This made it possible to introduce into the theory of radiolocation a new essential characteristic, namely, the interval (time) of prediction, which extended the techniques and circuitry of radio locators.

A reliable physical substantiation of the practical application of fractal methods in modern branches of radio physics, radio electronics, and information control systems was established. In the mid 80s of the XX century an operating model of coherent compact digital solid-state radar (DSR) on parametrons with a sounding wavelength of 8.6 mm with a complex signal base $> 10^6$ and processing an input sub-noise signal on a carrier frequency was made jointly with "Almaz" Central Design Bureau. While optimal processing, the energy potential of the DSR increased by 50 dB. Then, a DSR on two sounding frequencies in MMW and SHF ranges with a fractal slot antenna (the first in the USSR) was made. For the synthesis of images Radon transformation was used. In 1997, methods of fractal modulation and fractal signals were developed for the first time. They included H-signals, first introduced by the author.

The efficiency and perceptiveness of application of the fractional measurement and scaling ratios theory (for textures and fractals) in the case of detection and identification (general filtering) of one-dimensional and multidimensional radar signals from low-contrast targets against the background of intense non-Gaussian interference of various kinds were found and proved for the first time. Thus, that was *fundamentally new* radio engineering.

It is proved that when collecting, transforming and storing information in modern complex monitoring systems of remote and mobile objects under conditions of intense interference, the latest methods for processing information flows and multidimensional signals proposed by the author are of great importance. Typically, the characteristics of such complex systems are demonstrated on different space-time scales. The most adequate valuation of states of the system under study and the dynamics of the state change of its subsystems are realized when using the theory of fractals and processing multidimensional signals in a fractional dimension space with the necessary consideration of scaling effects, which was first proposed and developed by the author in V.A. Kotelnikov Institute of Radio Technologies and Electronics of the RAS.

A new method for measuring fractal dimension and the corresponding fractal signatures of signals, images and wave fields, called by the authors a "local- dispersive" one, was proposed and established. This method, as well as its effectiveness, was confirmed in practice by numerous examples of corresponding digital processing of optical and radar natural and synthesized images, including those with low contrast objects. Textural and fractal digital methods make it possible to partially overcome a priori uncertainty in radar problems using *geometry* or a *sample topology* — both one-dimensional and multidimensional. In this case, topological features of the sample, rather than averaged implementations, which are often of a different nature, are of great importance.

Methods of fractal classification, clustering and identification of many types of natural and artificial objects were studied for the first time on great arrays of experimental data in the form of optical and radar images of real land covers with surface and subsurface objects. The number of

areas around which fractal dimension values are grouped depends on the parameters of the algorithm and the measurement technique. For example, with a small size of the measuring window, we have a large number of groups; increasing its size, we obtain a fixed number of groups or clusters; and, finally, with a very large window size, there 2-3 groups remain (fractal objects – non-fractal objects – exception objects).

Investigation of the type or sampling topology of a one-dimensional (multidimensional) signal for tasks, such as artificial intelligence, for the first time has made for compiling fractal features dictionaries based on fractal primitives that are elements of a fractal language with fractal grammar. The obtained data have been introduced into the synthesis of reference and current radar maps of non-uniform terrain, as well as into developing non-energy radar detectors.

The results (UAV, SAR, medicine, etc.) show that fractal processing methods result in an increase in the quality, object and target details in passive and active modes by several times. These methods can be successfully applied to information processing from space and aviation complexes, stealth high-altitude pseudo-satellites (HAPS) or detecting HAPS and UAV clusters, synthesized clusters of space antennas and space debris. The fractal characteristics of elves, jets and sprites, the most interesting types of recently discovered altitude discharges in the ionosphere, have been investigated. The algorithms for extraction of a moving remote object of unknown shape (fractal or non-fractal) in a low-contrast image formed in optical-electronic systems have been synthesized with co-authors. Experimental results in images obtained in natural conditions, confirm the effectiveness of the proposed processing methods. The possibility of synthesizing new fractal functions and fractal functionals based on the theory of fuzzy sets has been proved for the first time. The construction of new classes of fractal and multifractal subsets on fuzzy sets has been formalized. As test functions, any classical non-differentiable functions can be used.

It has been shown for the first time that the physical content of the diffraction theory involving multiscale surfaces becomes more distinct with the fractal approach and regard of the fractal dimension D or the fractal signature as a parameter. Consideration of fractality significantly brings together theoretical and experimental characteristics of scattering patterns of land covers, which is important for radar and remote sounding tasks. For the first time ever, a long list of characteristic types of more than 70 fractal surfaces based on Weierstrass functions, as well as more than 70 three-dimensional scattering patterns and their cross sections calculated for $\lambda = 2.2\text{mm}$, $\lambda = 8.6\text{mm}$ and $\lambda = 3.0\text{cm}$ wavelengths at different values of the fractal dimension D and changing scattering geometry has been studied and presented.

Analogs of Maxwell's equations with Caputo fractional derivatives have been deduced. Gauge invariance has been considered and the diffusion-wave equation for scalar and vector potentials has been deduced. A particular solution of the diffusion-wave equation has been found and analyzed. A rigorous electrodynamic calculation of numerous types of fractal antennas, the design principles of which form the basis of fractal frequency-selective surfaces and volumes (fractal “sandwiches”) has been made.

Based on the topology of fractal labyrinths, a series of tiny broadband fractal antennas has been synthesized. The author has proposed to synthesize large stochastic robust antenna arrays using the properties of fractal labyrinths. Combination of several fractal labyrinth clusters with different fractal dimensions makes it possible to develop adaptive broadband fractal antennas. For the first time, a model of a “fractal” capacitor as a fractal impedance has been proposed and implemented. Fractal-scaling methods for the tasks of radiolocation and the formation of the fundamentals of a fractal element base, fractal sensors and fractal radio systems have been developed, substantiated and applied. A physical approach to modeling a fractal capacitor and fractal impedances has been developed. Promising elements of fractal radio electronics are functional elements, the fractal impedances of which are implemented on the basis of the fractal geometry of conductors on the surface (fractal nanostructures) and in space (fractal antennas), the fractal geometry of the material microrelief surface, etc. Advanced approaches can be extended to a wide class of electrodynamic

problems in the study of fractal magnonic crystals, fractal resonators, fractal screens and barriers, as well as other fractal frequency-selective surfaces and volumes.

A new type and a new method of modern radiolocation (namely, fractal-scaling or scale-invariant radiolocation) has been discovered, proposed and established. The efficiency of the functionals, which are determined by topology, fractional dimension and the texture of a received multidimensional signal for the synthesis of fundamentally new non-energy detectors of low-contrast objects against the background of interference has been proved. An increase in the sensitivity of the radio system (that is equivalent to an increase in the range of action) when using fractal and texture features in topological detectors, has been confirmed. This leads to fundamental changes in the very structure of theoretical radiolocation, as well as in its mathematical apparatus.

Fractal radiolocation can describe and adequately explain a much greater class of radiolocation phenomena. The basis of the scientific area created for the first time in Russia and in the world, is the concept of fractal radio systems and fractal radio elements, sampling topology and the global fractal-scaling method proposed and developed by the author in the V. A. Kotelnikov IRTE of the RAS. The theoretical radiolocation-related research makes it possible to solve effectively the problem of detecting signals in conditions of intense interference and develop new fractal multi-frequency MIMO systems.

The following postulates of fractal radiolocation have been developed:

- 1 – intelligent signal / image processing based on the theory of fractional measure and scaling effects for calculating the field of fractal dimensions;
- 2 – sampling a received signal in noise can be classified as stable non-Gaussian probability distribution of a D signal;
- 3 – topology maximum with a minimum of the input random signal energy (i.e. maximum “escape” from the received signal energy).

These postulates open up new possibilities for ensuring stable operation at a small signal / (noise + interference) relationship or an increase in the radar range.

The theoretical issues of fractal non-inertial relativistic radiolocation and quantum cosmology in a curved space-time of negative fractal dimension have been substantially developed together with colleagues from Russia and Israel (Haifa, Technion). *Example:* Based on the Schrödinger equation with the fractional calculus operator with respect to spatial coordinates, the Feynman path integral for the generalized Lagrangian with the fractional differentiation operator with respect to time has been calculated. Note that at present in the United States, this fundamental scientific trend acquired an imposing name of “*Fractal Cosmology*”.

The results of experimental and theoretical studies obtained by the author have been implemented by leading industry research institutes and design departments of the USSR and Russia and used in developing radio systems for various purposes, in interpreting data of remote radio physical studies of the environment and in other applied tasks in which optical and radar images of the ground surface serve as information materials.

Based on multi-year research, new theoretical trends were formulated and developed in the theory of statistical solutions, statistical radio engineering and statistical radio physics, for example, “The Statistical Theory of Fractal Radiolocation”, “Statistical Fractal Radio Engineering”, “Theoretical Foundations of Fractal Radiolocation”, etc. The results listed above formed the basis of the fractal paradigm and the unitary global idea of fractal natural science.

And one more thing:

In the book of I. I. Guay On the little-known hypothesis of Tsiolkovsky / Prefaced and ed. by Doctor of Technical Sciences P.K. Oschepkova. – Kaluga: Kaluga Book Publishing House, 1959. – 248 p. (pp. 24-25) one can find the following words:

“New scientific hypotheses almost always require new and unusual arguments because these hypotheses deal with the new, not the expected, and the necessary regularities that this hypothesis promises to create in the future are not obvious at first sight. This is the main vulnerability of new

hypotheses, whereas well-established theories confirmed by practice often seem to be unshakable. But not even the best hypothesis can be considered complete and absolutely motionless and, as Leonardo da Vinci said, a scientist following traces will never get ahead.”

2. On promising trends of research on fractals and textures

On the basis of the above mentioned author's works, let us try to bring into focus the most promising trends of fractal research in the field of progress in modern fundamental and applied sciences:

1. Investigation of the capabilities of textural (spatial and spectral), fractal and entropy features for radar detection tasks.

2. Synthesis of new models of radar signals scattering by land covers based on the theory of deterministic chaos, strange attractors and fractal probability distributions – stable distributions.

3. Investigation of wave phenomena (propagation and scattering of waves, diffusion processes) in fractal inhomogeneous media based on fractional integrodifferential operators. Further development of fractal electrodynamics.

4. Synthesis of channel models of radar and telecommunication system based on spatial fractal generalized correlators and fractal frequency coherence functions.

5. Investigation of the possibilities of identification of target shape or contours using fractal, textural and entropic features. Work on the singularities of the input function.

6. Investigation of the potential possibilities and limitations of fractal methods for processing radar and communication signals, including fractal modulation and demodulation, fractal coding and data compression, fractal image synthesis, fractal filters. Transition to fractal radio systems. Fractals in acoustic electronics.

7. Investigation of adaptive space-time signal processing based on fractional dimension and fractional operators.

8. Search and study of new combined methods for detecting and identification of low contrast target classes in high-intensity non-Gaussian noise.

9. Investigation of the possibilities of developing new media for transmitting information, multiple-band fractal absorbing materials, constructing fractal antennas and fractal frequency selective surfaces and volumes. Further development of the theory and technology of fractal impedances.

10. Synthesis of new classes of fractals and multifractals with a generalization of the concept of set measure.

11. Study of the type or sampling topology of a one-dimensional (multidimensional) signal, for example, for tasks of artificial intelligence in order to compile dictionaries of fractal features based on fractal primitives that are elements of the fractal language with fractal grammar, i.e. investigation of the *problem of “dimensional sclerosis”* of physical signals and signatures. These concepts, introduced by the author, suggest the study of the topological features of each specific individual sampling, but not average implementations, which are often of different nature.

12. The forecast of the formation mechanisms and roughness characteristics in order to control the geometrical parameters of the microrelief to obtain the desired physicochemical and operational properties of products with modern non-equilibrium processing technologies of their surface layer. Fractals in nanotechnology. (In 2008, the author proposed a new concept, namely, “Scaling of a rough fractal layer and nanotechnology”).

13. The development of fractal non-inertial relativistic radiolocation in curved space-time of connected structures, i.e. fractal geometry of space-time of deterministic structures. At present, in the USA this fundamental scientific trend has acquired an imposing name of “*Fractal Cosmology*”. Our works with co-authors are listed in publications on this theoretical trend (arXiv: Cornell University, USA).

Conclusion

The performed investigations are priority in the world and serve as the basis for further development and substantiation of the practical application of fractal-scaling and texture methods in modern radio physics, radiolocation and nanotechnology, as well as in development of fundamentally new and more accurate fractal-texture (topological) methods for detecting and measuring parameters of radio signals in the spatiotemporal radar channel of the propagation of electromagnetic waves with scattering. The crucial distinction of the proposed textural-fractal methods from the classical ones is due to a fundamentally different approach to the main components of the signal and field. This made it possible to get to a new level of information structure of real non-Markov signals and fields. Thus, this is fundamentally *new radio engineering*. The introduction of fractals, scaling effects and fractional operators gives "impetus" to modern electronics as well, since all foregoing and present-day electronics is based exclusively (and only!) on the basis of the theory of integral functions.

The results and conclusions made by the author together with his students also have great innovative potential, the realization of which, in their opinion, will provide a solution to a number of problems of modern radio physics, radio engineering, radiolocation, communication and control. They will ensure new quality of detection and identification systems, development of new information technologies and competitiveness enhancement of domestic radio electronics products.

The author has named only the most important issues related to the use of fractals, textures and scaling effects in radio physics and radiolocation. In the development of fractal trends, many important stages have already been passed, including the stage of formation of this field of science. However, many problems still remain to be solved. Not results, not specific decisions are of the greatest value, but namely, *the method of solution*, the approach to it. That is global fractal-scaling method created and developed by professor A.A. Potapov. B. Mandelbrot (1924-2010) deserves full credit for formulation of the theory of fractal geometry. But its radio physical / radio technical and practical implementation is the achievement of the world-famous Russian scientific school of fractal methods headed and led by the author of the article.

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