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ON THE ISSUES OF FRACTAL RADIO ELECTRONICS: Part 1. PROCESSING OF MULTIDIMENSIONAL SIGNALS, RADIOLOCATION, NANOTECHNOLOGY, RADIO ENGINEERING ELEMENTS AND SENSORS.

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The paper presents fractal approaches to solving problems of radio electronics at all stages of radio waves radiation and reception with the subsequent processing of incoming information. This part of the article deals with the processing of information flows in radio systems. The basics of circuit design of new types of fractal antennas and fractal sensors are presented, a sketch of the development of fractal nanotechnologies is given. A brief description of the features of electrodynamic modeling of real miniature fractal antennas is given. The rationale for fractal-scaling or scale-invariant radiolocation is given.

Keywords: Radio physics, radio electronics, nanotechnologies, image processing, fractal antennas, fractal generators, texture, fractal, scaling.

Introduction

The creation of broadband and ultra-wideband radio systems has always been one of the main tasks of modern radio electronics. The expansion of the operational frequency bandwidth is due to modern trends in the development of radiolocation, telecommunications, radio engineering in order to increase the speed of information transmission, the level of jamming immunity and the information capacity of radio systems of any range. Along with the increasing complexity of modern radio-electronic equipment and its functions, it is necessary to consider new physical principles for the element base and radiotechnical systems. In this case, the theory of fractals and the theory of deterministic chaos [1–4] become extremely important.

The main directions of design and development of new fractal radio elements, antennas, metamaterials, as well as fundamentally new radio systems for radiolocation and telecommunication problems, i.e. issues that apply to the entire radio electronics. The study is conducted within the framework of the research area “Fractal Radiophysics and Fractal Radioelectronics: Designing Fractal Radio Systems”, proposed and developed by the author based on the theory of fractals and deterministic chaos in IRE of RAS since the late 70s of the XX century [1-4].

1. Fractal processing of information flows in radio systems

When collecting, converting and storing information in modern complex systems for monitoring remote and mobile objects under conditions of intense interference, the latest methods for processing information flows and multidimensional signals become very important. Typically, the features of such complex systems exert at different spatial-temporal scales. The most adequate estimates of the state of the system under study and the dynamics of the change in the state of its subsystems are realized using the theory of fractals and processing multidimensional signals in fractional space with the necessary consideration of scaling effects [1-6]. The following briefly

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summarizes selected experimental results of the fractal processing of multidimensional signals from objects of different physical nature (Figures 1-5).

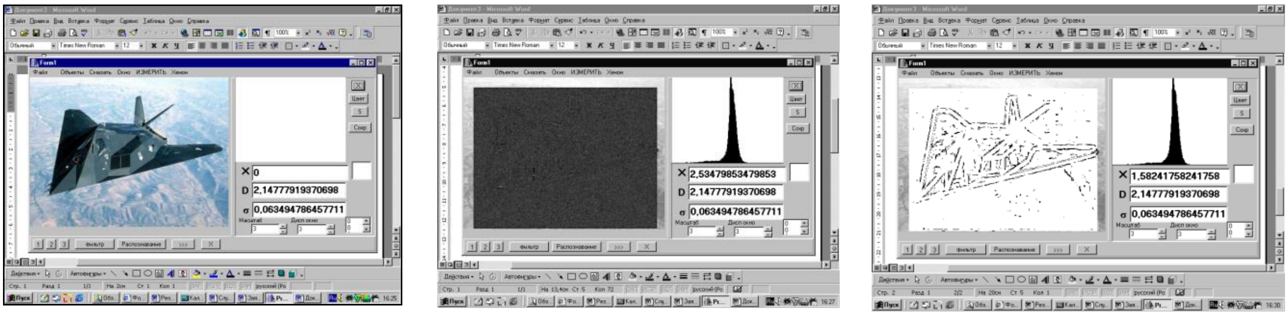
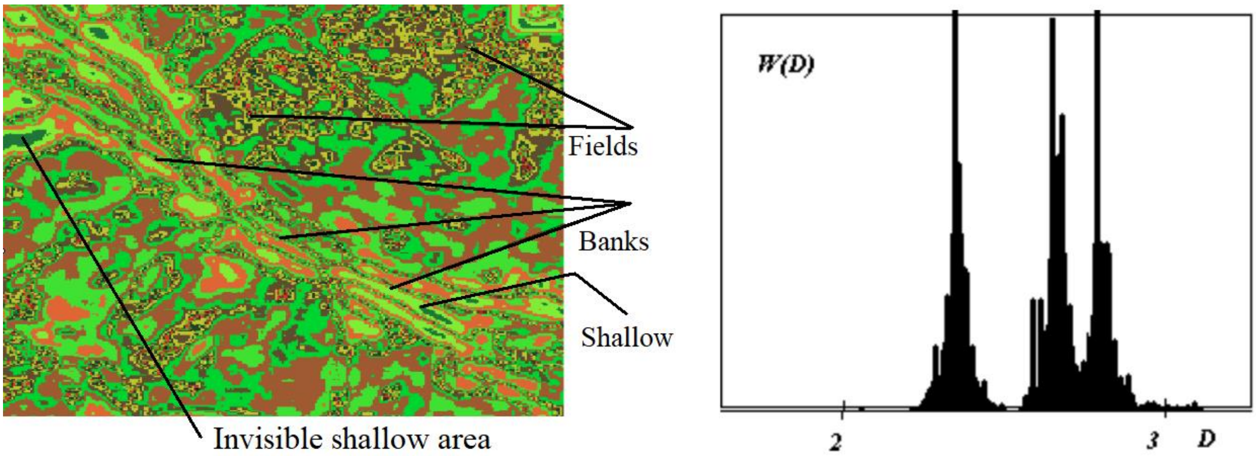
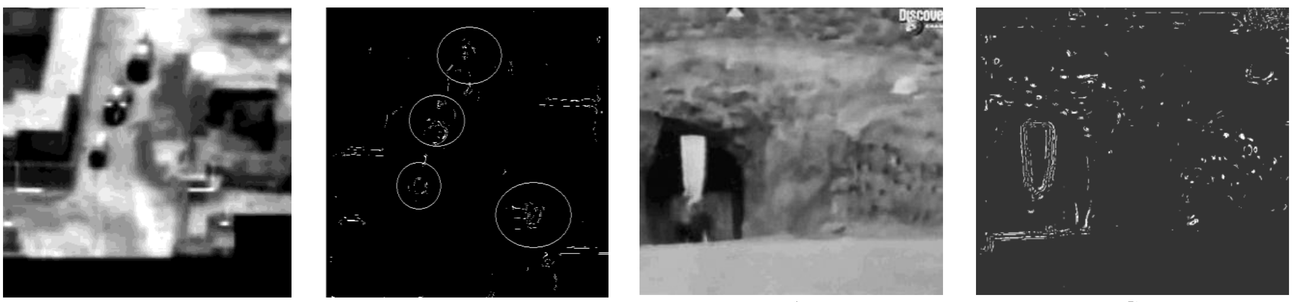


Fig.1. The original image of the aircraft (left), the image of the aircraft under the influence of noise jumming: signal-to-noise ratio q_0^2 = -3 dB (middle), the results of fractal detection (right)



a) b)

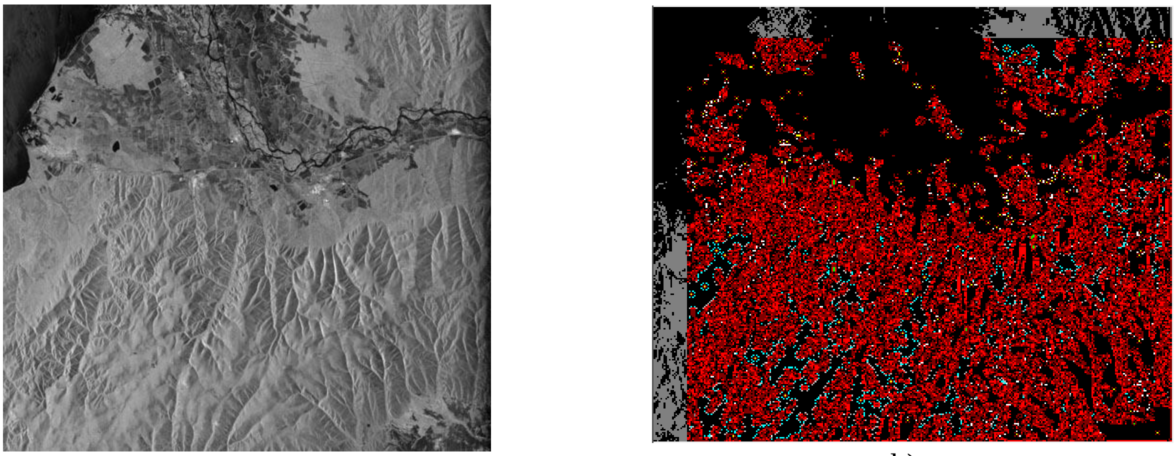
Fig.2. An example of earth surface differentiating by the field of fractal signatures D (a) and the empirical distribution of D when segmenting land cover textures in the radar image



a) b) c) d)

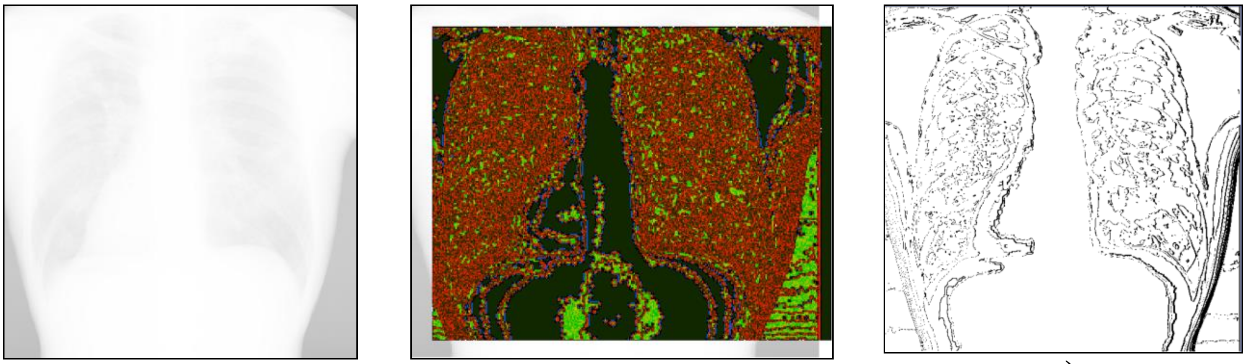
Fig.3. Images of the terrain with moving machines (a) and mountainous terrain with a tunnel (c) with UAVs and filtering results according to estimates of the fractal dimension D (b, d)

The results (UAV, SAR, medicine, etc.) show that fractal processing methods give an increase in the quality and detailing of objects and targets in a passive and active mode approximately by several times. These methods can be successfully applied to information processing from space, aviation complexes, low-profile high-altitude pseudo-satellites (HAPS) or detection of HAPS clusters and UAVs, synthesized clusters of space antennas and space debris.



a) b)

Fig.4. The Selenga river delta in the PALSAR SAR image (a) and the result of fractal processing (b).



a) b) c)

Fig.5. An example of solving the problem of fractal clustering of an X-ray image (a) by the value of estimating the fractal dimension D (b) and the fractal edge detection (c)

2. Fractal labyrinths as miniature fractal antennas

For the past few years, the fractal labyrinth topology has become a fast-growing object of interest for scientists. The software created by the author and his colleagues was called "Fractalizer" [7, 8]. The software (the window shown in Figure 6a) contains the first graphic area of the graph in order to select the shape of the fractal curve generator and the discretization interval. To the right of the generator panel there are graphical tools for determining parameters, such as the iteration number of the main branch, the number of branches, the number of branches iteration, the width and height of lines, the minimum gap between unrelated elements (elementary lines) of the structure, etc. Software can save fractal structures in a universal and well-known drawing size as Autodesk DXF. A DXF file can be imported as fractal antenna geometry into most modern computer developments and software modeling, such as ANSYS, Solid Works, etc. Moreover, the software "Fractalizer" has a setting panel for launching Ansoft HFSS as a software for fractal structure modeling. The process is automated for electrodynamic modeling of real miniature fractal antennas. The information exchange scheme you can see in Figure 6, b.

First, the program builds the main curve based on a user-defined generator, which is the first iteration of the fractal. Then the program calculates the number of break points of the curve (the number of angles) and stores them as points of a possible base of branches. Then, using a random

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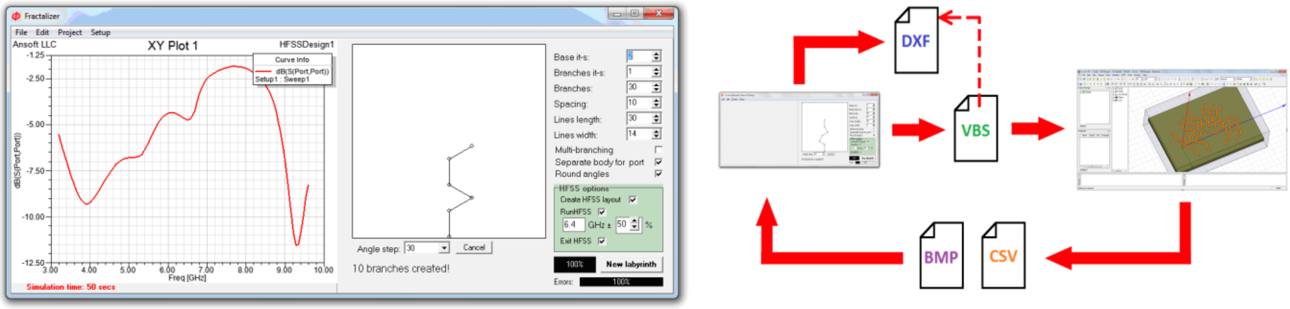
number generator, the loop program selects the base branch point and builds this branch before the specified user iteration is completed or before the obstacle is reached (another curve).



a) b)

Fig.6. Computer window for design stages software (a) and information exchange (b)

The number of loops must be specified by the user. After the structure is ready, the software reports the number of successfully created branches and saves the structure as a DXF file. Examples of the synthesis of fractal antennas are shown in Fig. 7. The results obtained using the software were automatically imported into the AnsoftHFSS 12 simulation environment based on the finite element method (FEM). The results of modeling a fractal antenna (Figure 7 a) are shown in Figure 7 b. A fractal antenna has two resonances. The first one corresponds to a frequency below 1 GHz, i.e., the antenna is capable of receiving a wave length of 0.32 m.

3. Fractal labyrinths and genetic algorithms in the synthesis of apertures of large robust antenna arrays

Antenna arrays are one of the main components of large modern radio systems. The theory of application of fractals and fractional calculus makes for combining the achievements of classical amplitude and stochastic arrays [3]. The first type of antenna arrays has relatively small side lobes in the directivity pattern, but it is sensitive to element placement errors and excitation current values. The second type of arrays is resistant to element placement errors and their failure, but is characterized by a relatively high level of side lobes in the directivity pattern. The application of the principle of scaling (fractals) for antenna arrays makes it possible to more flexibly control the directivity pattern in the side lobes area.

The author has proposed to synthesize large stochastic robust antenna arrays using the properties of fractal labyrinths. This will make it possible to control the energy of the side lobes. The second step is to unite several fractal labyrinth clusters with different fractal dimension D in the synthesis space of a large antenna array. Therefore, in this natural way we come to adaptive fractal antennas. Here it is necessary to use genetic algorithms [9] to optimize the space-time large and extra-large antenna apertures that conform by specified quality and detection criteria.

5. Fractal generator

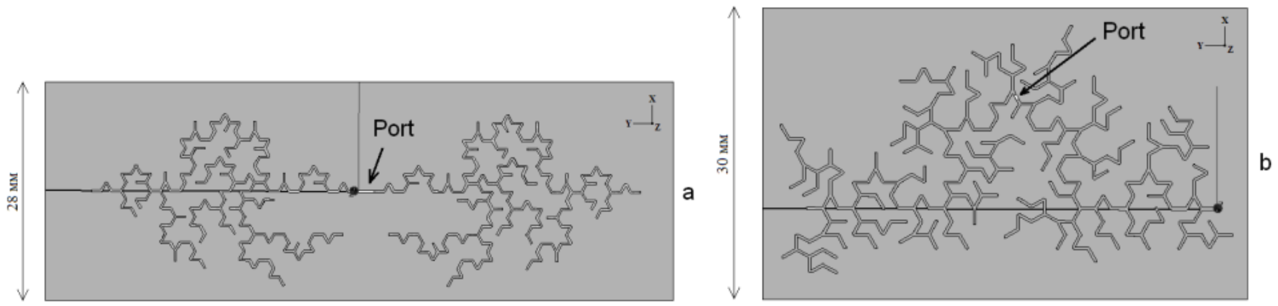
Consider an example of mathematical modeling of the basic fractal self-oscillatory system (FSOS) [10]. An oscillator with a small degree of nonlinearity was chosen for research, namely, a generalized oscillator of a sinusoidal signal (Figure 8 a), the action of which in the classical theory is given by the equation of motion:

$$u'' + \lambda(a)u' + \omega^2 u = 0\,, \tag{1}$$

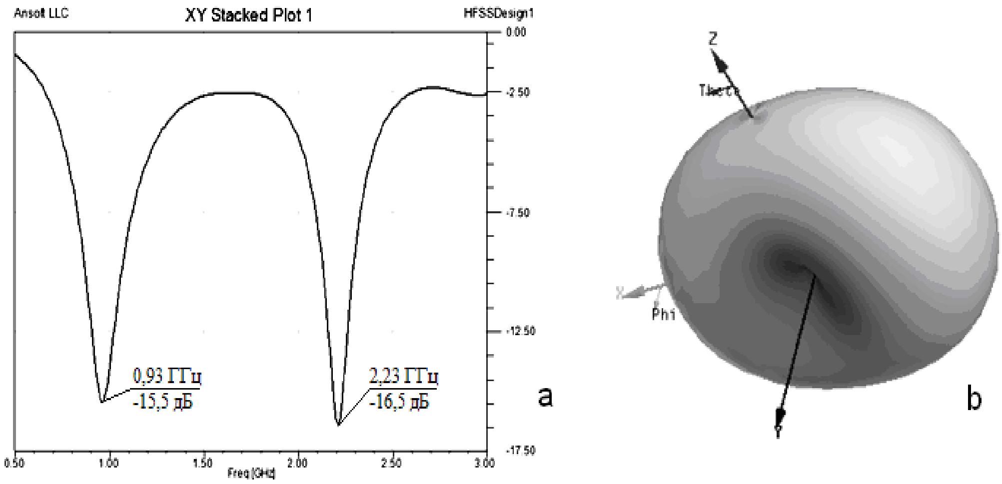
where ω is the oscillation frequency of the system, a is the amplitude of the signal, $\lambda(a)$ is the equivalent attenuation coefficient, equal to:

$$\lambda(a) = \frac{\omega}{Q}\left(1 - k(a)R\right) = \frac{1}{C}\left(\frac{1}{R} - k(a)\right), \tag{2}$$

where Q is the quality factor, R and C are the load resistance and the capacitance of the circuit, respectively.

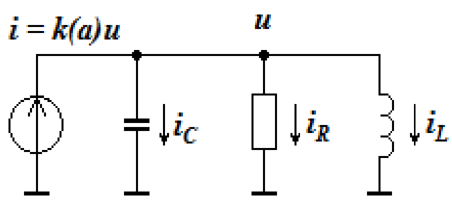


a)

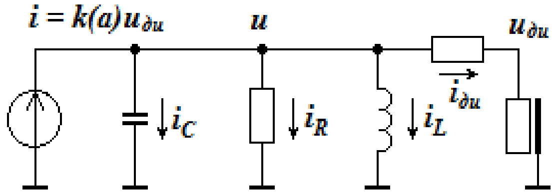


b)

Fig. 7. Created fractal labyrinths for the synthesis of fractal antennas (a), the reflectivity factor in the frequency domain and the three-dimensional directivity pattern of the fractal antenna (b).



a)



b)

Fig.8. Classical self oscillator (SO) - (a), SO with a fractal chain of positive feedback (b).

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Assume that the positive feedback (PFB) loop in the generator circuit is a fractional differentiating circuit based on a long *RC* line that can be interpreted as a certain distribution of the PFB loop parameters, for example, such as shown in Figure 8 b. In this case, assuming the current by the fractional integrator $i_{\partial u}$ being much smaller than the current *iR*, the equation of motion becomes:

$$u'' + \frac{1}{RC}u' + \omega^2 u = \frac{1}{C}k(a)_L D^{\alpha}(u), \tag{3}$$

where $_L D^{\alpha}$ is a left-side Liouville derivative of α order [3].

Considering that $u \approx a\cos(\omega t)$, we have:

$$\lambda_{\partial}(a) = \frac{1}{C}\left(\frac{1}{R} - k(a)k_{\partial u}\sin(\alpha\pi/2)\right). \tag{4}$$

In equation (4), α = 0 ... 1 is the order of the fractional impedance [3, 9] of the PFB loop, and $k_{\partial u}$ is the amplitude coefficient of the fractional chain transmission. The resulting expression (4) indicates a greater oscillation damping of the fractional system in comparison with the classical one at equal *L*, *C*, *R* and and $k_{\partial u} = 1$.

The growth of the motion amplitude, in particular, of the signal, as a slow function of time in accordance with the method of equivalent linearization, will be determined by the following expression:

$$a' = \frac{\lambda_{\partial}(a)}{2}a = \frac{a}{2C}\left(\frac{1}{R} - gS(a)\sin(\alpha\pi/2)\right), \tag{5}$$

where *g* is the gain, *S*(*a*) is the magnitude of the nonlinearity, $S(a) \le 1$ and $gS(a) = k(a)$.

The growth of the amplitude at different *g* is illustrated in Figure 9. From the first to the third graph, the value of *g* takes on increasing values 0, 166; 0.175 and 0.184.

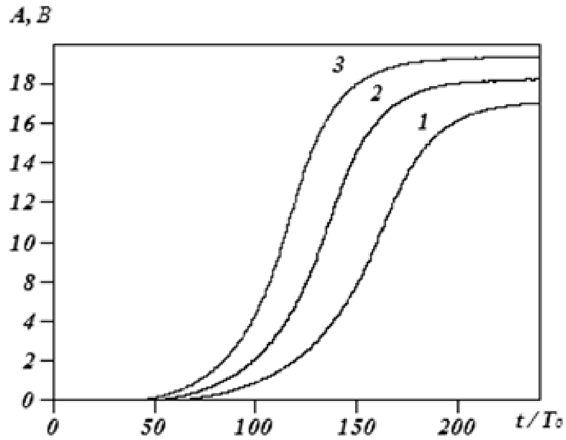

Fig.9. Excitation of a fractal auto-oscillatory system for various *g*.

Thus, a fractional or fractal PFB is identical to a retarded PFB. Note that the delayed PFB can be only a special case of the fractional one, and can also be a feature of the fractality of a dynamic system.

5. Fractal nanotechnologies and fractal radar absorbing materials

The elementary extension of a Cantor mathematical set, when proceeding to the physical level, makes it possible to come over to the cantor blocks in the plane technology of nanostructures [8, 11]. Percolation synthesis for nanostructured composites proposed by the authors in 2007 is also possible [12]. The use of the recursive procedure makes for a self-similar hierarchical structure up to the formation of separate conductive bands on the chip and in nanostructures. It is necessary to take into account and calculate the mutual and collective influence of electromagnetic fields on all components of the chip: conductive tracks, semiconductor, insulator, etc. The non-linear Cardar-Parisi-Zwang equation (CPZ) is used when spraying a substance on a solid surface. In [13], the CPZ equation for the anisotropic growth of the surface before the onset of a gradient catastrophe is solved in the small-angle approximation.

Modern and promising absorbing materials and surfaces should have a wide spectrum of electromagnetic radiation absorption at arbitrary angles of incidence and polarization of the incident radiation. From this perspective, the use of fractal metamaterials and artificial composites, which can be attributed to “smart” materials, is the most promising way [3, 8, 11]. In addition to direct use, they can have many functions. The inverse problem is solved in estimating the effective coefficients of the dielectric and magnetic permeability of a multilayer fractal medium, which can be tensors in the case of anisotropic materials. The medium can be formed by packets (fractal "sandwiches") of miniature fractal antennas [14]. The associated topological fractal structure makes for modulating the transmittance of electromagnetic waves. The lowest attenuation frequency corresponds to wavelengths, which can significantly exceed the external dimensions of a fractal plate that makes such fractal structures super-wave reflectors. Photonic crystals use Bragg scattering to create bandpass gaps [3, 14]. As a result of the Bragg scattering mechanism, the width and transverse dimensions of the photon crystals should be several wavelengths. Fractal photon and magnon crystals have a number of advantages compared to their classical analogs and are essentially new media to transmit information.

6. Fractal signatures in microrelief evaluation problems

Based on the experiments the researchers carried out, they were among the first to propose evaluating methods for using of fractal characteristics of surface quality of the products and the microrelief properties of modern materials [3, 15]. The intensive development of processing methods using concentrated energy flows leads to significant difficulties in the description and evaluation of roughness compared with the profile method.

In these cases, the shape of the roughness elements and the distribution of the elements are significantly different from the conventional Gaussian concept, which was formed long ago as part of processing materials by chiseling, see Figure 10 [3, 15].

Title	Type of terrain	Title	Type of terrain
Mushroom shaped		Hollows	
T - shaped		Globules	
Peaks		Dispersion (globular-dispersion)	
Splats		Cogs	
Botiroid		Moire pattern	

Fig.10. Types of relief elements of modern micro-surfaces

Problems of forming surface quality, including such important quality characteristics as its roughness, become especially important due to the development of new energy technologies for metalworking. These problems also dominate in the field of nanotechnology, when the formation processes are considered not as a secondary property, but as a "response" of the structure of the surface layer to the influence of a certain physical process, and as a property of the structure itself; the more so the sizes of such layers are comparable with electron free path.

In [15], at the microrelief level of such processed surfaces, the authors demonstrated the existence of fractal clusters with irregularities distributed according to power laws with heavy tails (Figure 11). The presence of fractality in various environments can be controlled, in particular, by changing the skin effect and impedance. It is the spatial / temporal evolution of the current that makes for the electromagnetic fields to "feel" the fractal properties (fractal signatures) of the physical medium under study [3].

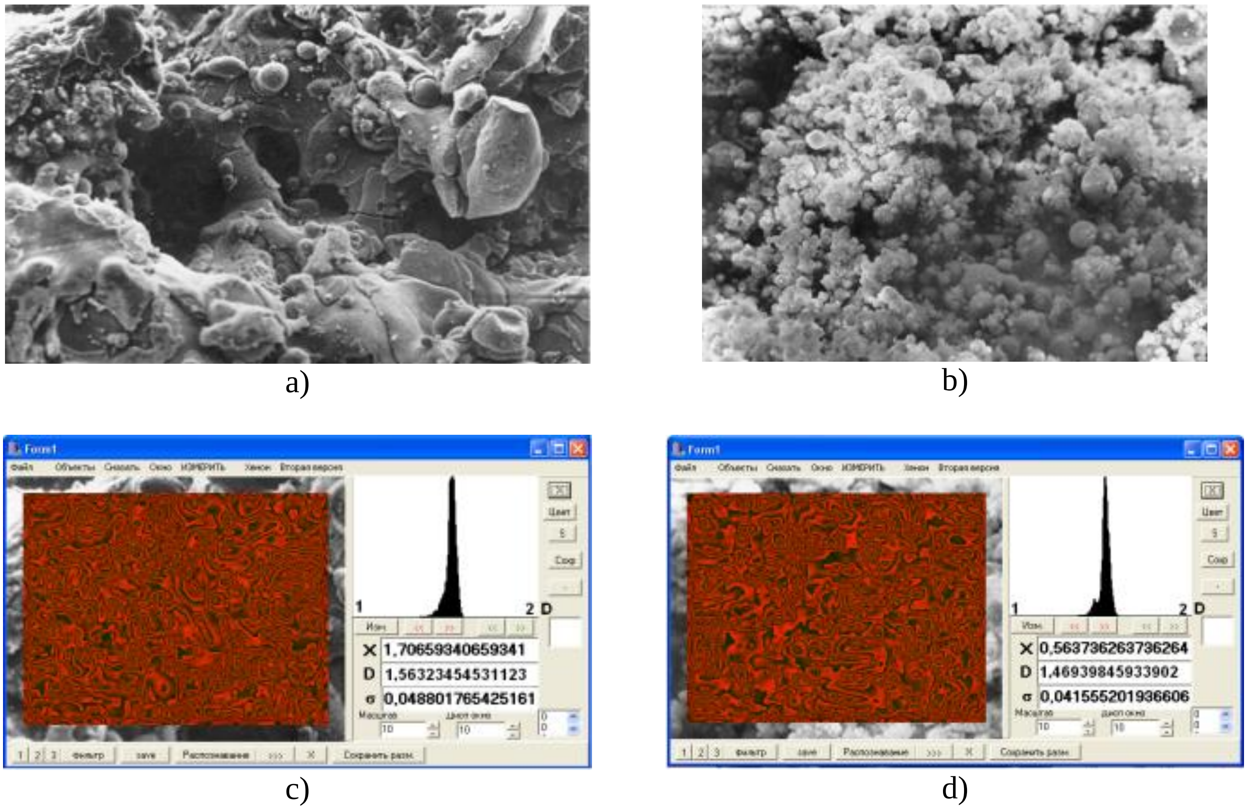

Fig.11. Fractal analysis of samples with plasma spraying: (*a, b*) – a 2D-image of the surface of the samples; (*c, d*) - the field and histogram of local *D*

7. Fractal radio systems

The increasing complexity of radio-electronic equipment and its functions makes it necessary to consider the fractal theory to develop new elementary base and new radio systems. The development of the world's first fractal non-parametric detector of radar signals makes for creating an entire fractal radio system [3, 16]. Fractional memristor on the quantum Hall effect is considered in [17].

Fractal structures and processes open up a new field of applications in radio electronics. Such fractal radio systems are described in detail in [18], in which Figure 3 shows the developed concept of fractal radio systems and fractal radio elements. Fractal radio systems contain fractal antennas, as well as digital fractal detectors, and use fractal methods for data processing; future devices will be able to use fractal methods of modulation and demodulation of radio signals.

8. Fractal-scaling or scale-invariant radio location

Detection of low-contrast objects against the background of natural intense interference inevitably requires the calculation of a fundamentally new characteristic that differs from the functionals related to interference and signal energy, and is determined only by the topology and dimension of the received signal. Introduction of radar concepts of "deterministic chaos", "texture", "fractal" and "fractal dimension D" [1-5] to scientific use allowed us for the first time in the world to propose and then apply new dimensional and topological (and not energy!) features or invariants (Figure 13), which are combined under the generalized concept of “sampling topology” ~ “fractal signature”.

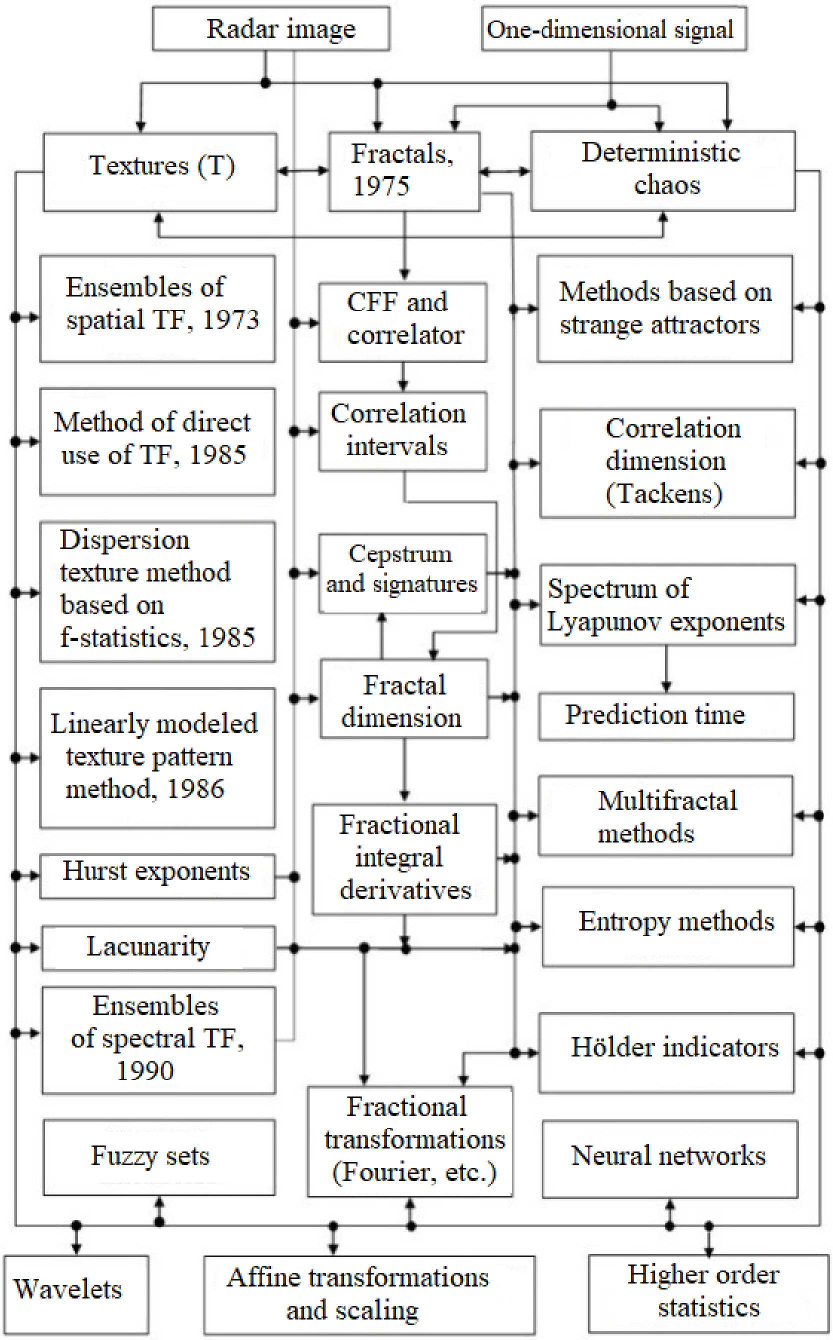

Fig.13. New topological features and methods for detecting low-contrast objects against interference (TF - textural features, CFF - coherence frequency function)

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Fractal radiolocation [16, 19] is based on three postulates: 1 – signal / image intelligence, based on the theory of fractional measure and scaling effects to calculate the field of fractal dimensions; 2 – the sample of the received signal in the noise relates to the class of stable non-Gaussian probability distributions of D signal; 3 – topology maximum for minimum energy of the input random signal. These postulates open up new possibilities for stable operation support at small q_0^2 or for increasing radar range. Algorithms for detecting extended objects and targets in optical and radar images using texture processing were created by the authors as early as in the 80s of the 20th century (see the left column in Figure 13).

Classical methods for processing multidimensional signals fundamentally only distinguish the information constituent related to an integer-valued measure. Fractal-scaling methods for processing signals, wave fields and images in a broad sense are based on that part of the information that was not taken into account in the classical methods of radar data processing.

Based on many years of research, new theoretical directions were formulated and developed in the theory of statistical solutions, statistical radio engineering and statistical radiophysics, for example, “Fractal analysis and its application in the theory of statistical solutions and statistical radio engineering” or, briefly, “The statistical theory of fractal radiolocation”, “Statistical Fractal Radio Engineering, Theoretical Foundations of Fractal Radiolocatio”, etc.

Conclusion

For the first time in Russia and in the world, fractal-scaling methods have been created, developed and applied for the tasks of radiolocation, the formation of a fractal element base and fractal radio systems. For the technical implementation of the methods of fractal radioelectronics, it is necessary to have a base of new elements that makes it possible to process signals in a fractional measure space and simulate fractal objects and processes with the dynamics of fractional order differential equations. Promising elements of fractal radio electronics are functional elements with the implementation of their fractal impedances based on the fractal geometry of conductors on the surface (fractal nanostructures) and in space (fractal antennas), the fractal geometry of the surface microrelief of materials, etc. The results (UAV, SAR, medicine, etc.) show that fractal processing methods give an increase in the quality and detailing of objects and targets in passive and active modes approximately by several times. These methods can be successfully applied to processing of data from space, aviation complexes, low-profile high-altitude pseudo-satellites (HAPS) or detection of HAPS and UAV clusters, synthesized clusters of space antennas and space debris.

A new type and method of modern radiolocation has been discovered, proposed and substantiated, namely, fractal-scaling or scale-invariant radiolocation. This results in fundamental changes in the very structure of theoretical radiolocation, as well as in its mathematical apparatus. Fractal radiolocation can adequately describe and explain a much wider class of radar phenomena. Conducted research in the field of theoretical radiolocation can effectively solve problems of detecting signals in conditions of intense interference and develop new fractal MIMO systems.

This study continues the author's series of studies on the rationale to apply the fractal theory, physical scaling and fractional operators in matters of radio physics and radio electronics, first started in the USSR at the Institute of Radio Technologies and Electronics of the USSR Academy of Sciences in the late 1970s. Scrupulous bibliographic studies prove the complete and absolute world priority of the author in all "fractal" areas in radio physics and radio electronics (the list of author and his students’ works includes more than 1000 scientific papers, including 35 monographs and chapters in monographs in Russian and English).

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REFERENCES

1 Potapov A.A. *Fractals in radiophysics and radiolocation*. Moscow, Logos. 2002, 664 p.

2 Bunkin B.V., Reutov A.P., Potapov A.A. et al. *Issues of advanced radiolocation*. Moscow, Radio Engineering, 2003, 512 p. [in Russian]

3 Potapov A.A. *Fractals in radiophysics and radiolocation: Sample Topology*. 2nd revised and enlarged edition. Moscow, University Book, 2005, 848 p. [in Russian]

4 Potapov A.A. *Fractals and chaos as a basis for new innivative technologies in modern radio systems. Supplement to the book: Kronover R. Fractals and chaos in dynamic systems*. Moscow, Technosphere, 2006, pp. 374-479.

5 Potapov A.A., Gulyaev Yu.V., Nikitov S.A., Pakhomov A.A., Herman V.A. *The latest techniques of image processing*. Moscow: FIZMATLIT, 2008, 496 p. [in Russian]

6 Potapov A.A., Rekhviashvili S.Sh. Simulation of Properties of Images with Atomic Resolution in a Scanning Probe Microscope. *Technical Physics*. 2018, Vol. 63, No. 6, pp. 777 – 781.

7 Potapov A.A., Slezkin D.V., Potapov V.A. Fractal labyrinths as the basis of the geometry of new types of fractal antennas and fractal antenna arrays. Radio Engineering, 2013, No. 8, pp. 31-36. [in Russian]

8 Potapov A.A., Potapov Alexey A., Potapov V.A. Fractal Radioelement's, Devices and Fractal Systems for Radar and Telecommunications. *Proc. 14th Sino - Russia Symposium on Advanced Materials and Technologies*. Beijing: Metallurgical Industry Press. 2017, pp. 499 – 506.

9 Potapov A.A., Shifrin Ya.S., Kuzeev R.R. Genetic and Self-Similar Approaches for the Fractal Antennas Designing. *Antennas*. 2014, No. 3(202), pp. 25–48.

10 Potapov A.A. Oscillator with Fractional Differential Positive Feedback as Model of Fractal Dynamics. *J. Computational Intelligence and Electronic Systems*. 2014, Vol. 3, No. 3, pp. 236–237.

11 Potapov A.A., Potapov A.A. (junior), Potapov V.A. Fractal capacitor, fractional operators and fractal impedances. *Nonlinear world*. 2006 Vol. 4, No.4-5, pp. 172 – 187. [in Russian]

12 Potapov A.A. Fractal antennas, impedances, and radar absorbing coatings – "smart" materials. *Materials of the First International. scientific conf. "Nanostructured Materials - 2008: (NANO - 2008)"*. Minsk: Belarusian science, 2008, pp. 532. [in Russian]

13 Kulikov D.A., Potapov A.A., Rassadin A.E., and Stepanov A.V. Model for growth of fractal solid state surface and possibility of its verification by means of atomic force microscopy // IOP Conf. Ser.: Mater. Sci. Eng. 2017, Vol. 256, No. 012026, 10 p. https://doi.org/10.1088/1757-899X/256/1/012026.

14 Potapov A.A. Fractal antennas, nanotechnologies, resonances and plasmons. *Advances of modern radio electronics*. 2011, No. 5, pp. 5-12. [in Russian]

15 Potapov A.A., Bulavkin V.V., German V.A., Vyacheslavova O.F. Investigation of the microrelief of processed surfaces using fractal signature methods. *Journal of Technical Physics*. 2005 Vol. 75, No. 5, pp. 28-45.

16 Potapov A.A. On strategic directions in the synthesis of new types of texture-fractal radar detectors of low-contrast targets with contour extraction and coordinate location against the background of high-intense ground, sea and rainfall clutters. *Proceedings of IV All-Russian «RTI Systems of ASD-2016» STC to mark 100th anniversary of the Scientific and Research Institute for Long-Distance Radio Communications and the 70th anniversary of the Academician A.L. Mints RTI.* Moscow, N.E. Bauman MSTU Publishing House, 2017, pp. 438 – 448.

17 Rekhviashvili S.Sh. and Potapov A.A. Memristor and the Integral Quantum Hall Effect // J. Communications Technology and Electronics. 2012, Vol. 57, No. 2, pp. 189 – 191.

18 Potapov A.A. Analysis and synthesis of topological radar detectors of low-contrast targets against the background of high intensity noise as a new branch of radiolocation and theory of statistical solutions. *Eurasian Physical Technical Journal*, 2016, Vol.13, No.2 (26), pp. 13 – 24.

19 Potapov A.A. Textural and fractal-scaling methods for detecting, processing and recognizing weak radar signals and low-contrast images against the background of intense interference. *Bulletin of aerospace defense (PJSC "SPA" Almaz ")*. 2018, No.2 (18), pp. 15-26.

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