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Fractal applications in radio electronics as fractal engineering

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Abstract: **The use of the fractal paradigm is presented - the main directions for introducing textures, fractals, fractional operators, dynamic chaos and methods of nonlinear dynamics for the design and creation of real technical projects in radio electronics - fractal radio systems, taking into account the hereditarity, non-Gaussianity and scaling of physical signals and fields. The substantiation of the use of fractal-scaling and texture methods for the synthesis of fundamentally new topological texture-fractal methods for detecting signals in the space-time channel of scattering waves (a new type of radar) is discussed. It is shown that the use of fractal systems, sensors and nodes is a fundamentally new solution that significantly changes the principles of constructing intelligent radio engineering systems and devices. It is shown that the use of computational dielectric metasurfaces brings to a new level all the functional characteristics of a multifunctional system of topological texture-fractal processing of signals and fields in solving classical problems of detection, measurement, recognition and classification by intelligent radio engineering systems and devices. The concept of "fractal engineering" is introduced, the methodology of its use is discussed.**

Keywords: **fractal, texture, scaling, signature, target detection and recognition, radar, fractal aggregation, computational metasurface, nonlinear dynamics, radiophysics, fractal engineering**

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"Scientists study the world as it is;
engineers create the world,
that didn't exist before."
Theodor von Karman

Contents

1. INTRODUCTION

The description of real processes occurring in modern radio-physical and radio-technical systems currently involves taking into account the hereditarity (memory), non-Gaussianity and scaling (self-similarity, self-similarity) of physical signals and fields. All these concepts are included in the definition of fractal sets or fractals, first proposed by B. Mandelbrot in 1975 [1,2].

At the Kotelnikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences (IRE RAS) from 1979 to the present, research has been initiated and is being developed in the fundamental scientific direction "Fractal radio physics and fractal radio electronics: design of fractal radio systems". The obtained results allow us to speak about the Russian school of fractal engineering and fractal engineering in the field of radio electronics. The purpose of this work is to review the formation of this school on the examples of the main results of the research carried out at the IRE RAS.

2. REVIEW OF THE MAIN RESULTS OF THE IRE RAS IN THE FIELD OF FRACTAL RADIO ELECTRONICS

2.1. Primary information radio systems

Primary radiophysical information comes from various modern radio systems in the form of a one-dimensional signal and/or radar image (RLI) - **Fig. 1**. Here, SAR is a synthetic aperture radar; UAV is an unmanned aerial vehicle. MIMO (Multiple input-multiple output) spatial signal coding technology generally implies that each radio device participating in data exchange will have several spatially distributed weakly correlated receiving and transmitting antennas. The main idea of fractal MIMO radars is the use of fractal antennas and fractal detectors [3-6,16,17,24-30].

The ability of fractal antennas to operate simultaneously at several frequencies or emit a broadband probing signal gives a sharp increase in the number of degrees of freedom, which determines many important advantages of this type of radar and greatly expands the possibilities of adaptation.

To reflect these features, a new term "fractal-frequency MIMO systems (FF

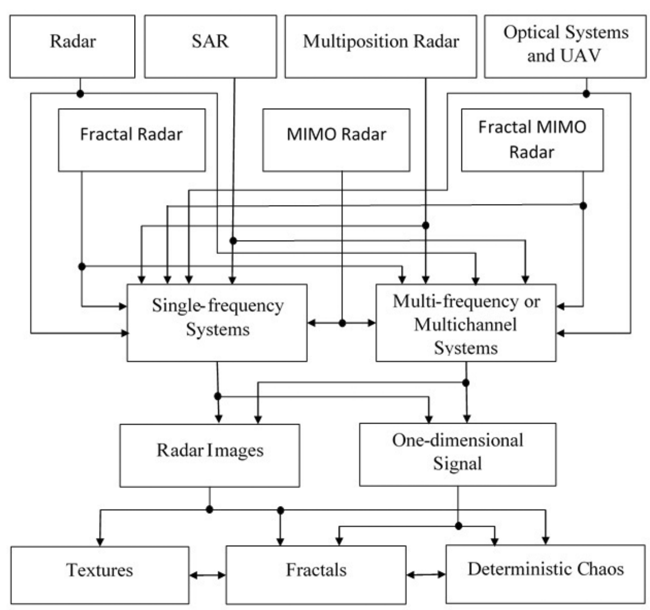


Fig. 1. *Radio systems of initial primary information (fractal radar and fractal MIMO radar included).*

MIMO)" has been introduced, which more fully reflects their physical capabilities.

2.2. Ensembles of topological texture-fractal features

All currently existing new dimensional and topological (and not energy!) features or invariants and methods for detecting subtle objects against the background of intense reflections from the sea, land and meteorological precipitation are compactly presented in **Fig. 2.** Functional relationships between various features and methods are also noted here. Data Fig. 2 logically continue the data of Fig. one.

Thus, the introduction of the concepts of "deterministic chaos", "texture", "fractal", "fractal dimension *D*" and "fractal signature *D*(*t*,*f*)" into the scientific use of radar made it possible to propose and then apply new non-energetic (!) signs or invariants (Fig. 2), which are combined under the generalized concept of "sample topology" ~ "fractal signature". Their application is widely and in detail presented in articles and monographs [3-17,21-30]. Data Fig. 2 are based on long-term full-scale experiments that were carried out jointly with the Central Design Bureau "Almaz" and other leading industrial organizations of the USSR, starting from the now distant 80s. XX century [31].

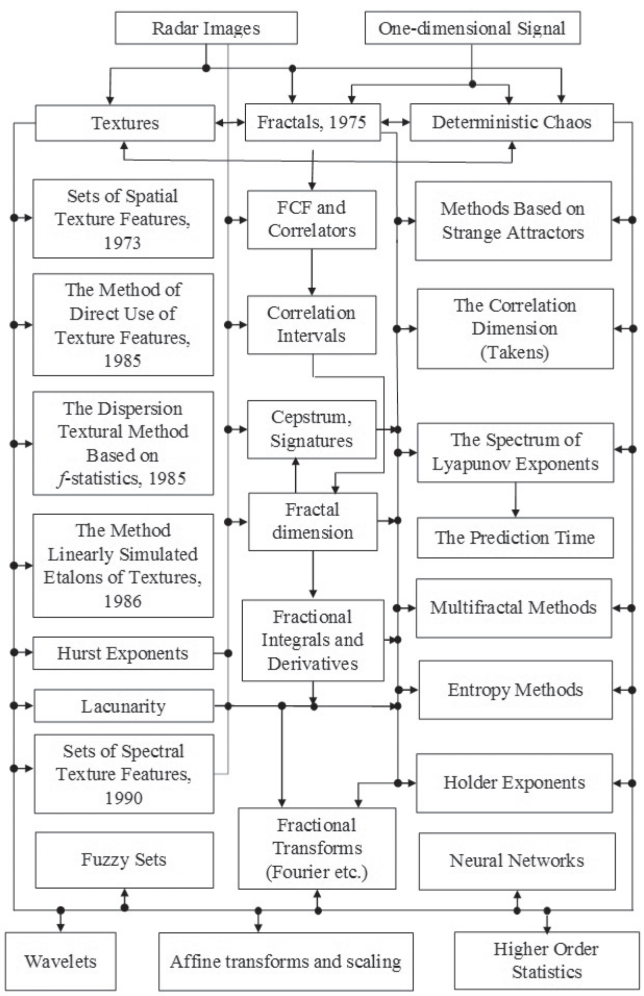


Fig. 2. *Topological features and methods for detecting low-contrast (inconspicuous) objects against the background of intense noise and interference.*

2.3. Development of fractal technologies

On **Fig. 3** and **Fig. 4** schematically shows the main stages of fundamental research in texture and fractal areas. Here, compared with the data for 2021 [23], in the diagram below Fig. 3, two additional and very important sections appeared – "Fractal complexing

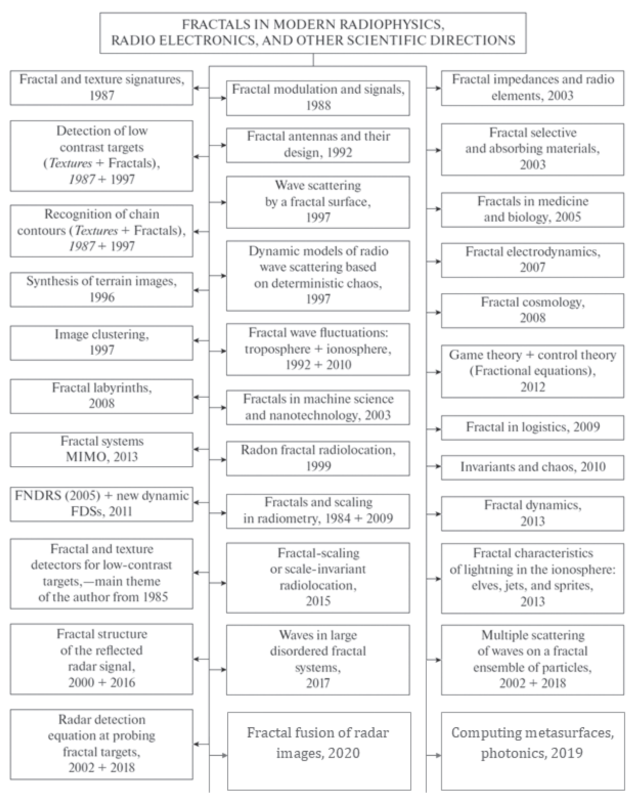


Fig. 3. *A sketch of the development of breakthrough fractal technologies (this includes results related to texture): FNORS – fractal non-parametric radar signal detector, FOS – fractal signal detector.*

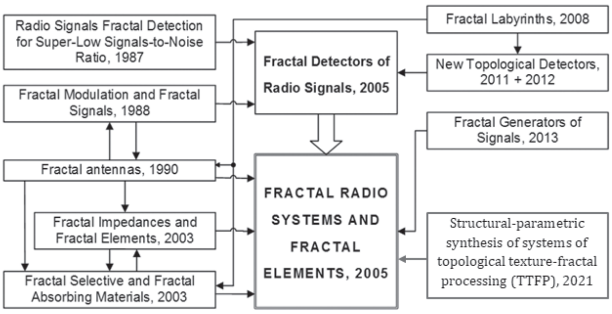


Fig. 4. *The concept of fractal radio systems, sensors, devices and radio elements.*

of radar images" and "Computational metasurfaces, photonics", and in Fig. 4 – section "Structural-parametric synthesis of systems of topological texture-fractal processing (TTFP)". On the first topic (Fig. 3), together with co-authors-students from the Air Force Acad. Professor N.E. Zhukovsky and Yu.A. Gagarin received a patent of the Russian Federation [32] and published a number of articles [33-37].

On Fig. 4, one additional and very significant section appeared – "Structural-parametric synthesis of topological texture-fractal processing systems (TTFP), 2021." [35]. The presented scheme of structural-parametric synthesis allows us to speak about *the optimality* of TTFP of multidimensional images, since the efficiency criterion is the maximum of one or several probabilistic characteristics simultaneously – classification (segmentation), detection or recognition, depending on the tasks solved by the system.

2.4. A NEW CLASS OF TOPOLOGICAL TEXTURE-MULTIFRACTAL FEATURES

For the proposed structural-parametric synthesis, we for the first time and specifically proposed in [37] a fundamentally new class of topological textural-multifractal features that allow us to jointly evaluate various fractal texture properties. In this case, all issues of joint estimation of scaling, singular, multifractal and anisotropic properties of the texture of images of any kind are solved. We called this class of features a *directed morphological multifractal signature* (DMMFS) [37].

The calculation of the DMMFS begins with the calculation of local morphological multifractal indices (LMMFI) $L_q(\varepsilon,r)$ for the required number of angular directions of analysis rmax of the processed image $I(m,n)$, here $m = 1, 2, ..., M$, $n = 1, 2, ..., N$ are the number of rows and columns, respectively. In this case, an array of corresponding values is formed in the "direction-scale" coordinates for each order of the scaling moment q, where $-\infty \le q \le \infty$, $q \ne 0$.

The calculation of the generalized statistical sum $Z(q,\varepsilon,r)$ for each direction of analysis r ($r = 1, 2, ..., r_{max}$) is carried out according to the generated set of "upper" $\{U_{\varepsilon,r}(m,n)\}$ and "lower" $\{X_{\varepsilon,r}(m,n)\}$ of "coverings" obtained as a result of morphological processing (dilation and erosion, respectively) of the array $\{B_r(m,n)\}$, rotated by the required number r_{max} of the angular positions of copies of the original image using the set "flat" horizontally oriented structural elements $\{Y_\varepsilon, \varepsilon = 1, 2, ..., E\}$, whose length w ($w = 2\varepsilon + 1$) corresponds to the analyzed scale. The generalized partition function $Z(q,\varepsilon,r)$ of the q_{th} order on each analyzed scale ε for each rotated image $B_r(m,n)$ is determined by the following relationship

$$Z(q,\varepsilon,r) = \left((2\varepsilon)^{-1}V(\varepsilon,r)\right)V^{-q}(\varepsilon,r)\times$$
$$\times\left(\sum_{m=1}^{M}\sum_{n=1}^{N}\left(\left|U_{\varepsilon,r}(m,n)-X_{\varepsilon,r}(m,n)\right|\right)^{q}\right), \qquad (1)$$

where

$$V(\varepsilon,r) = \sum_{m=1}^{M}\sum_{n=1}^{N}(U_{\varepsilon,r}(m,n)-X_{\varepsilon,r}(m,n)) \qquad (2)$$

is the "volume" of the image surface $B_r(m,n)$ on the scale ε enclosed between the corresponding coatings.

The determination of the multifractal signature (MFS) $\mathbf{S}_{q,r}$ is carried out by calculating the values of the LMMFP, measured between adjacent analysis scales by the expression

$$L_q(\varepsilon,r)=\left(\log\frac{\varepsilon}{\varepsilon+1}\right)^{-1}\log\frac{Z(q,\varepsilon+1,r)}{Z(q,\varepsilon)}, \qquad (3)$$

followed by the formation of an array

$$\mathbf{S}_{q,r}=\begin{bmatrix}\mathbf{L}_{-\infty}(\varepsilon_1) & \mathbf{L}_{-\infty}(\varepsilon_2) & \cdots & \mathbf{L}_{-\infty}(\varepsilon_{\max}-1)\\ \vdots & \vdots & \cdots & \vdots\\ \mathbf{L}_{-1}(\varepsilon_1) & \mathbf{L}_{-1}(\varepsilon_2) & \cdots & \mathbf{L}_{-1}(\varepsilon_{\max}-1)\\ \mathbf{L}_{1}(\varepsilon_1) & \mathbf{L}_{1}(\varepsilon_2) & \cdots & \mathbf{L}_{1}(\varepsilon_{\max}-1)\\ \vdots & \vdots & \cdots & \vdots\\ \mathbf{L}_{\infty}(\varepsilon_1) & \mathbf{L}_{\infty}(\varepsilon_2) & \cdots & \mathbf{L}_{\infty}(\varepsilon_{\max}-1)\end{bmatrix}, \qquad (4)$$

where $\mathbf{L}_q(\varepsilon)=\left[L_q(\varepsilon,\mathrm{r}_1)\;L_q(\varepsilon,\mathrm{r}_2)\;\cdots\;L_q(\varepsilon,\mathrm{r}_{\max})\right]^T$ is the column vector of the LMMFP for $r_{\max}$, the number of rotations of the q_{th} order for the analysis scale ε and $[\bullet]^T$ is the transposition operator. Next, the prevailing orientation directions of the texture elements are determined on the corresponding analysis scales based on the approximation by ellipses of the set of LMMFP values $\{L_q(\varepsilon,r)\}$ formed for a given index q in the polar coordinate system, and the determination of the ellipticity parameters $k_{\mathrm{el}}(q,\varepsilon)$ and the angle $\psi(q,\varepsilon)$ ellipse tilt. All further mathematical operations and notation are given in [37].

The results of image processing (**Fig. 5**) from an array of real radar images showed that the segmentation accuracy using NMMFS turned out to be 24.8–63.5% higher compared to the accuracy achieved using MMFS.

The use of the developed class of topological features of DMMFS in segmentation problems provides an increase in the differentiation accuracy when processing anisotropic images up to 86.5% and improves the segmentation accuracy by 35.6% when processing images with multifractal properties. In the case when the only differentiating characteristic for segmented images is information about the angular dependence of their texture elements, the segmentation accuracy increases by 78%. The use of a new class of topological features in RLI segmentation problems improves the accuracy of their differentiation up to 63.5%.

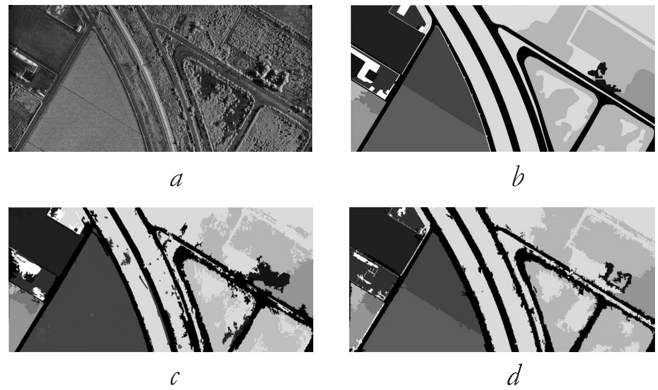


Fig. 5. *Results of fractal segmentation of rural radar data (a), performed by an expert manually (b) and using the (Fuzzy C-Means) algorithm using the features of MMFS (c) and NMMFS (d)* [37].

2.5. Fractal aggregation of radar images obtained by multiband SAR

Despite the current existence of methods, methods and algorithms for texture-fractal processing of two-dimensional images, the problem of efficient integration of multidimensional radar images has not yet been solved (see **Fig. 6***a,b* and **Fig. 7**).

Taking into account the results of a statistical analysis of the brightness values and fractal dimension D of two-dimensional radar images in [32-35], we proposed a new method for complexing radar images obtained by multiband SAR. Multifractal aggregation is based, in contrast to the known ones, on the simultaneous calculation of local multifractal dimensions by the sliding window over all initial radar images by the method of iterative coverage, and can significantly increase the information content of images, estimated by entropy.

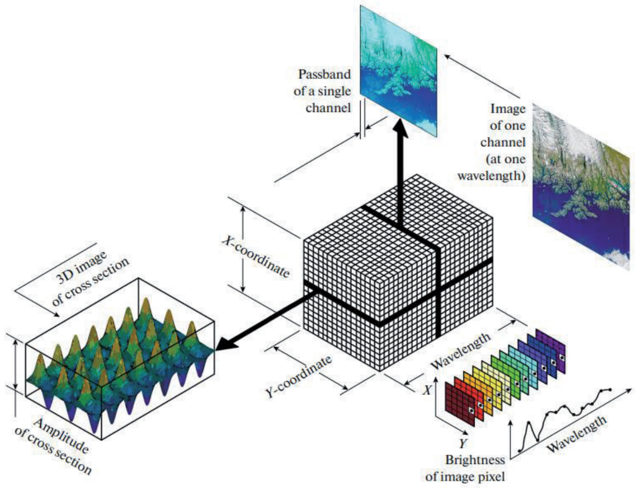


Fig. 6*a. Model for storage and analysis of multi- and hyperspectral data* [35].

The use of this method can significantly increase the information content of radio systems, especially in the case of jamming and masking objects in some or all frequency ranges.

In general, the scheme of structural-parametric synthesis of systems for optimal texture-fractal processing of multidimensional images is shown in **Fig. 8** [35]. Here R_{psegm}, R_{po}, R_{psp} are the probabilities of correct segmentation, detection and recognition.

The presented scheme of structural-parametric synthesis allows us to speak about the optimality of texture-fractal processing of multidimensional images, since the efficiency criterion is the maximum of one or several probabilistic characteristics simultaneously – classification (segmentation), detection or recognition, depending on the tasks solved by the system.

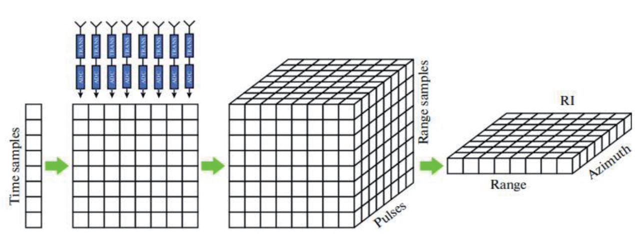


Fig. 6*b. Model of Radar Data Cube Formation* [35].

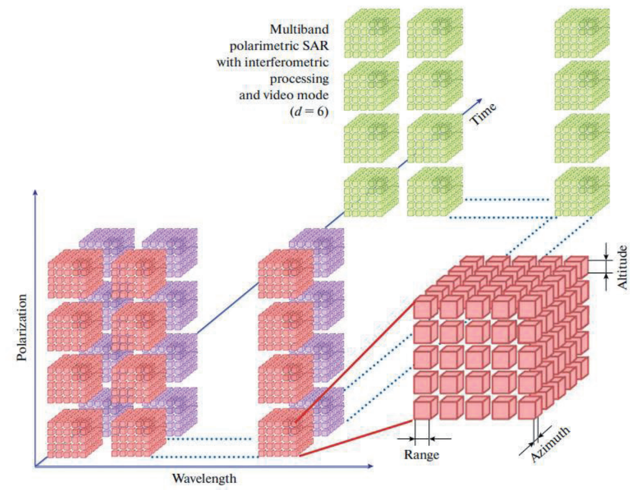


Fig. 7. *Model for the formation of a multidimensional cube of radar data* [35].

2.6. Selected classical examples of fractal processing

Let us present selected experimental results of TTFI of multidimensional signals from objects of different physical nature (**Fig. 9-14**).

In particular, in **Fig. 14** shows the unique multifractal characteristics of high-altitude discharges in the ionosphere. Every day, 4 million lightning strikes the sky, about 50 every second. And above the lead thunderstorm fronts, in the upper atmosphere, a light show of "ghost lightning" unfolds: blue jets, red-violet sprites, red rings of elves soaring in the sky. These are discharges of very high energy, which strike not into the ground, but into the ionosphere!

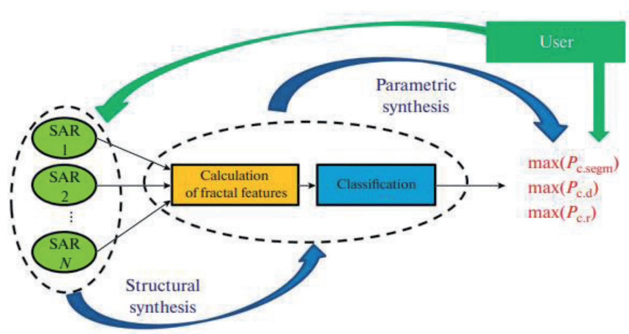
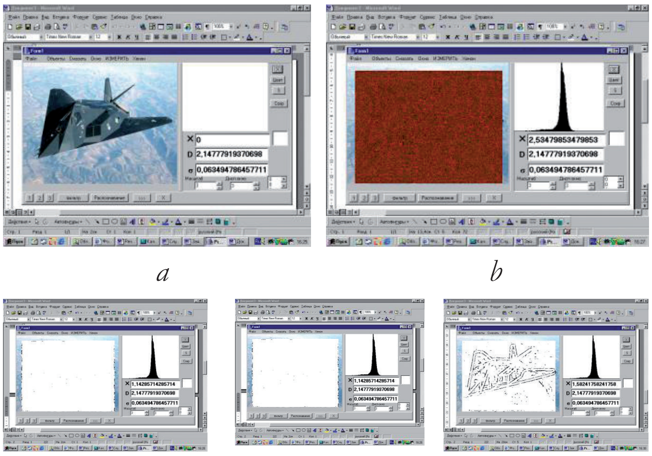


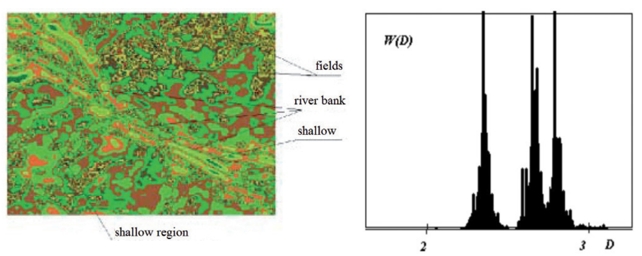
Fig. 8. *Scheme of structural-parametric synthesis of the system of texture-fractal processing of multidimensional radar images* [35].



a b

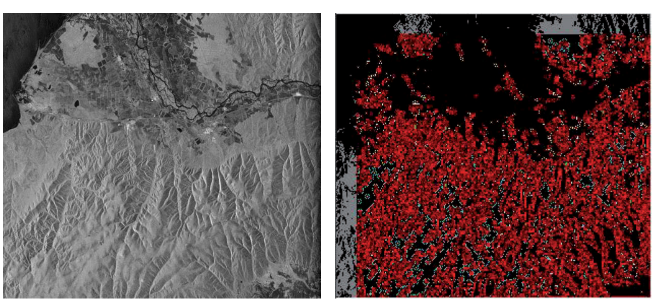
c d e

Fig. 9. *Fractal image processing of the F117 aircraft image – (a): (b) image of the F117 aircraft in noise at* $q_{02} = -3$ *dB, (c) example of fractal nonparametric filtering (FPF) of the aircraft image at the current value* $D^{(1)} \propto X$*, (d) example of the image FPF of the image aircraft at the current value D(2) > D(1), (e) – an example of the FTF of an aircraft image at the value D(3) > D(2) > D(1); everywhere on the right is the current paretian D.*



a b

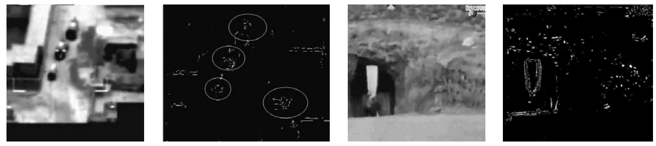
Fig. 10. *An example of distinguishing types of earth surfaces by the field of fractal signatures D (left) and the empirical distribution D (right) during segmentation by D of land cover textures on radar imagery.*



a b

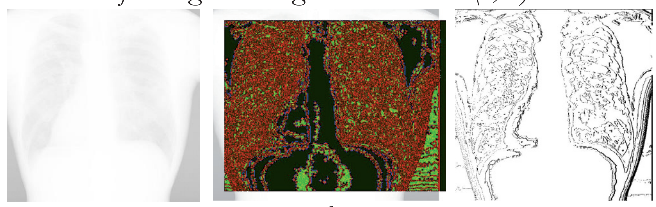
Fig. 11. *Delta of the Selenga River in the PALSAR SAR image (left), the result of fractal processing (right); wavelength 23 cm, spatial resolution about 7 m.*

The history of their discovery is very interesting. Sprites, for example, were discovered by accident on the night of July 5-6, 1989 in the United States.



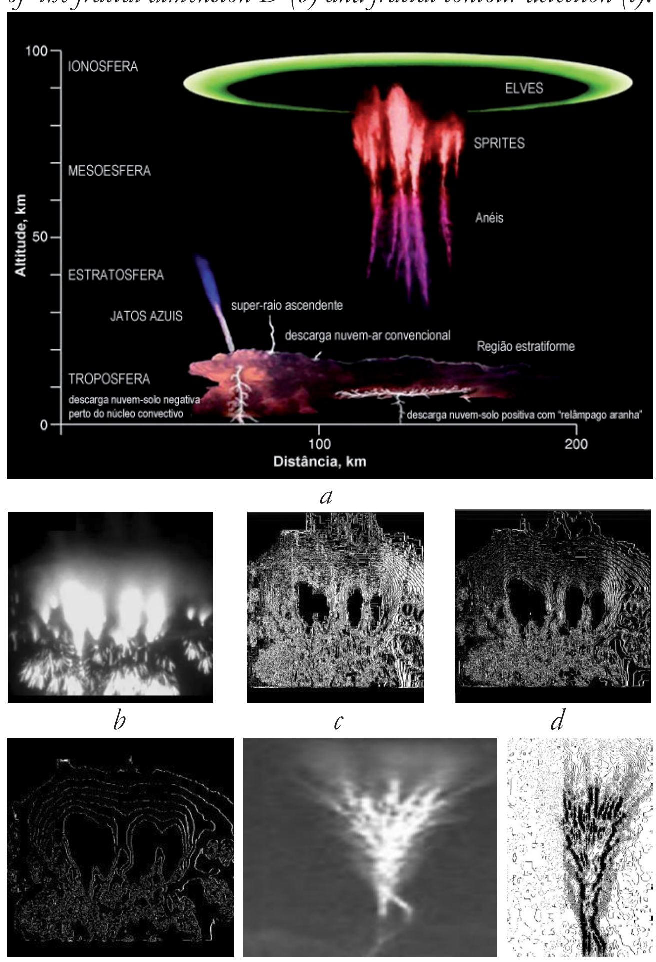
a b c d

Fig. 12. *UAV images of the terrain with moving cars (a) and mountainous terrain with a tunnel (c) and the results of filtering according to estimates D (b, d).*



a b c

Fig. 13. *An example of solving the problem of fractal clustering of an X-ray image (a) by the value of the estimate of the fractal dimension D (b) and fractal contour detection (c).*



a

b c d

e f g

Fig. 14. *Dynamic fractal structures in the atmosphere - (a), sprite (shooting from a spacecraft - USA, NASA) - (b); jet (IR - survey from spacecraft - China) - (f); multifractal filtering of the sprite image: map D = 2.3 – (c); map D = 2.6 (d); map D = 2.8 (e); fractal filtering of the jet image: map D – (g); KA is a spacecraft.*

High-altitude electric discharges (20-100 km) are divided into several main types: elves, jets, sprites, halos, etc. They clearly confirmed the existence of a global electric circuit (GEC) on our planet and provided new opportunities for its study. This literally shocked specialists in astronomy, atmospheric electricity, radiophysics, atmospheric acoustics, gas discharge physics and aerospace safety. On maps of fractal dimension (Fig. 14), external, basic and hyperfine structures are clearly distinguished. Dynamic spatiotemporal features and sprite morphology can be explained, in particular, by the multifractal geometry of discharges and percolation. Here, modeling based on fractal labyrinths is also applicable, which well reflect the physics and morphology of such ionospheric structures. By the way, the data in Fig. 14 are the world's first results of fractal processing of such structures, which at one time caused a stir at radar conferences in the USA and China.

Conclusion: numerous results (SAR, UAV(unmanned aerial vehicle), medicine, space, mechanical engineering, etc.) show that fractal processing methods improve the quality and detail of objects and targets in active and passive modes by about several times. These methods can be successfully used to process information from space, aviation systems, low-observable high-altitude pseudo-satellites (HAPS) or detect HAPS and UAV clusters, synthesized space antenna clusters, space debris, etc.

2.7. Radar Equation for a Fractal Target

In [14], questions of the general theory of multiple scattering of electromagnetic waves in fractal discrete randomly inhomogeneous media are considered in detail on the basis of modifications of the classical Foldy-Tverskoy theory. An integral equation is obtained for a coherent field and the second moment of the field for a fractal scattering medium.

Based on the developed theory, the value of the backscattered signal from the fractal medium [4,14] was calculated using the classical radar equation. The received signal power P_s is determined by the radar equation.

Here we end up with two cases:

- for the far zone and a flat fractal target (Euclidean dimension $\mathbf{E} = 2$); then

$$P_s \propto \frac{1}{r^{4-D}}, \tag{5}$$

- for the far zone and volumetric fractal target (Euclidean dimension $\mathbf{E} = 3$); then

$$P_s \propto \frac{1}{r^{5-D}}. \tag{6}$$

Here r is the distance to the target. The results (5) and (6) show that the reflected radar signal can be used to estimate the fractal dimension D of the probed fractal medium or fractal target (such as a dynamic layer of snow, rain, etc.).

Similarly, on the basis of (5) and (6), one can obtain a solution for anisotropic disordered large fractal systems: cascades of fractals nested into each other, graphs from chains of fractals, percolation systems, nanosystems, space debris, clusters of UAVs, or small-sized space satellites (SSCs), including mini- and microclasses, dynamic synthesized space antenna constellations (cluster apertures), low-observable high-altitude pseudo-satellites (HAPS), spatially distributed space systems (clusters) from small SSCs for solving problems of monitoring emergency situations, etc.

3. COMPUTATIONAL DIELECTRIC METASURFACES AND TTFS

Continuous improvement of topological texture-fractal processing (TTFP) of signals and fields in modern radio physics and radio electronics implies a constant improvement in the speed of information processing and the search for new physical principles for its implementation. Here, undoubtedly, the future belongs to photonic and radio-photonic technologies. Below are selected results in the field of photonics, radiophotonics, computational meta-optics and 2*D* dielectric *metamaterials* (MM) or *computational metasurfaces* (MS), which were obtained by us with Chinese scientists at the Joint Laboratory of Information Technology and Fractal Signal Processing of Jinan University in Guangzhou, China for period 2019-2021. The results have been published in leading international scientific journals [38-45] in the USA and Switzerland. It should be noted that China has a special state program, and in 2015 China became the world leader in terms of production of photonics devices.

3.1. Principles

The concept of *computational metamaterials* was first introduced in 2014: computational MMs are metamaterials that can perform desired mathematical operations on arbitrary wave signals as they propagate through them. By designing the geometry of dielectric metasurfaces (MS), optical analog computing devices with various functions, such as spatial differentiators, integrators, equation solvers, etc., can be obtained. The most common are MMs, in which the structure of the elements (*meta-atoms* a few nanometers in size), the size, and the distance between the elements are much smaller than the wavelength of the exciting field. In this case, the result of the interaction of individual elements leads to the fact that the properties of the MM are determined not so much by the properties of its constituent elements, but by an artificially created periodic structure.

MSs as a typical device prototype consist of artificial subwave structures over flat surfaces of a dielectric material, which facilitate flexible control of the amplitude, phase, and polarization of electromagnetic waves. The use of diffuse and transmissive MMs for optical analog computing paves the way for the realization of fully integrated spatial filtering devices. It can be said that MT is *the root of many fascinating topological phenomena in physics and exotic manipulations with waves*.

Despite the huge interest in MS and the presence of a large number of English-language reviews, this issue is practically not covered in the Russian-language literature, with rare exceptions. Multipole resonances of dielectric nanoparticles provide a promising way to tune the optical transfer function (OTF) of an MS. Compared to plasmonic structures, dielectric nanostructures can not only solve the problem of losses and increase the efficiency of the MS, but also facilitate the control of light scattering and propagation. In addition to resonant schemes for realizing spatial differentiation and image edge detection, non-resonant schemes such as spin-orbit interaction in Pancharatnam-Berry phase MSs have been investigated for image edge detection. The use of dielectric MMs instead of classical plasmonic structures reduces ohmic (thermal) losses and makes it possible to control not only the electric, but also the magnetic component of the light wave. In other words, due to the free penetration of the electromagnetic field into dielectrics, such nanostructures have both electric and magnetic Mie resonance.

3.2. Design

Next, we present the design of a polarization-insensitive MS. Our papers present a way to implement high-performance optical MSs that perform isotropic and polarization-insensitive edge detection on an arbitrary *2D* image [39,40,43,44].

The implementation of the Laplace operation as optical analog computing has recently attracted attention, and a compact device with high spatial resolution has not yet been invented. The spatial differentiation operation is important in image processing and its applications such as sharpening and edge-based segmentation. In this case, the Laplacian, the simplest operator of the isotropic derivative in two dimensions, is of particular importance. Here we would like to emphasize that our device operates in transmission mode, while almost all previous ones usually worked in reflection mode. Transfer mode operation is important for image processing because this device can be used directly as the first layer of a recognition system and in image processing applications.

We have proposed a *Laplace metasurface* that can perform almost perfectly the Laplace operation for different configurations of the incident light field – **Fig. 15.** The proposed Laplace MS is based *on the excitation of a bound state in a continuum*, which has demonstrated exotic optical properties. The unit cell (metaatom) consists of a silicon brick (blue) with a thickness h = 163 nm and a bottom glass substrate (gray). On the right in Fig. 15 is a top view of the unit cell. The period is a = 331 nm, the width of the silicon brick is d = 251 nm. Four square voids s = 33 nm wide are located in the center of all edges.

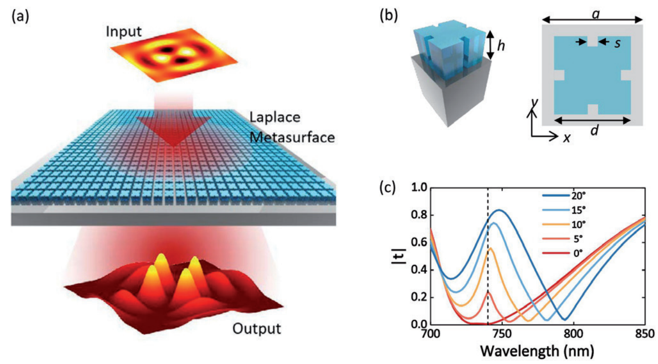


Fig. 15. *(a) Dielectric Laplace MS transforming the input two-dimensional space function into another function as the Laplace operator; (b) Unit cell of the Laplace dielectric MS; (c) Transmission spectra of the Laplace MS at various angles of incidence along the x direction for the p-wave.*

The highly symmetric mode profile provides an almost isotropic Laplace OTF. The proposed Laplace MS can be configured to operate at different wavelengths in transmit mode, which is advantageous for applications in optical computing, medical diagnostics, machine vision, and more. We emphasize that although we are everywhere talking about the scattering of electromagnetic waves, the results presented can be easily transferred to the case of scattering of waves of a different nature, for example, acoustic waves.

3.3. Results

One of the applications of the Laplace operation is to detect the edges of problematic targets, etc. on the image. We demonstrate that Laplace's proposed MS [44] can be used for traffic sign recognition, which is critical for automated driving (**Fig. 16**).

We also used a typical *QR*-code as an input *2D* image since *QR*-codes are now important in our daily life and edge detection for them plays a critical role in *QR*-code region detection (**Fig. 17***a*). The *QR*-code we have chosen carries information about the Chinese hieroglyph meaning "Light". Through the processing procedure discussed

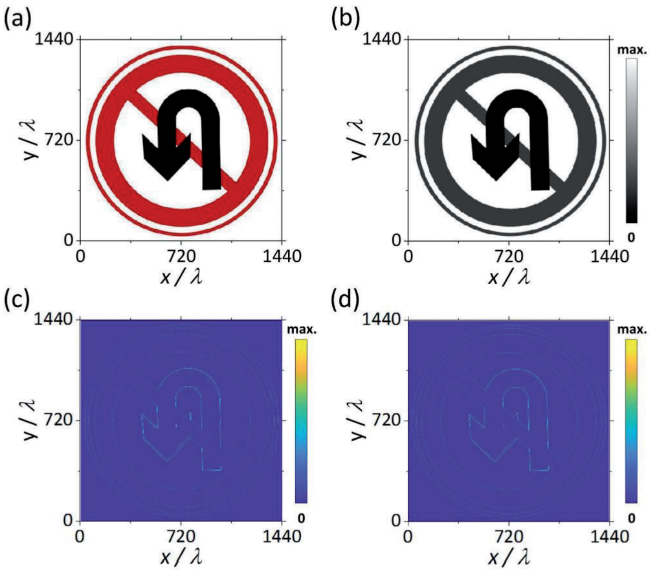


Fig. 16. *(a) Color image of a road sign; (b) The corresponding grayscale image as input; (c) and (d) Output image from the ideal Laplace operator and Laplace MP for (b), respectively.*

in this context, we can obtain the results from the ideal Laplace operation and from the Laplace MS, which are shown in Fig. 17*b* and Fig. 17*c*.

Due to the limited volume of this article, here we only briefly list other areas of photonics, which are also studied in our joint papers [38-45] and are presented in detail there. These are: control of light scattering by nanoparticles using magnetoelectric coupling and zero backscattering (the theory of light scattering by nanoparticles and electromagnetic multipoles, numerical simulation, verification experiments in the frequency range from 4 to 7.5 GHz) [38,41,42]; strong optomechanical coupling in chain waveguides made of silicon nanoparticles with quasi-bound states in a continuum (photon-phonon interaction with microstructures) [45], etc.

The use of computational dielectric MSs as a whole brings to a new level all the functional characteristics of the multifunctional system of *topological texture-fractal processing* (TTFP) of signals and fields proposed by us at the end of the 20th century in solving classical problems of detection, measurement, recognition and classification by intelligent radio engineering systems and devices. So, the continuum of all the data in **Fig. 1-17** shows our use of the fractal paradigm to create real technical projects in radio electronics.

4. FRACTAL ENGINEERING AND PHILOSOPHY OF FRACTAL ENGINEERING

As you know, the use of scientific principles for the design and creation of real technical objects and structures is a field of human activity called engineering. Currently, on the basis of the results of modern science, technology (technologies) and engineering, the world is showing an active interest in posing problems of the philosophy of

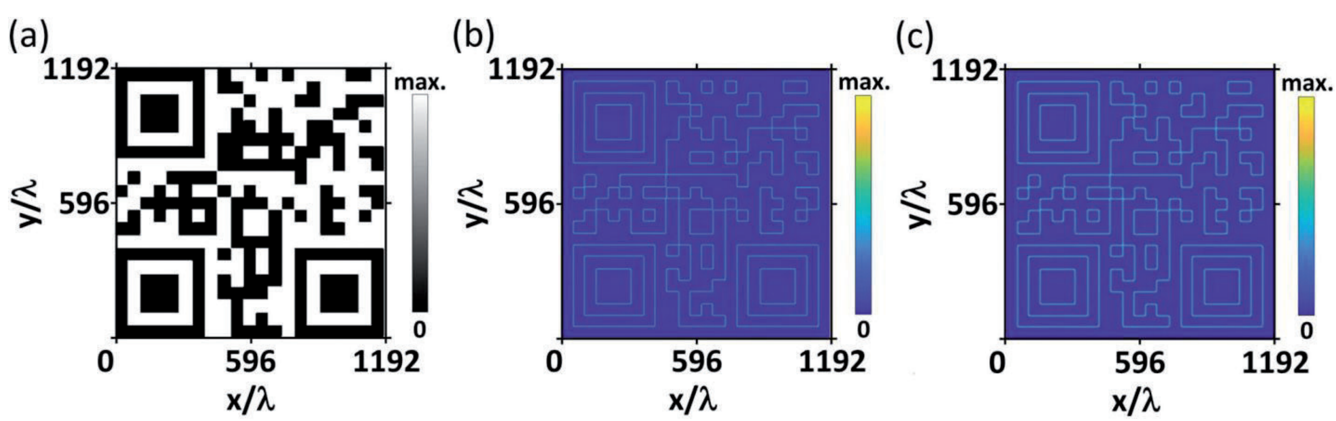


Fig. 17. *(a) Input image consisting of a QR code; (b) the output image of the ideal Laplace operation; (c) exit from the Laplace MS. All images are a light intensity profile; the pixel sizes are set to 2.88λ.*

engineering. In 2002, the Chinese scientist Li Bocun published the book "Introduction to the Philosophy of Engineering" [18], then in 2003 the American scientist Luis Buchiarelli published the book "Philosophy of Engineering" [19]. In [18], the concept of "three principles" (science, technology, engineering) was introduced, in which they were clearly separated. More than fifty categories of philosophy of engineering (plan, decision-making, goal, drawing up a plan, etc.) were considered, and the problems of philosophy of engineering were analyzed [18,20].

This article proposes the concepts of "*fractal engineering*" in the hope of contributing to the problems of the philosophy of engineering. The triad of science, technology and engineering (of course, using fractals as an example), regardless of the aforementioned Chinese book on the philosophy of engineering [18], was presented by the author 10 years ago in Issue No. 1 of the RENSIT journal for 2012 – all 142 pages of the issue were given to two large articles [46,47] (essentially a book; thanks to RENSIT Editor-in-Chief for that).

Here it seems appropriate to also present the results on fractal antennas obtained by us at the end of the 20th century. In 1988, the author, together with the Almaz Central Design Bureau, carried out the first development and design of such unusual (for that time) fractal antenna structures (in particular, an operating model of a fractal slotted antenna array was made in the millimeter and centimeter wave range (MMW and SMW) for a portable solid-state dual-frequency coherent radar based on parametrons with a complex phase-shift keyed signal of an extra-large base (patent [54]). This digital radar (the size of a small case) was installed on a helicopter, and the author worked with it for a long time and received the first radar images of land covers and objects (**Fig. 18** [3-5,7,31,49-54]. And before that it was also necessary to be able to strictly calculate the parameters of a unique two-frequency fractal receiving-transmitting antenna for two bands and then to make several almost industrial samples.

It should be noted that it was on this radar that the author first studied the fractal properties of code M-sequences with a period of up to $2^{20} - 1$ (the base of a complex signal on MMW is up to 1048576). The quantization of the input signal in the radar took place in the stochastic number system. The signal represented by such a code exhibits its fractal properties. Like a hologram, any fragment of which carries

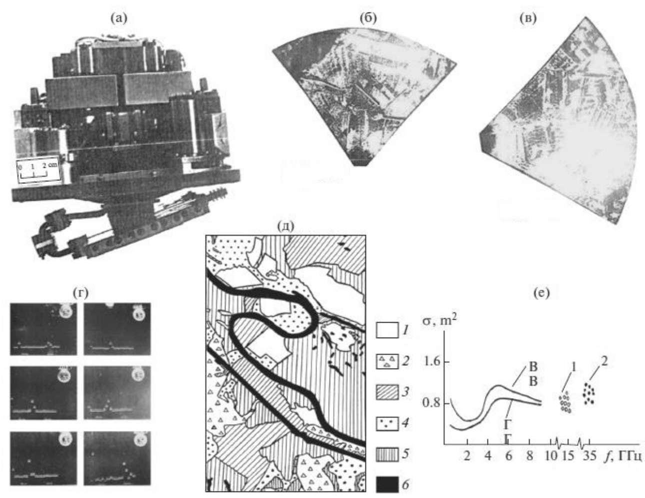


Fig. 18. *Portable digital solid-state dual-frequency coherent radar based on parametrons with a complex phase-shift keyed signal of an extra-large base and with a fractal slit grating in the MMW and CMW ranges (a) and some results of field tests of the radar: (b and c) – the first radar images at a wavelength of 8.6 mm; (d) are the characteristic shapes of the envelope of the signal reflected by the ground cover; (e) – an example of a reference synthesized map of an inhomogeneous terrain in terms of energy, textural and fractal features; (f) is the average effective scattering area as a function of frequency for horizontal (H) and vertical (V) polarizations, 1 and 2 are the data of the author, who participated in the field experiment as a "located object"* [31,49-54].

information about the complete object, any fragment of a stochastic code contains information about the amplitude of the quantized signal [31]. Then, on this module, a new radar method based on the Radon transform was also implemented for the first time [5,7,31,49-52,54].

All this is actually fractal engineering and fractal engineering with elements of the philosophy of engineering. We can say that that time, namely, the 80s of the XX century, was the beginning of the birth of the Russian philosophy of fractal engineering and fractal engineering! And it was a serious and advanced project in the great USSR.

5. CONCLUSION

The global fractal method was created and demonstrated in many ways in the published works of the author and directly in the references to this work. As a result, a new semantic space has been formed in the scientific world with its properties and tasks unusual for classical radiophysics, radio engineering and radar. I consider the problem of "sample topology" [3-5] to be one of the most important in all radio electronics, and at the same time I am convinced that without fractality and scaling, the entire classical theory of detection and recognition of multidimensional signals in the future will lose its causal significance for the fundamental concepts of signal and noise.

The performed studies are a priority in the world and serve as a basis for further development and substantiation of the practical application of topological fractal-scaling and texture methods in modern radiophysics, radar, nanotechnology and photonics, as well as in the improvement of fundamentally new and more accurate topological texture-fractal optimal methods for detecting and measurement of signal parameters in the space-time radar and navigation channel of propagation of waves with scattering [3-17,21-37,46-59].

The use of fractal systems, sensors and nodes is a fundamentally new solution that significantly changes the principles of building intelligent radio engineering systems and devices. Fractal processing methods improve the quality and detail of objects and targets by several times.

Computational meta-optics is revolutionizing hardware with the advantages of ultra-fast speed, ultra-low power consumption, and parallel information processing in general-purpose, including fractal, applications. The recent advent of metasurfaces has made it possible to fully manipulate electromagnetic waves at subwavelength scales, promising feature-rich, high-performance, compact, and flat optical processors.

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