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The origin and formation of fractal radiophysics and fractal radio electronics at the IRE RAS

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Abstract. *Purpose.* The article describes the main points of the origin, formation and development of the application of fractal theory, topology, fractional dimension theory and scaling in solving problems of radio electronics and radiophysics in the USSR and Russia in the IRE of the USSR Academy of Sciences and IRE RAS, since the 80s of the XX century. *Methods.*The relevance of the author's research is related to the need for a more accurate description of the real processes occurring in modern intelligent radio systems. First of all, this takes into account the hereditarity (memory), non-Gaussianity, scaling (self-similarity, self-similarity) and topology of physical signals and fields. *Results.* All research is carried out in the fundamental scientific direction "Fractal Radiophysics and Fractal Radioelectronics: Design of Fractal Radio Systems", initiated and developed by the author at the V. A. Kotelnikov IRE RAS from 1979 to the present. *Conclusion.* The author develops and reinforces his ideas that a new "fractal" dimension should be firmly introduced into radiosciences, and not as an auxiliary role, but as a fundamental explanatory factor. This allows us to move to a new level of the information structure of real non-Markov signals and fields. The important role of RAS academician Yuri Vasilyevich Gulyaev in the development of this fundamental scientific field is shown. His participation is expressed, in particular, in his diverse assistance to the author in promoting his ideas in the USSR, Russia and the world.

Keywords: fractal, texture, scaling, fractional derivatives, radio physics, radio electronics, multi-profile radio.

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Introduction

The ideas presented in this work are the result of extensive personal experience in researching specific problems in fractal theory, particularly in the field of fractal radiophysics and fractal radioelectronics[1]. I recently celebrated exactly 45 years of my work at the IRE of the USSR Academy of Sciences. The fact is that I joined the IRE of the USSR Academy of Sciences on September 3, 1979 and sought to realize my dreams and ideas about fractals in radio engineering and radiophysics. During this period of my life, when I was already an established radio engineer, and a concept was emerging that defined my lifelong research interests in the field of creating the foundations of fractal radiophysics and fractal radioelectronics, namely: a new — «fractal» — dimension should be firmly introduced in science and technology, and not for a supporting role, but as a fundamental explanatory factor.

In this article, I wanted to cite some very important scientific points related to the name of Academician of the Russian Academy of Sciences Yuri Vasilyevich Gulyaev, without whom there would not have been such a rapid and powerful development of fractal radioelectronics and fractal radiophysics in the USSR. And I am proud that all this happened precisely within the walls of the IRE of the USSR Academy of Sciences. In general, it is the introduction of topology, fractional dimension theory and scaling into classical radioelectronics (radio engineering, radar, etc.). In particular, we are talking about creating the world's first fractal topological (non-energetic!) detector of ultra-weak signals. This can be commented on as follows.

Nowadays, in radiophysics, radioelectronics, multidimensional signal processing, streams of various big data (for example, digital Earth), etc. mainly, integer measures (integrals and derivatives of whole order), Gaussian statistics, Markov processes, etc. are commonly used. The relevance of the author's research was related to the need for a more accurate description of real processes, occurring in modern intelligent systems. First of all, this takes into account the hereditarity (memory), non-Gaussianity, scaling (self-similarity, self-similarity) and topology 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 [7, 8]. The term «fractal» was perceived as exotic at the end of the last century. We can say that fractals formed a thin amalgam on the powerful backbone of science at the end of the 20th century. The situation has changed radically with the use of fractal structures in technical applications for processing stochastic signals and images, propagation and scattering of radio waves, electrodynamics, design of antenna devices, other electrodynamic and radio engineering structures, radio elements with fractal impedance, artificial intelligence, etc. Currently, we can confidently talk about designing fully fractal radio systems. At the same time, physicists have included a new mathematical apparatus (fractional integro-differentiation) in their arsenal, and mathematicians have been enriched with new heuristic considerations and joint problem statements [1–6]. Thus, in the current situation, numerous attempts to belittle the importance of fractals and multifractals and rely only on classical knowledge have suffered an intellectual fiasco. Note that the class of continuous functions that have no derivative at any point is immeasurably richer than the class of functions with derivatives.

The paper considers the basic directions of introducing textures, fractals, fractional operators, scaling effects and nonlinear dynamics methods into fundamental problems of radiophysics, radio engineering, radar and a wide range of radio engineering sciences for the creation of new information technologies. The research is carried out within the framework of the fundamental scientific field «Fractal radiophysics and fractal radioelectronics: design of fractal radio systems», initiated and developed at the V. A. Kotelnikov IRE RAS since 1979 to date, based on the

[1]The terms «fractal radiophysics», «fractal radar», «fractal radioelectronics», etc. were introduced by the author [1–6] and are used exclusively to highlight the dominant role of fractals and for brevity. These terms are also included in the name of a new fundamental scientific direction, initiated and developed by the author from 1979 to the present.

author's work with his students (the first in the USSR and Russia) [1–6,9,10]. It is no exaggeration to say that currently the main institute in Russia, which on an ongoing basis conducts fundamental research on fractals and their application in science and technology, is the Kotelnikov Institute of Physics and Technology of the Russian Academy of Sciences [1–6, 9–51].

The important role of Academician of the Russian Academy of Sciences Yuri Vasilyevich Gulyaev in the development of this fundamental scientific field is shown, expressed, in particular, in his diverse assistance to the author in promoting ideas about fractals in the USSR, Russia and the world.

At first, I worked alone. Then with the help of the deputy Director Andrey Vladimirovich Sokolov gradually created and headed a group engaged in the development of various fractal applications. Among the first young specialists involved in the creation of the foundations of fractal radioelectronics and fractal radiophysics, the following should be noted: V. A. German (Bauman Moscow State Technical University), A.V. Laktyunkin (Lomonosov Moscow State University), E. N. Matveev (MIPT), V. A. Potapov (MIREA). Under my leadership, they successfully developed the following areas: V. A. German, non-energy fractal detectors and fractal processing of multidimensional signals; A.V. Laktyunkin, propagation and scattering of waves in fractal randomly inhomogeneous media; E. N. Matveev and V. A. Potapov, fractal antennas and frequency-selective devices («fractal impedances», the term was coined and introduced for the first time by us) based on them.

1. Historical roots (A time of bold decisions)

In August 1979 Vasily Sergeevich Kozlov called me from the personnel department of the IRE of the USSR Academy of Sciences and said that there was a vacant engineer's rate at the Institute. I immediately agreed and began to process the documents. The only catch was that at that time I was a leading designer at the A. A. Baykov Institute of Metallurgy of the USSR Academy of Sciences, my device was supposed to go abroad to an international exhibition with me, my salary was several times higher than the one offered, my first son was already born, and my wife and I were waiting in line for a cooperative the apartment. But there was youth, only 28 years old, and a time for bold decisions. Now my wife and I remember that time of our debates with a smile... That's how I ended up at the IRE of the USSR Academy of Sciences (which I dreamed of since school) as an engineer, and then as a junior researcher, and from 2002 to the present, as a chief researcher.

I would like to note that all the issues related to the applications of fractal theory, scaling relations and fractional operators in radio engineering and radiophysics were also of great interest to Academician of the USSR Academy of Sciences, Director of the Institute Vladimir Aleksandrovich Kotelnikov. At his meetings and discussions of these issues with the author, Vladimir Aleksandrovich noted the great importance of these areas for the development of fundamental and applied sciences, as well as significant difficulties in putting them into practice and understanding them by specialists educated in traditional mathematical and radio engineering courses. There were several such meetings. And this is despite his extreme busyness! By the way, Academician V. A. Kotelnikov readily agreed to join the editorial board of the «Nonlinear World» magazine, created by the author in 2003, covering all the above-mentioned areas, and participated in its work (talking to me) from the beginning of 2004 until his death.

In the 80s of the 20th century, Vladimir Yakovlevich Kislov and Evgeny Pavlovich Chigin organized several seminars with my presentations on fractals and fractional operators in radiophysics and radioelectronics at the IRE of the USSR Academy of Sciences, which also influenced the further expansion of research on fractals and the formulation of exploratory research.

Corresponding member of the USSR Academy of Sciences L.D. Bakhrakh, at a meeting of the dissertation council at MIPT (department of Academician of the USSR Academy of Sciences

B. V. Bunkin) in 1989, proposed to reclassify my dissertation on a special topic from a candidate's thesis to a doctoral thesis. In response, I warmly thanked the dissertation council and said that I wanted to defend my open doctoral thesis, which successfully happened in October 1994 at the IRE RAS. The topic of my doctoral dissertation for the degree of Doctor of Physico-mathematical Sciences was «Synthesis of images of the earth surface in the optical and millimeter wave ranges» (the leading organization of the «Almaz» Central Design Bureau, specialty «Radiophysics», the official opponents are Doctor of Technical Sciences, Professor. Kulemin G. P., Doctor of Physico-mathematical Sciences, senior researcher Rzhiga O. N., Doctor of Physico-mathematical Sciences, Professor. Fuchs I. M.).

It was Yuri Vasilyevich Gulyaev who called B. V. Bunkin much earlier in my presence, introduced me to him and told him in detail about me and my scientific activities. This is how I met with Academician B. V. Bunkin and the famous «Almaz» Central Design Bureau, with whom I had been actively working for several decades. In December 2016 I was awarded the A. A. Raspletin Medal from the A. M. Prokhorov Academy of Engineering Sciences. There were a lot of meetings and discussions about current affairs and research plans with my older friend Evgeny Mikhailovich Sukharev from «Almaz» Central Design Bureau [5].

2. General characteristics of the pioneering research and development work on fractals and multifractals

The problem of the fractal-scaling approach to a wide range of scientific and technical problems, put forward in the title of the section, began to be studied for the first time in the world by the author more than 45 years ago at the IRE of the USSR Academy of Sciences in connection with the implementation of a cycle of fundamental research with leading industrial research institutes and design bureaus of the USSR and Russia (approximately 20 organizations) dedicated to the creation of new breakthrough technologies for radar. The main thing is the detection of one-dimensional (probabilistic statistical signal) and multidimensional (stochastic optical and radar images - RLI) samples of various low-contrast objects against the background of intense interference from the earth surface. Over the period of his work at IRE RAS, more than 50 fundamental and exploratory research projects and many projects of the Russian Foundation for Basic Research have been completed. In the period 2001-2005, the author was the scientific director of the research carried out by solving the Applied Problems Section at the Presidium of the Russian Academy of Sciences.

As a result of many years of field experiments, a statistical analysis of large amounts of data on the spatiotemporal characteristics of the scattering of ground cover in the ranges of millimeter and centimeter radio waves was performed and their reliable interpretation was given. A new class of informative features based on the fine structure of reflected radar signals is proposed and substantiated. For the first time, complete ensembles of textural features of optical and radar images of real land covers have been studied. Based on previous results, new methods for detecting weak radar signals in the presence of intense non-Gaussian interference have been proposed and tested. A model of stochastic autoregressive synthesis of optical and radar images of the land covers with objects has been developed. The high degree of reliability of synthesis (up to 90%) allows it to be used when creating digital reference terrain maps for aircraft. It is important to note that the work carried out by the author on the study of the informative value of radio images of the above types using new technologies of textural measures had no analogues both in Russia and abroad, and have not lost their relevance at the present time.

In the early 90s of the XX century, the author proposed and justified topological fractal (non-energy) methods for detecting low-contrast objects against the background of intense non-Gaussian interference from the surface of the earth, sea and precipitation, highlighting their contours. Currently, we can talk about a reliable justification for the practical application of fractal methods based on fractional measures and scaling ratios in the modern fields of radiophysics, radar, telecommunications, radioelectronics, nanotechnology and in the design of an element base based on completely new physical principles.

In 2005, our work led to the formation and development of the concept of creating fundamentally new fractal radio systems and a fractal element base. Also in 2005, an operational model of a fractal nonparametric radar signal detector (FNRSD) was created at the V. A. Kotelnikov IRE of the Russian Academy of Sciences. Based on the analysis of some types of fractal broadband and multiband antennas, it is shown that promising elements of fractal radioelectronics are functional elements whose fractal impedances are realized based on the fractal geometry of conductors on the surface (fractal nanostructures, metasurfaces) and in space (fractal antennas), the fractal geometry of the surface microrelief of materials, etc. The developed approaches can be extended to a wide class of electrodynamic problems in the study of fractal magnon crystals and fractal metasurfaces, fractal resonators, fractal screens and barriers, as well as other fractal frequency-selective surfaces and volumes. The problem of wave scattering by fractal surfaces with the calculation of three-dimensional scattering indicatrices is solved.

A rigorous electrodynamic calculation of numerous types of fractal antennas has been carried out, the design principles of which underlie fractal frequency-selective surfaces and volumes (fractal «sandwiches»). A model of a «fractal» capacitor as a fractal impedance is proposed and implemented, as well as fractal labyrinths for the synthesis of microwave structures. In 1997, fractal modulation methods and fractal broadband and ultra-wideband signals, including H-signals, were developed for the first time.

In the period 2001–2005, together with the «Almaz» Central Design Bureau, the author was the co-director of the international project No. 0847.2 on the ISTC line to create a multifunctional automated radio measuring system with a complex signal on centimeter and millimeter waves, using fundamentally new patented technologies of circuit design and digital information processing based on fractal and Radon algorithms in real time. Twice through the ISTC (2000 and 2005), the author traveled to the United States on research trips (Huntsville, Franklin, Washington, Atlanta, New York) to give lectures on fractal technologies in radar and radio engineering. In an official letter to Academician of the Russian Academy of Sciences Yu.V. Gulyaev dated 12/14/2005, American specialists (Center for Space Plasma and Aeronautical Research, Huntsville, USA) noted the global priority of the author's work on the application of fractal theory in information and radar technologies, Fig. 1 [5]. In particular, it is noted that «...The seminars were of essential interest and confirmed the high scientific credentials of Dr. A.Potapov. RADAR technologies presented by Dr. Potapov are novel and based on the fractal theory. Their importance for the international community of specialists and scientists is undeniable».

At the same time, the author met with the founder of fractal geometry, B. Mandelbrot, at his home in the USA, when he accepted and approved the definition of fractals introduced by A. A. Potapov, and his work (Fig. 2 [5,6]). The author's monograph [2] was included by Mandelbrot in his famous international list of the best books on fractals. Since then, the author has kept 6 volumes of selected works by B. Mandelbrot with his inspiring autographs in Moscow.

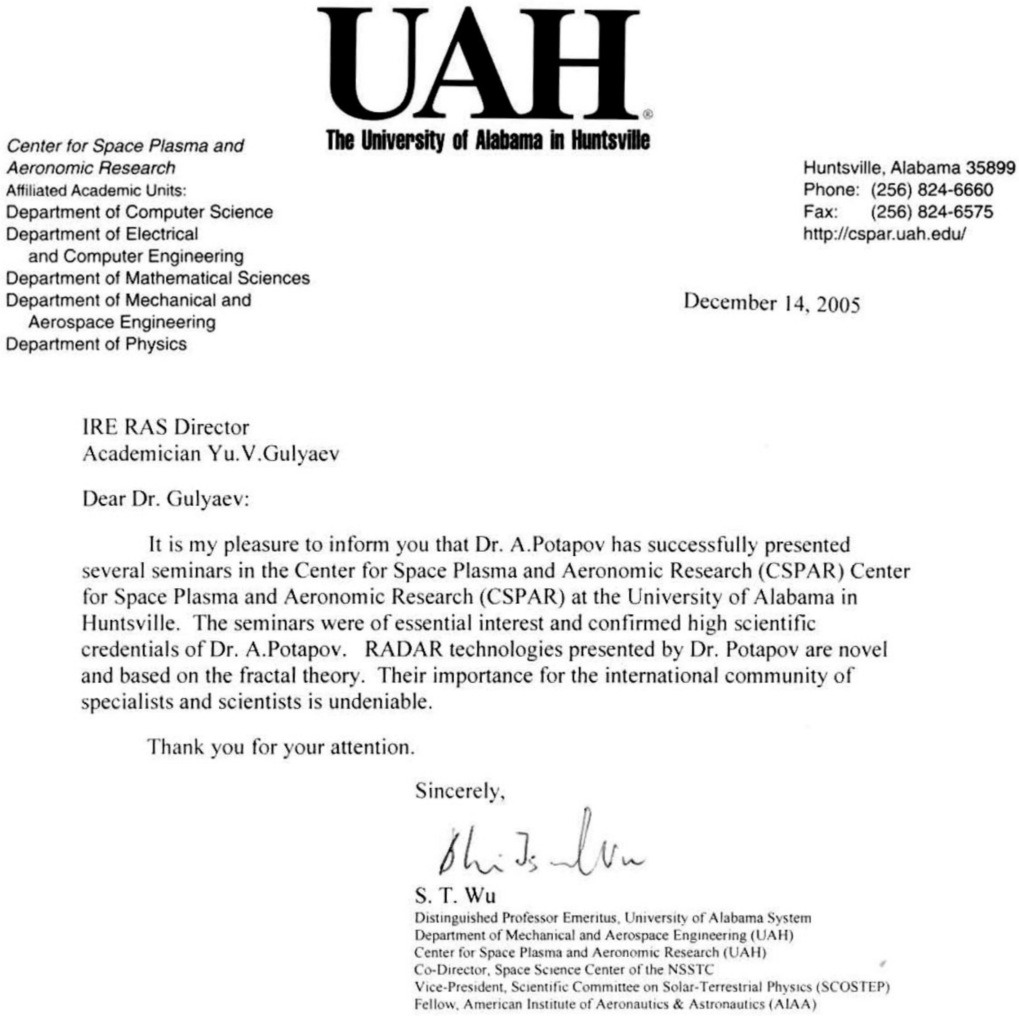
A. A. Potapov was appointed President of the joint Chinese-Russian Laboratory of Information Technology and Fractal Signal Processing (2011). In April 2015, the author won an international scientific competition in Beijing and won the Chinese Government Grant «Leading Talents» on fractal methods of signal and image processing.

Over the period 2019–2024, the author and Chinese scientists collaborated on about a dozen papers on photonics and radiophotonics, which were published in highly ranked international scientific journals. The topics of these articles are: optical-analog calculations of spatial differentiation and contour detection; Huygens meta-surfaces; control of light scattering by nanoparticles using magnetoelectric coupling and zero backscattering; theory of light scattering by nanoparticles and electromagnetic multipole; numerical modeling; verification experiments in the frequency range from 4 to 7.5 GHz; strong optomechanical coupling in chain waveguides and ring resonators made of silicon nanoparticles and nanorods with quasi-coupled states in a continuum (photon — phonon interaction with microstructures), etc.

In 2015, the author discovered, proposed, justified and developed the fundamental principles of a new type and a new method of modern radar, namely fractal-scaling or scale-invariant radar (SIR) [5, 6]. The effectiveness of functionals, which are determined by the topology, fractional dimension and texture of the received multidimensional signal, for the synthesis of fundamentally new non-energy detectors of low-contrast objects against the background of interference has been proven. The fundamentals of fractal radar are formulated:

1) intelligent signal/image processing, based on the theory of fractional measure and scaling effects, for calculating the field of fractal dimensions D;
2) sampling of the received signal in noise belongs to the class of stable non-Gaussian probability distributions D of the signal;
3) the maximum topology with the minimum energy of the input random signal (that is, the maximum «departure» from the energy of the received signal).

These principles open up new possibilities for ensuring sustainable operation with small ratios of signal /(noise + interference) or increasing the range of radars. An increase in the



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December 14, 2005

IRE RAS Director
Academician Yu.V.Gulyaev

Dear Dr. Gulyaev:

It is my pleasure to inform you that Dr. A.Potapov has successfully presented several seminars in the Center for Space Plasma and Aeronomic Research (CSPAR) Center for Space Plasma and Aeronomic Research (CSPAR) at the University of Alabama in Huntsville. The seminars were of essential interest and confirmed high scientific credentials of Dr. A.Potapov. RADAR technologies presented by Dr. Potapov are novel and based on the fractal theory. Their importance for the international community of specialists and scientists is undeniable.

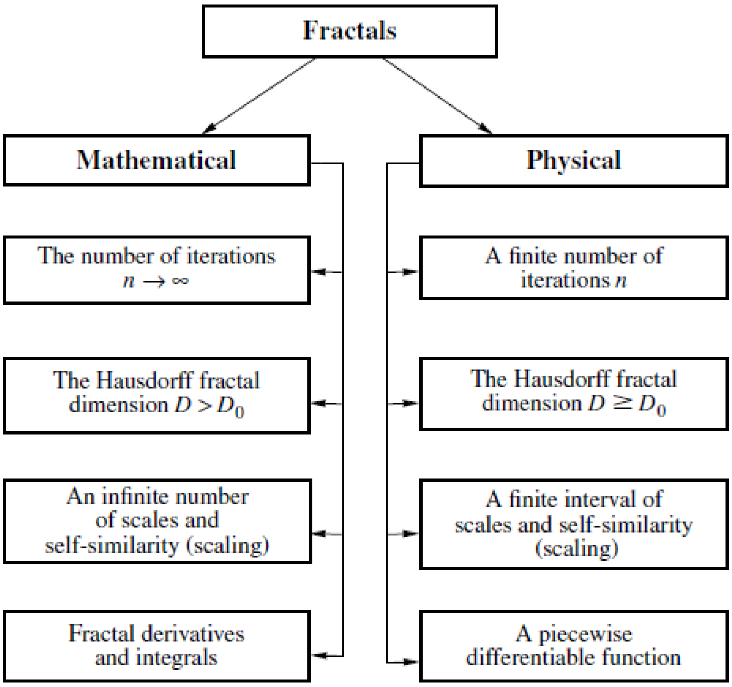
Thank you for your attention.

Sincerely,

S. T. Wu
Distinguished Professor Emeritus, University of Alabama System
Department of Mechanical and Aerospace Engineering (UAH)
Center for Space Plasma and Aeronomic Research (UAH)
Co-Director, Space Science Center of the NSSTC
Vice-President, Scientific Committee on Solar-Terrestrial Physics (SCOSTEP)
Fellow, American Institute of Aeronautics & Astronautics (AIAA)

Fig. 1. Letter to Academician Yu. V. Gulyaev about Russian priorities in fractals

a



b

Fig. 2. *a* — Meeting with B. Mandelbrot in New York (16.12.2005); *b* — the author's classification of fractal sets and signatures, approved by B. Mandelbrot (D_0 is the topological dimension of the embedding space)

sensitivity of the radio system (which is equivalent to an increase in range) has been confirmed when using fractal and textural features in topological detectors. This entails fundamental changes in the very structure of theoretical radio engineering and radar, as well as in their mathematical apparatus.

Below in Fig. 3–6 schematically considered (including data from the beginning of 2025) are the main directions for the implementation of topological texture-fractal processing (TTFP) information created by the author in new breakthrough technologies. The introduction of the above-mentioned concepts into scientific use allowed the author to propose and apply new dimensional and topological (rather than energy!) features or invariants based on the study of the topology of the received signal sample.

A. A. Potapov is an academician of the A.M. Prokhorov Academy of Engineering Sciences

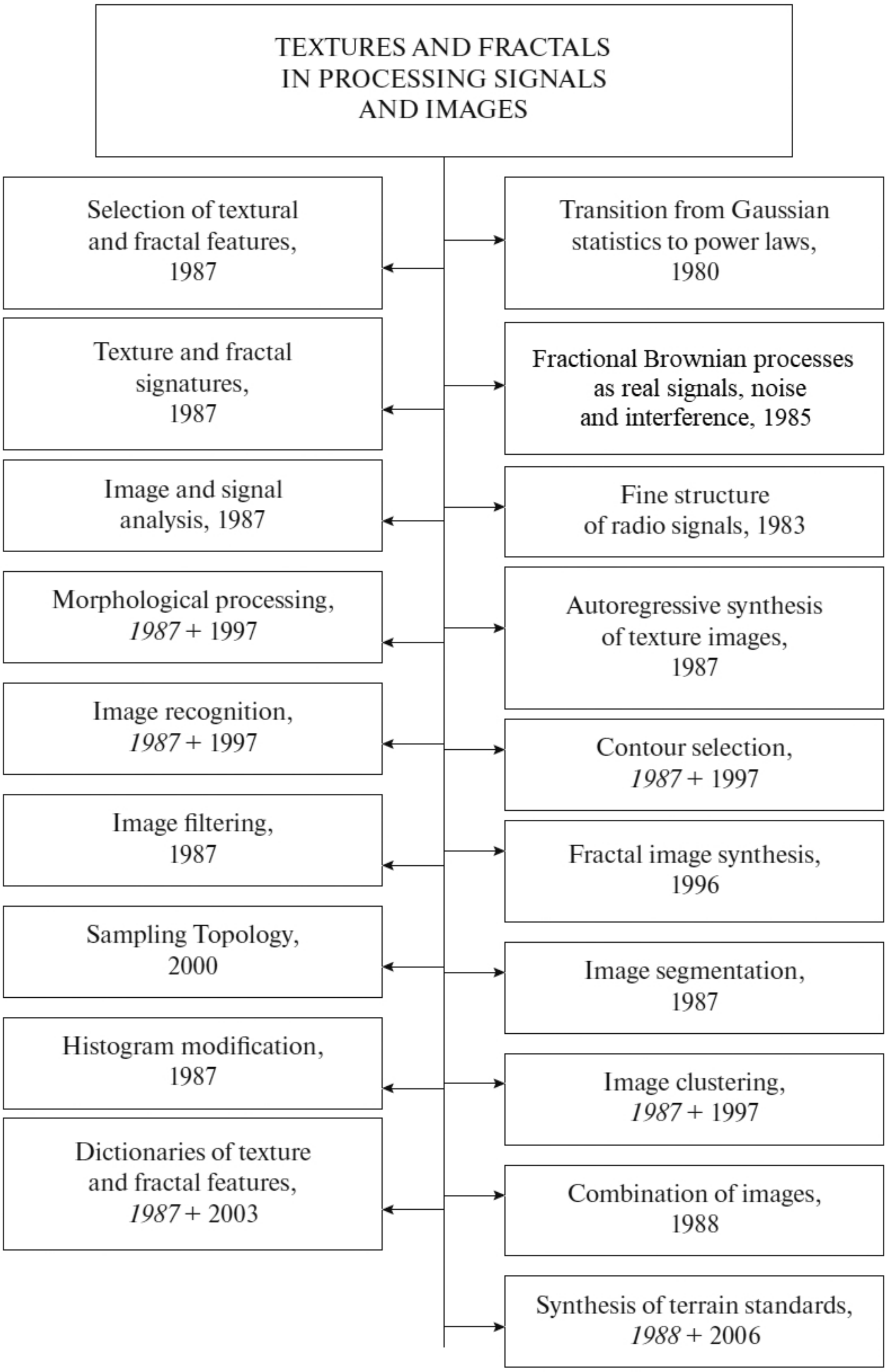


Fig. 3. Textures and fractals for processing low-contrast images and ultra-weak signals in noise and interference

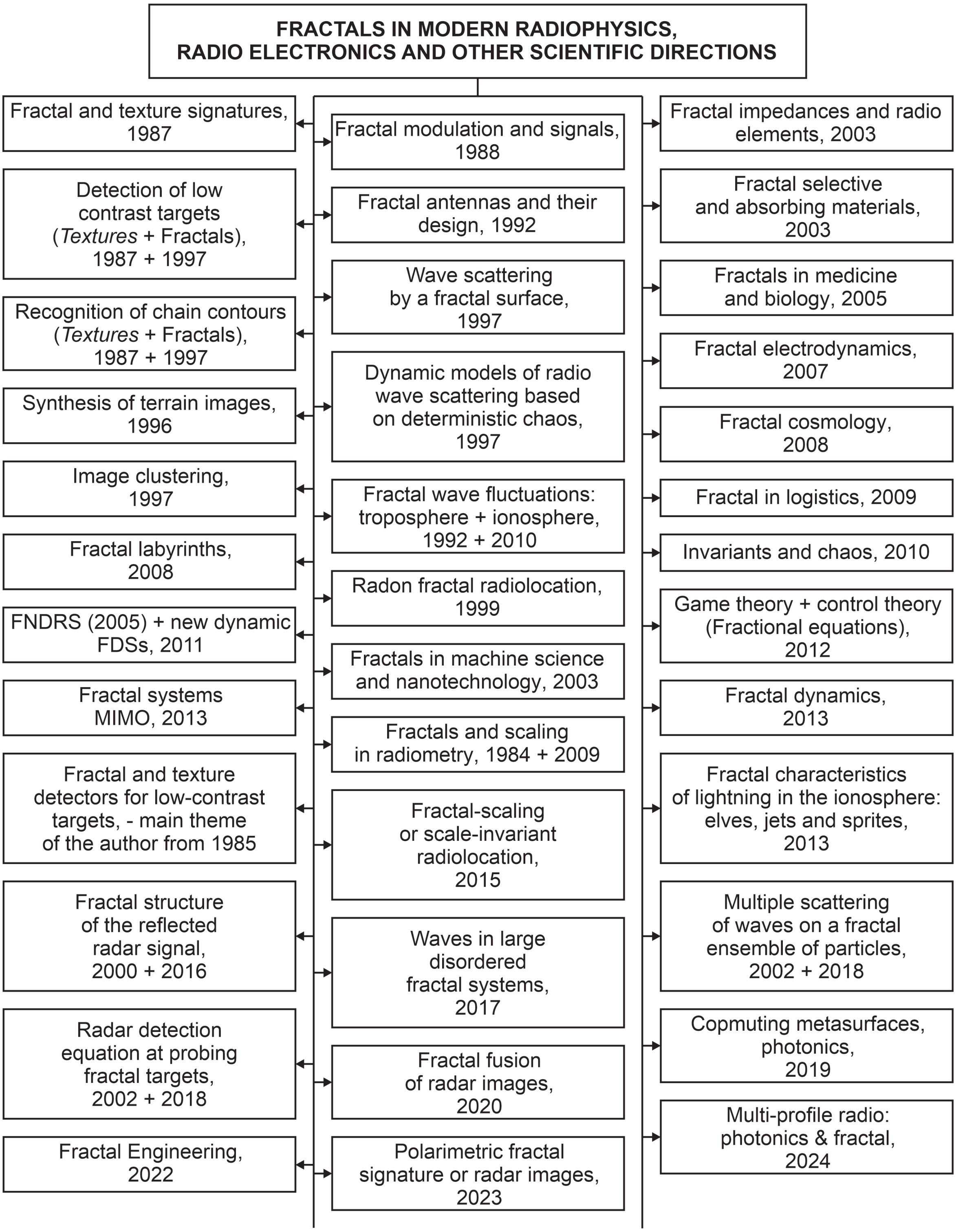


Fig. 4. A sketch of the author's development of breakthrough technologies based on fractals, scaling effects and fractional operators for physics and radio electronics (FSD — fractal signal detectors, SAR — synthetic aperture radar)

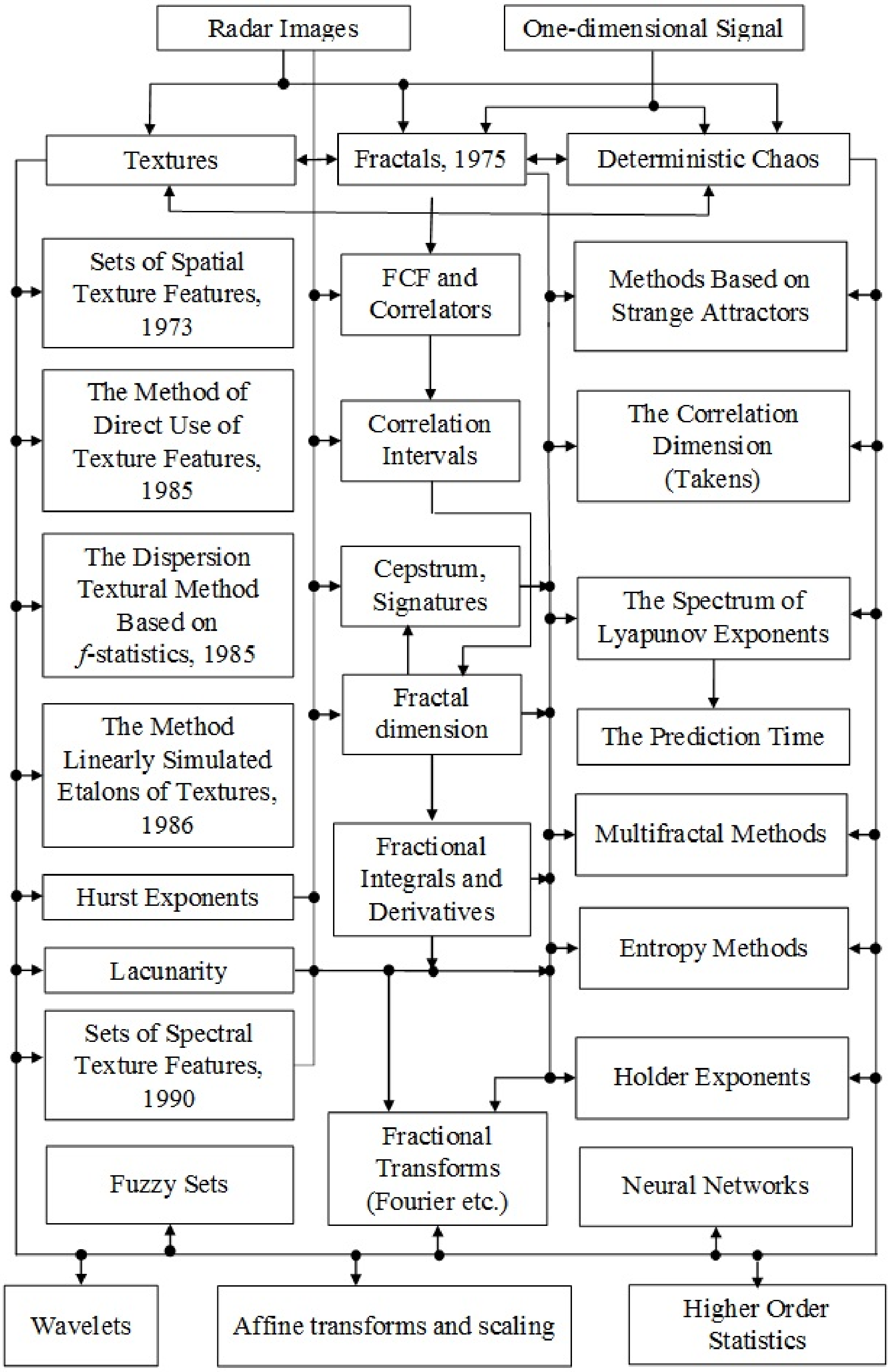


Fig. 5. New topological features and methods for detecting low-contrast (barely noticeable) objects against a background of intense noise and interference (TF — textural features, FCF — frequency coherence function)

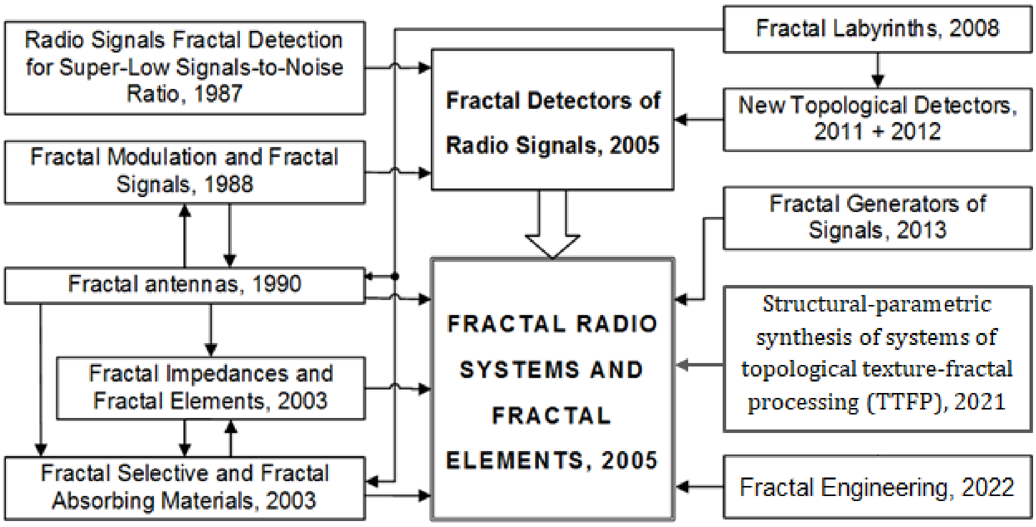


Fig. 6. The author's concept of fractal radio systems, sensors, devices and radio elements

(2008) and an academician of the Russian Academy of Natural Sciences (2007). He prepared the program, developed and lectured for a number of years on a special course «Application of fractals and wavelets in radar» for the Specialist Training Center at the RTI Systems Concern (RTI named after Academician A. L. Mints and JSC NPK NIIDAR). According to A. A. Potapov's monographs, lecture courses «Fractals in statistical radiophysics», «Statistical theory of fractal radar», «Fractals in Radiophysics and radar», «Statistical fractal radio engineering», «Fractals in Mechanical Engineering», etc. have been delivered at various universities in Russia and neighboring countries.

For his developments in the field of breakthrough information technologies and the implementation of scientific projects on textures, fractals and fractional operators in radar, radio engineering and radiophysics, A. A. Potapov was awarded 18 medals (Russian Federation of Cosmonautics, A. M. Prokhorov Academy of Engineering Sciences, K. E. Tsiolkovsky Russian Academy of Cosmonautics, Russian Academy of Natural Sciences, Non-departmental Expert Society on issues of the Aerospace sphere, etc.). In 2006, A. A. Potapov was awarded the title of «Honorary Radio Operator of the Russian Federation». By the decision of the Presidium of the Central Council of the Russian Scientific and Technical Society of Radio Engineering, Electronics and Communications named after A. S. Popov in 2015, A.A.Potapov was awarded the medal «For Services to the development of radio electronics and communications». In honor of the 40th anniversary of his scientific activity at the V. A. Kotelnikov IRE RAS and for outstanding achievements in the field of engineering sciences, he was awarded a tabletop medal named after. academician A.M. Prokhorov (2019).

3. Our results on fractals are presented in the reports of the Presidium of the RAS and in the report to the Government of the Russian Federation

Let us consider the universality of the topology of fractal sets. A thorough bibliographic analysis has proved our absolute priority [1–6, 9–51] in all «fractal» areas (in radiophysics and radio electronics) in the USSR and in Russia, as well as in world science. It's simple and clean: it wasn't before my work, it was after. I would like to note that my ideas about fractals and fractional operators, which I presented almost 45 years ago, have now confidently moved from the purely speculative stage to the stage of tangible reality and have reached their maturity as a powerful analytical tool for describing classical and anomalous stochastic processes. There is a serious confirmation of this, namely:

1. In the book «The report of the Presidium of the Russian Academy of Sciences. Scientific achievements of the Russian Academy of Sciences in 2007» (M: Nauka, 2008. 204 p.) contains the following text in the subsection «Location Systems», section «Information technologies and computing systems» (p. 41), the following text is given: «A reference dictionary of fractal features of optical and radio images has been created, which is necessary for the implementation of fundamentally new fractal methods for processing radar information and synthesizing highly informative devices for detecting and recognizing weak signals against the background of intense non-Gaussian interference. It has been established that fractional dimension, fractal signatures and caps, as well as textural signatures of the terrain background (IRE RAS) are essential for the effective solution of radar problems and the design of fractal detectors of multidimensional radio signals» — 2007, published in 2008.

2. In the book «The report of the Presidium of the Russian Academy of Sciences. Scientific achievements of the Russian Academy of Sciences in 2009» (M: Nauka, 2010. 486 p.) in the subsection «Location systems. Geoinformation technologies and systems», section «Nanotechnology and information technology» (p. 24) the following text is given: «For the first time in world practice, the principles of constructing new fractal adaptive radio systems and fractal radio elements for modern radio engineering and radar tasks have been proposed and experimentally proven. The principle of operation of such systems and elements is based on the introduction of fractional transformations of the emitted and received signals in a space of non-integer dimension, taking into account their scaling effects and non-Gaussian statistics. This allows us to reach a new level of the information structure of real non-Markov signals and fields (IRE RAS)» — 2009, published in 2010.

3. In the book «The report of the Presidium of the Russian Academy of Sciences. Scientific achievements of the Russian Academy of Sciences in 2011» (M: Nauka, 2012. 620 p.) in the subsection «Location systems. Geoinformation technologies and systems», section «Informatics and Information Technologies» (pp. 199–200) and in the book «Report to the Government of the Russian Federation. On the results of the implementation in 2011 of the Program of Fundamental Scientific Research of the State Academies of Sciences for 2008–2012: in 3 volumes» (M.: Nauka, 2012. 1015 p.) (p. 242) the following text is given: «Based on fractal analysis, a systematic study of the electrodynamic properties of fractal antennas has been carried out. The broadband and multiband properties of fractal antennas and the dependence of the number of resonances on the iteration number of fractals have been confirmed. It is shown that on the basis of miniature fractal antennas, it is possible to effectively implement frequency-selective media and protective screens that distort the radar portrait of the target. Fractal frequency-selective 3D media or fractal "sandwiches" (engineering radioelectronic micro- and nanoconstructions) have been studied (IRE RAS)» — 2011, published in 2012.

4. In the book «The report of the Presidium of the Russian Academy of Sciences. Scientific achievements of the Russian Academy of Sciences in 2012» (M.: Nauka, 2013. 616 p.) in the subsection «Element base of microelectronics, nanoelectronics and quantum computers. Materials for micro- and nanoelectronics. Nano- and microsystem engineering. Solid-state electronics» (p. 195) the following text is given: «It has been established that the integer quantum Hall effect is the physical basis of the memristor operation. The relations between current and voltage for an arbitrary type of memristor are obtained. The results are aimed at the practical implementation of memristors as new elements of electronic circuits (Research Institute of AMA KBSC RAS, IRE RAS)» — 2012, published in 2013.

4. Example 1: Fractal antennas and frequency-selective devices based on them

Antenna devices are an integral part of any radio engineering system. The key problems of antenna theory and technology are always the reduction of their size, wide regulation of electromagnetic characteristics and the expansion of the operating frequency band. The geometric dimensions of the antenna are determined by the operating wavelength and, in turn, affect the mass and dimensional characteristics of the radio system. Broadband and ultra-broadband antennas are currently gaining exceptional importance.

Fractal antennas work through the geometry of the conductors, rather than through the accumulation of individual components or elements (as in classical antennas), which in the latter case increases complexity and potential failure points. Fractal antennas make it possible to create multiband variants with a reduced size and often optimal or «gorgeous» technology of such devices [1–3, 5, 10, 26, 37, 46]. The undoubted advantage of fractal antennas (monopoles and dipoles) is that they often have lower resonant frequencies compared to classical (Euclidean) antennas of the same size. Since effective lengths play an important role in antenna design, fractal packing can be used as a viable aspect of miniaturization techniques. An increase in the fractal dimension D of the antenna aperture leads to a higher degree of miniaturization. The inherent broadband qualities of fractal antennas are ideal for intelligent applications.

Unlike traditional methods, when smooth radiation patterns (RP) of antenna are synthesized, the theory of fractal synthesis is based on the idea of realizing radiation characteristics with a repeating structure on arbitrary scales. This makes it possible to create new modes in fractal electrodynamics, obtain fundamentally new properties, as well as fractal radio elements (for example, a fractal capacitor) [1–3, 5, 10, 37].

It should be noted that back in 1988, the author, together with the «Almaz» Central Design Bureau, carried out the first developments in the USSR and the design of such fractal antenna structures unusual for that time (see below). A rigorous electrodynamic calculation of numerous types of fractal antennas has been carried out, the design principles of which underlie fractal frequency-selective surfaces and volumes (fractal «sandwiches» and fractal labyrinths, Fig. 6 [1, 2, 5, 9, 10]). Promising elements of fractal radioelectronics are functional elements whose fractal impedances are realized on the basis of 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. Now fractal antennas are a completely independent new class of antennas.

5. Example 2: Non-energetic fractal weak signal detectors

The creation of the first reference dictionary of fractal features of target classes, including fractal primitives, fractal language elements, fractal symbols, fractal grammar for fractal words, and continuous improvement of algorithmic support were the main stages in the development and prototyping of the first fractal nonparametric radar signal detector (FNRSD) in the form of a special processor [1–3, 5, 6, 20, 21, 23, 32, 33, 47]. The basic principles of the texture-fractal detector were discovered and proposed by the author back in the 80s of the XX century, and the output to the current model of the fractal nonparametric radar signal detector (FNRSD) was made in 2003-2005. One of the main conclusions made by the author back in the 80s of the XX century: the work on the point estimation of the fractal dimension D often leads to absurd results due to ambiguity. At the same time, almost all authors who use fractal processing (and often do not understand its physical meaning) give exclusively point estimates, and even with a standard deviation (nonsense!). We also proved for the first time that the intensity of the target image affects the change in fractal dimension much less than the ratio of the areas covered by the target and the entire image. The presence of spatial Gaussian fluctuations in the target area with a standard deviation of about 35% showed almost the same degree of detection.

As examples of the effective operation of the global fractal methodology and the concept of fractal radio systems and devices, we present below a number of fundamentally new FSD (Fig. 4–7). Here, the author has limited himself to basic functional examples to illustrate the developed general theoretical and heuristic principles of dynamic FSD. There is a separate question about

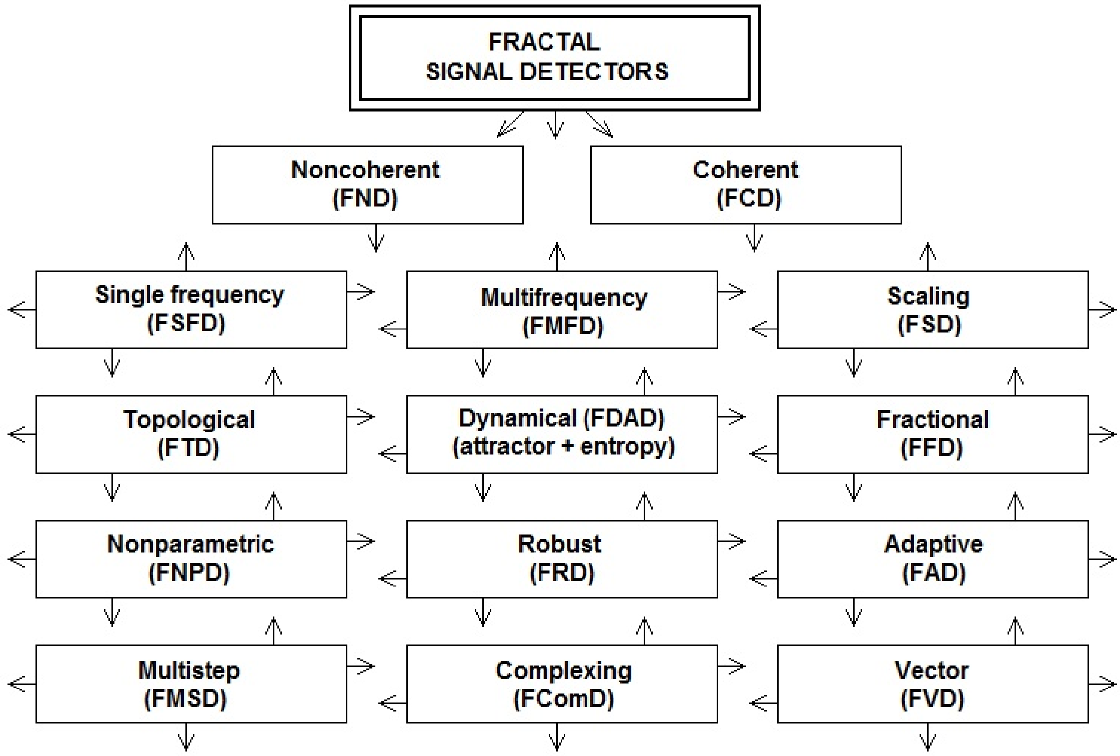


Fig. 7. The main types of proposed topological fractal-scaling detectors of multidimensional signals

the need to develop decisive rules based on fractal singular and topological characteristics of the accepted stochastic sample of a non-Gaussian mixture (signal + noise + interference). All FSD consist of two classes: noncoherent (FND) and coherent (FCD). Then there are single-frequency (FSFD, in particular, one radiated frequency of the radar), multi-frequency (FMFD, several operating frequencies of the radar; in this case, it is elementary to detect scaling in the received sample), as well as directly scaling fractal detector (FSD). The efficiency of the FSD has been successfully tested in practice when detecting and locating an acoustic signal against the background of a forest area. It was shown to be highly effective in conditions of strong background interference, when classical correlation and spectral analysis did not give correct results in real time.

Fractal topological detector (FTD), representing the space of received signals in the form of a topological connected structure with fractional dimension («fractal labyrinths» situation), we can identify channels with hypothesis H_0 and hypothesis H_1, isolate them and then detect them. The fractal labyrinths is a new object of mathematical physics and nanotechnology, which is a topologically connected structure with a fractal dimension $D > 1$ and a scaling character of the conducting paths [10,37]. Thus, the problem of expanding the classes of fractal-scaling signal detectors and their integration with equal fractal signatures of the object and background can also be considered from the angle of mathematics of fractal labyrinthine structures. In addition to fractals, the fractal dynamic detector (FDD) uses the characteristics of deterministic/dynamic chaos. A strange attractor is reconstructed in the phase plane of the received signal samples, and its characteristics are calculated, including Lyapunov exponents, prediction interval, and Kolmogorov entropy. We have also successfully tested this type of FSD in practice under vegetation conditions [19]. Its further improvement is the use of statistical measures of entropy and information of the Renyi, Havrd–Charvat–Daroshi, Rathye–Kannappan, Sharma–Mittal, Kulback–Leibler differences and group-theoretic aspects of information theory. The Fractal Fractional Number

Detector (FFD) uses fully integro-differentiation of fractional order.

The development of adaptive methods for fractal information processing is of considerable interest. An adaptive task is characterized by a change in the parameters and/or structure of the system in accordance with external conditions. The fractal adaptive detector (FAD) is exclusively considered here. The adaptation of nonlinear fractal filtering under conditions of a priori uncertainty is provided, in particular, by the current estimate of the Hurst index H. The Hurst index, depending on its value relative to $H = 1/2$ (Gaussian process), characterizes either the persistence ($1/2 < H < 1$), or the anti-persistence ($0 < H < 1/2$) of the current sample. In the first case, we observe a process that maintains a tendency to increase or decrease the instantaneous amplitudes in the sample, that is, a process with memory. In the second case, we observe a process that is more susceptible to change, which is referred to as «return to the average». It is also of interest to deduce the rules for using additional information about the H parameter of the sample for optimal reasons.

Parametric and nonparametric detectors complement each other. In the case of signal detection, nonparametric algorithms do not use the values of the observed quantities, but rather some degree of their ordering. Their most important property is an almost fixed probability of false detection under arbitrary sampling distribution laws. For cases of nonparametric a priori uncertainty, we have introduced a fractal nonparametric detector (FNPD). An example of this kind of detector is FNRSD (see above). Sequential combination of parametric and nonparametric FSD is possible. In the variant we are interested in, this is a translation to combine classical energy and fractal algorithms.

Robust detectors (FRD) use synthesis methods that occupy an intermediate position between parametric and nonparametric ones. At the same time, the class of possible distributions narrows down, for which the algorithms remain stable. With a training sample, it is possible to build a fractal adaptive-robust detector. In our case, the combination of FNPD, FNRSD and FAD.

A fractal multistep detector (FMSD) solves problems when hypotheses are accepted at each nth step, confirming the decisions made or changing them at subsequent observation steps. At each step, the likelihood ratio is calculated and compared with thresholds that vary depending on the loss functions. In practice, radar often uses a two-step detection procedure. A fractal vector or multi-channel detector (FVD) is typical for multi-position radar.

The topic of integrating radio information processing systems was thoroughly studied by us in the 80s–90s of the XX century for systems of millimeter and optical waves. The fractal integrated detector (FComD) in Fig. 7 uses various combinations with classical detectors and is based on experiments conducted to verify the operability of the FNRSD as well as when the FNRSD is docked with the output of the current radio system [13,14,47]. It has been shown that in this case, the probability of correct detection and recognition increases. At this stage, this task is no longer of deep scientific interest, but refers practically to engineering technical solutions.

Functional connections between individual types of fractal detectors (Fig. 7) were not specifically introduced so that the FSD platform would be as free as possible for future researchers and designers. Previously, we applied Radon transformation in conjunction with fractal processing in a radar with a complex signal in the millimeter wave band [9,16]. Dynamic FSD can also be widely used in nonlinear radar.

6. Example 3: Fractal processing of multidimensional signals

Every day, the sky is streaked with 4 million lightning bolts, approximately 50 every second. And above the leaden storm fronts, in the upper atmosphere, a light show of «ghostly lightning»: unfolds: blue jets, red-purple sprites, red rings of elves soaring in the air. These are very high-energy discharges that do not hit the ground, but the ionosphere! High-altitude electrical discharges (20...100 km) are divided into several main types: elves, jets, sprites, halos, etc., see Fig. 8.

The story of their discovery is very interesting. Sprites, for example, were discovered by accident on the night of 5 to 6 July 1989 in the USA. They clearly confirmed the existence of a global electrical circuit (GEC) on our planet and provided new opportunities for its research. On the fractal dimension maps (Fig. 8) , the external, basic, and ultrathin structures are clearly distinguished. Dynamic space-time features and morphology of sprites can be explained, in particular, by the multifractal geometry of discharges and percolation. Fractal labyrinth-based modeling [37] is also applicable here, which well reflects the physics and morphology of such ionospheric structures. It should be noted that the data presented in Fig. 8 are unique results of fractal processing of such structures, which aroused considerable interest at radar conferences in the USA and China.

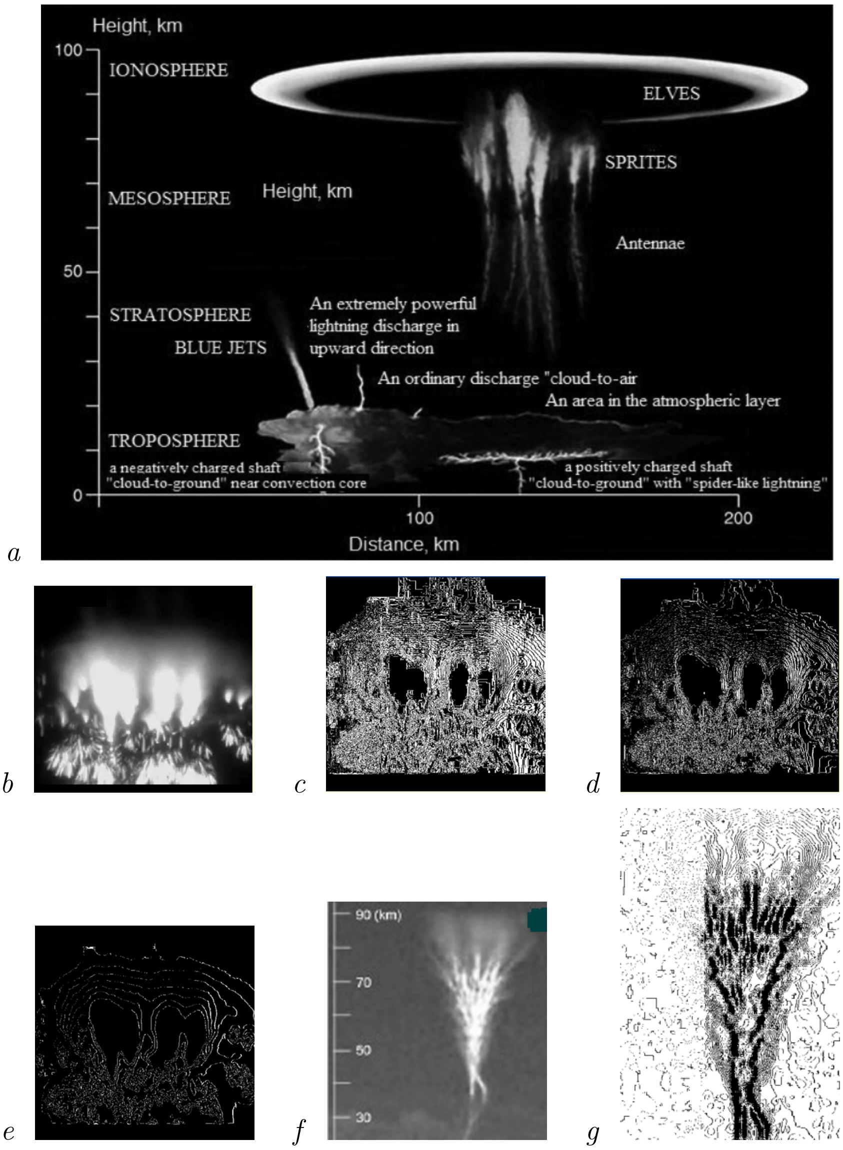


Fig. 8. Dynamic multifractal structures in the atmosphere: a — dynamic multifractal structures, b — sprite (shot from the spacecraft — USA, NASA); fractal filtering of the sprite image: c — map $D = 2.3$, d — map $D = 2.6$, e — map $D = 2.8$, f — jet (IR shot from the spacecraft — China), g — fractal filtering of the jet image: map D (color online)

Numerous results [4, 21, 22] show that fractal processing methods improve the quality and detail of objects in active and passive modes by about several times.

7. Fractal engineering

The scope of topological texture-fractal processing of signals, fields and images is constantly expanding, and it is hard to believe that about thirty years ago there were many skeptical statements about the prospects of this new fundamental scientific field, related exclusively to fractals and their dynamics, created and developed by the author first in the USSR and then in Russia. These sceptical remarks were linked to incompetence, sheer ignorance and lack of knowledge.

Here is a typical example (there were many). Publications on the history of fractal antennas usually mention the 1986 work of Pennsylvania State University scientists Y. Kim and D. Jaggard. Since 1993, K. Puente, a scientist at the Technological University of Catalonia, has been credited with the primacy in theoretical studies of the formation of multiband frequency antennas. The beginning of the practical application of fractal antennas in 1995 was laid, as is commonly believed in foreign and even some Russian-language journals, by American engineer Nathan Cohen. But the last sentence is just nonsense (absurdity)!

The author's reference as a response to this absurdity, see Fig. 9 [1, 2, 5, 9, 10]: «In 1988, the author, together with the «Almaz» Central Design Bureau, carried out the first development and

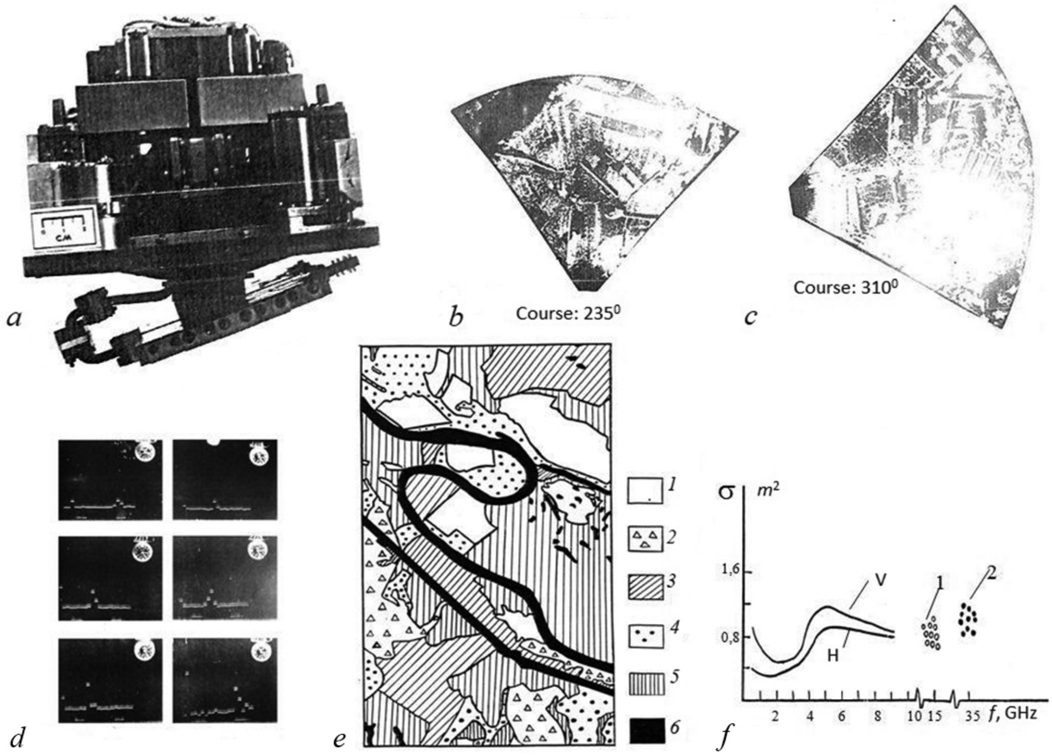


Fig. 9. Portable digital solid-state dual-frequency coherent parametron radar with complex signal of very long base $m = 2^{17} - 1$ with fractal slot array in MMW and SMW ranges (a) and some results of full-scale tests of the radar: b, c — first radar images at 8.6 mm wavelength; d — characteristic shapes of signal envelope reflected by characteristic textural land covers; e — example of reference synthesized map of heterogeneous terrain by energy, textural and fractal features; f — average human RCS as a function of frequency for horizontal (H) and vertical (V) polarizations, 1 and 2 — data of the author, who participated in full-scale experiment as a "located target"

design of such unusual (for that time) fractal antenna structures (in particular, a working model of a fractal slit antenna array in the MMW and SMW ranges was made) for a portable solid-state dual-frequency coherent radar based on parametrons with a complex phase-modulated ultra-large base signal (there is our patent). 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». And before that, we still had to be able to strictly calculate the parameters of a unique dual-frequency fractal receiving and transmitting antenna for two bands and then produce several almost industrial samples!

I note that it was on this radar that the author first investigated the fractal properties of code M-sequences with a period up to $2^{20} - 1$. The quantization of the input signal in the radar took place in a stochastic number system. The signal represented by such a code exhibits its fractal properties. Like a hologram, any fragment of which carries information about the complete object, any fragment of the stochastic code contains information about the amplitude of the quantized signal. Then, for the first time, a new radar method based on Radon conversion was implemented on this module [5, 9, 16].

This is actually fractal engineering with elements of the philosophy of engineering (one can say that that time, namely the 80s of the XX century, was for the author the beginning of the emergence of the Russian philosophy of fractal engineering)! This was a serious and advanced project in the great USSR, and not some elementary «children's trinkets» that were bent and placed on the balcony in 1995 by an American engineer!

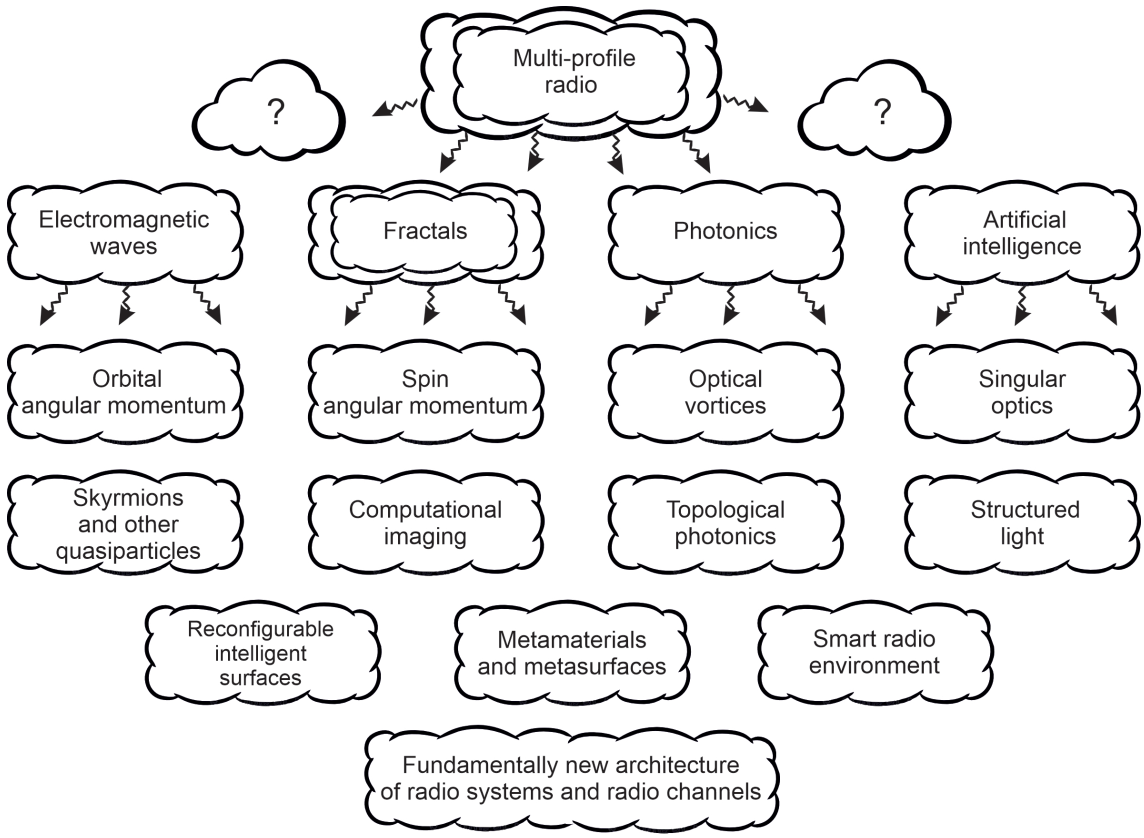


Fig. 10. The author's paradigm "Multi-profile radio" as a framework for new ideas

8. Multi-profile radio

The concept or paradigm of «Multi-profile radio was finally formed by the author in early May 2024, Fig. 10. This was preceded by a cycle of our work in Russia and China in 2022–2024, where possible and necessary, combining the roadmaps «Fractals», «Photonics» and «Artificial Intelligence» for end-to-end technologies (see, for example, [48, 49]). The author's paradigm is based on a fundamentally new approach to the joint use of the physical properties of electromagnetic waves (EMW) in a wide range of frequencies and the universality of the topology of fractal sets. The idea of our scientific research was to apply topology and dimensional theory in an open set of problems in radiophysics, radar and radio engineering, inspired by modern physics and photonics. The articles [48, 49] cover the individual components of the following series 3–5. The ultimate goal is a fundamentally new architecture of radio systems and radio channels. Adding new segments in Fig. 10 is not only possible, but also extremely necessary. EMW carrying orbital angular momentum are of great interest and open up opportunities for future breakthroughs in the field of radio. [48,49] presents a modern picture of the development of research in the field of topologically nontrivial spin textures, such as skyrmions. Optical skyrmions are quasi-particles with nontrivial topological fractal textures that have significant potential in optical processing, transmission, and storage of information.

A «smart» or intelligent radio environment is a wireless environment that transforms into an intelligent reconfigurable space and plays an active role in transmitting and processing information, making data exchange between transmitters and receivers more reliable. The concept of «smart» radio environments is not limited to improving wireless communication, but is aimed at creating a truly distributed intelligent wireless communication, sensing and computing platform that connects the physical and digital worlds.

The Table shows the physical properties of electromagnetic wave and the universality of the topology of fractal sets, and their joint potential use from the point of view of multi-profile radio, as well as research institutes and universities with which the author has worked since 1979 at the IRE of the USSR Academy of Sciences (IRE RAS).

Table. Physical properties of electromagnetic waves together with fractal topology and their use for multi-profile radio

Physical properties / directions	Application	Remark
TTFP of signals and fields (taking into account the hereditarity (memory), non-Gaussian and scaling), fractal coding (EARLY 20th century)	EMF and acoustics, radar, radiometry, UAV, SAR, mechanical engineering, materials science, nanotechnology, medicine, biology, sensing, communications, economics, logistics, dynamic chaos, big data	IRE USSR Academy of Sciences, IRE RAS, — A. A. Potapov
Non-energetic textural and fractal detectors of ultra-weak signals (D, dimension, Hurst and Helder exponents, lacunarity , stochastic autoregressive synthesis, etc.)	New dimensional and topological (not energy!) features or invariants (signatures), sampling topology, fuzzy sets, artificial intelligence	Beginning — 1979 and so on into THE FUTURE, IRE USSR Academy of Sciences, IRE RAS, — A. A. Potapov
Propagation and diffraction of waves in fractal and turbulent media, theory of catastrophes in wave physics, stochastic equations with fractional operators, Feynman integral over trajectories, asymptotics, etc.	Wave scattering by a fractal surface (coherence functions, speckles, EPR variations, indicatrices, strange attractors, prediction time), fractal wave fluctuations (troposphere, ionosphere — elves, jets, sprites), solitons	IRE USSR Academy of Sciences, IRE RAS, Technion (Haifa), VNIIOFI, — A. A. Potapov
Fractal antennas, chiral media, antenna arrays for MIMO, fractal labyrinths, metamaterial screens for antenna decoupling	Broadband or multiband, EPR variations, growth of fractal structures and boundaries, origami, etc.	IRE RAS, «Almaz» CDB, VSU, MIPT, MIREA, ETU LETI, PSUTI, UNN, NSTU, — A. A. Potapov
Fractal elements, sensors, selective and absorbing materials, devices and systems	Fractal generator, fractal filters, new materials, memristor, negative capacitor, fractal interfacial boundaries, magnetic phase transitions, mesoporous ferromagnetic materials, fractional order regulators, MEMS, nanoscale coatings with fractal topology, etc.	IRE RAS, BMSTU, MAMI, ETU LETI, KISTU, KSU, UNN, IOMC RAS, NSTU, USATU, AMA KBSC RAS, — A. A. Potapov
Fractal radar and fractal frequency MIMO systems	Multi-frequency operation and other modes and variants, nonlinear radar	IRE RAS, — A. A. Potapov
Fractal signals, interference, and power-law noise processes	Simple and complex signals, chaotic signals, H-signals, fBm, flicker noise (report at S. M. Rytov's seminar on fluctuation phenomena in IAP RAS)	IRE USSR Academy of Sciences, IRE RAS, — A. A. Potapov
Fractal electrodynamics and fractal impedances, nonlinear electrodynamics, chiral nanostructures based on DNA origami	Maxwell equations, wave equation, fractal capacitor, study of fractional operators and fields	IRE USSR Academy of Sciences, IRE RAS, MSU, MIPT, PSUTI, DSU, AMA KBSC RAS, — A. A. Potapov

Continuation of the Table on p. 768

Physical properties / directions	Application	Remark
Fractal aggregation and FPS, forming portraits of complex objects	Optics, MMW, SMW, radar images, SAR. — The patent	IRE USSR Academy of Sciences, VVS VVA, IRE RAS, — A. A. Potapov
Fractal-scaling or scale-invariant radar; active-passive radar; Radon Transform into radar (for the first time in the world)	Complete ensembles of textural and fractal features and caps, dictionaries of fractal features, first introduced by the author. — The patent	IRE RAS, «Almaz» CDB (Fractal radar and fractal frequency MIMO systems); (the radar equation for fractal purposes), — A. A. Potapov
Fractal engineering: fractal radioelectronics, fractal radiophysics, fractal radio engineering, etc.	Everything done above on fractals and THE FUTURE	IRE RAS, — A. A. Potapov
Game theory, control theory, fractal geometry of space-time, fractal quantum fields (fractional equations and operators)	Fractional equations and operators, fractional Green functions, negative fractal dimensions of Hausdorff-Columbo D (theory) [44] etc.	IRE RAS, Technion (Haifa), VNIIOFI, — A. A. Potapov
Photonics/ radiophotonics and other research; participation in various international conferences, release of highly rated articles and monographs [10]	Signal and field processing, meta-surfaces, zero backscattering, multipolyes, light scattering control, numerical modeling, microwave verification experiments, artificial intelligence, new classes of antennas, optomechanics of silicon waveguides and resonators, etc.	IRE RAS, Jinan University (Guangzhou, China), Joint Chinese-Russian laboratory information technology and fractal signal processing (since 2011), — A. A. Potapov

In the Table: fBm is a fractal (generalized) Brownian motion, FPS are fractal-polarization signatures introduced by [43].

Thus, it is a concept document (Fig. 10 and Table), which summarizes the author's paradigm of the new architecture of radio systems and radio channels (i.e., «Multi-profile radio») based on the roadmaps «Fractals», «Photonics» and «Artificial Intelligence» [48, 49].

Conclusion

With great gratitude, I would like to say once again that without the benevolent support of academicians B. V. Bunkin, V. A. Kotelnikov, and Yu.V. Gulyaev, my work in the field of fractal theory and their wide application in radiophysics, radio engineering, radar (in general, all radioelectronics), as well as in digital information processing would not have been so effective, systematic and fruitful for more than 45 years of work at the IRE of the USSR Academy of Sciences (IRE RAS).

Fractal radiophysics and fractal radioelectronics are peculiar radio sciences imbued with the spirit and ideas of classical radiophysics and radioelectronics, at the same time they are fundamentally new directions. Fractal methods similar to those described in this paper can be applied when considering wave and oscillatory processes in optics, acoustics, and mechanics.

In his works, for more than 45 years, the author has practically «from scratch», overcoming the difficulties of those who go first, laid the fundamental foundations of what will be applied in the future. It is not only the results and specific solutions that are of the greatest value, but the method of solution and the approach to it. The fundamental difference between the fractal methods proposed by the author and the classical ones is due to a fundamentally different approach to the main components of the signal and field. The global fractal method was created by the author and comprehensively demonstrated in [1–6, 9–51] and directly here in this work. As a result, a new semantic space has been formed in the scientific world with its unusual properties and tasks for classical radiophysics and radioelectronics. The obtained scientific results are the source material for the further development and practical application of fractal methods in modern fields of radiophysics, radio engineering, radar, electronics and information control systems [52]. All of this defines fractal engineering.

Fractal geometry is the great and brilliant contribution of B. Mandelbrot (1924–2010). But its radiophysical/radio engineering and practical implementation is an exceptional achievement of the world-renowned Russian Scientific School of Fractal Methods under the leadership of Professor A. A. Potapov (Kotelnikov IRE RAS).

The author develops and reinforces his ideas that a new «fractal» dimension should be firmly introduced in science and technology, and not as an auxiliary role, but as a fundamental explanatory factor. Our priority in these areas for May 2025 is fixed by more than 1250 papers and 68 domestic and foreign monographs and individual chapters in them in Russian, English and Chinese; reports have been made in 23 countries. In the scientific information network Research Gate (A. A. Potapov (researchgate.net)) the author's works are now read by more than 72 thousand correspondents.

On the eve of my 75th birthday, I would like to note the following. There have been and still are three great passions in my life: science (fractals and radar), books (a great home library), and family. Despite all the difficulties, these areas are in balance. And this is an exceptional achievement of my wife Potapova (Samborskaya) Valentina Yakovlevna and our two sons Alexey and Victor [5].

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