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Fractal scaling or scale-invariant processing signals and images to create new telecom technology

Abstract: This article analyzes the current research on the application of methods of fractal analysis in radio physics, electronics and radar, showing the advantages and effectiveness of it, where the classical methods of analysis does not work.

Keywords: fractal signal processing, fractal radio physics, fractal radar, radiolocation, radio navigation, power laws.

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Фрактальные обработки сигналов масштабирования или масштабно-инвариантными изображения для создания новой технологии телекоммуникацый

Аннотация: Статья посвящена анализу современных исследований по применению методов фрактального анализа в радиофизике, радиоэлектронике

и радиолокации, показаны его преимущества и эффективность, где классические методы анализа не работают.

Introduction

The wealth of content and the role of classical statistical physics, radio equipment and radar provides both great opportunities for the development of alternative methods. This paper presents an alternative solution to the problems of modern radar is based on the ideas and methods of fundamental new scientific direction "Fractal radio physics and electronics: fractal design of radio". This direction is initiated by the first author from about 1980 IRE them. V.A. Kotelnikov RAS and by now widely developed in his papers [2 - 3].

The intensive development of modern electronic technology and technology poses radar theory and new requirements [3]. Some of these requirements are not for-touch upon the foundations of the theory and reduced mainly to an increase in accuracy, improvement of existing and development of new methods of calculation. Others are more fundamental and concern the very foundations of the theory of radar. These latter requirements appear to be most important both in theoretical and in practical terms.

Needless to say, the whole of modern radio technology is based on the classical theory of integral action and integral calculus. Thus, historically, "overboard" was a vast area of mathematical analysis, called fractional calculus, dealing with derivatives and integrals of arbitrary (real or complex) of the order, as well as the whole theory of fractals (!).

Note that the radar (RLS) can be used to detect various purposes, for communication for identification purposes, for detecting radiation, to accompany and irradiation targets for review (mapping) of the Earth surface, the broadcast information to the navigation Jamming and to provide scientific-Research (such as astronomy).

Fractal Radio Physics and Fractal radar have major significance for a number of both theoretical and practical problems. Questions scattering and propagation of electromagnetic waves, signal processing, and image fields, antenna theory, etc. Is not currently possible to formulate and solve at the present level of science without the use of the theory of fractals and scaling.

Basic theory of fractal radar and related mathematical and physical issues detailed by the author in the monographs [2]. There's also introduced new radar for concepts and definitions associated with a wide range of theoretical issues fractal-ray processing.

1. Fractal scaling methods and invariants in radio physics and radar

Currently, radio physics, electronics and processing of multidimensional signals, as noted above, preferably, familiar and widely used measures integer (integrals and derivatives of integer order), the statistical Gaussian on, Markov processes, etc. [2]. The theory of Markov processes has already reached its saturation and research carried out at the level of complication sharp synthesized algorithms. Improving classical radar detectors signals and software, as well, in fact, it reached its saturation and limits. This forces to seek innovative ways to address the problem of increasing sensitivity or increasing range of different radio systems.

Now for a given fundamental direction of the author's works with a list of nicknames scientists-has more than 700 publications, including 20 monographs.

With the creation of 70-ies XX century fractal geometry (B. Mandelbrot, 1924-2010 years) in science and technology began to rapidly penetrate the idea of fractional dimensions, fractional operators, non-differentiable functions, scaling. These mathematical concepts, combined with the physics of fractals, a new form "bridges" is quite unexpected, not only between the related disciplines, which often leads to effective methods of solving problems, sometimes intractable at this level of development of the classical scientific fields.

Basically, fractals and fractional operators are not possible without the other [3]. Fractional Calculus has a rich and in some cases even dramatic story. The first recorded attempt in history to discuss such ideas contained in his correspondence with Leibniz and Bernoulli G. L' Hospital. It should be noted that great importance was the work of corresponding member of the St. Petersburg Academy of Sciences AV Letnikova (1 (13) .01.1837 - 27.02. (10.03) .1888), who during his 20 years of scientific activity has developed a complete theory of differentiation with an arbitrary pointer. The equations with fractional derivatives describe non-Markov processes with memory. That they are in demand today, both in theory and in practice.

Relatively radar. Radar since its inception has come a long and difficult path of development. Radar - one of the most complex devices, created at the dawn of

Radio Electronics [1-2], and it stimulated the development and creation of important devices that are extremely widely used today. Radar and to this day is one of the most important tools and is used by all countries of the world. Today, work to improve radars and technology is ongoing, and it seems to never end. Advances in radar technique was associated mainly with the use of the statistical theory of signal detection and evaluation of their parameters on the background noise or interference. The basis of this theory is based on the assumptions of the theory of statistical-call solutions and other sections of classical mathematics. The problem of detection of the object is reduced to detect the signal emitted or re-emitted these sites, that on the background of various kinds of random noise and interference. At the same time the problem of optimal-term processing of radar signals are focused specialists. In the classical theory it is generally accepted that the interference based on the first central limit theorem describes a Gaussian Markov process.

It is now abundantly clear that the application of the ideas of scale invariance - "scaling" in conjunction with the theory of sets, the theory of fractional size alia, general topology, geometric measure theory and the theory of dynamical systems offer great potential and new perspectives in the treatment of the set-multidimensional signals and in related scientific and technical fields. In other words, a full description of the processes of modern signal processing and fields is not possible with the aid of classical mathematics formulas [2]. When fractal scaling approach proposed and developed by the author for 35 years, description and signal processing fields and carried out exclusively in the space of fractional steps with the use of the scaling-eat hypotheses and distributions with heavy tails.

It will focus on principles rather than details, which are detailed in [2]. To understand the sufficient knowledge of the basic concepts of general set theory, dimension theory, and probability theory.

2. Measure and Hausdorff dimension

The main characteristic of fractals is a non-integer value of their dimension. The development dimension theory began with the work of Poincaré, Lebesgue, Brouwer, Urysohn and Menger. In various areas of mathematics there are sets in one sense or another is negligibly small and indistinguishable in the sense of Lebesgue measure. To distinguish between these sets with pathologically complicated topological structure necessary to attract non-traditional characteristics of smallness, for example, capacity, potential measures and the Hausdorff dimension, etc. Most rewarding was the use of fractional dimension Hausdorff closely related to the concept of entropy, fractals and strange attractors in the theory of dynamical systems [2, 3].

The concept measures and the Hausdorff dimension - one of those mandatory terms, which do not derive organically, no researcher cannot become an expert in fractals and deterministic chaos. This fractional dimension is determined p - action-term measure with any real positive number p, which introduced Hausdorff in 1919 year.

Hausdorff dimension is determined by the Hausdorff -measure sets in the form of

$$mes_{H,\alpha} = \lim_{\varepsilon \to 0} \inf_{\Gamma(A)} \sum [d(U)]^{\alpha} \tag{1}$$

where the lower bound inf is taken over a finite or countable set *A G* coverages balls *U* diameters $d(U) < \varepsilon$. The dimension is defined as a number that me-ra (1) is zero, and when - infinity.

In general, the concept of a measure is not associated with a metric or a topology. However Hausdorff measure can be constructed in an arbitrary metric space on the basis of its OS-metric, and she Hausdorff dimension associated with the topological dimension.

$$f(\lambda x, \lambda y, ..., \lambda u) = \lambda^{\alpha} f(x, y, ..., u), \tag{2}$$

where - the degree of homogeneity or uniformity measurement function.

For example, a power function f (t) = b satisfies the homogeneity (2) or scaling:

$$f(t) = \lambda^{\alpha} f(t) \tag{3}$$

for all positive values of the scale factor. Naturally, the grade-valued function, as well as many other features that meet NIJ-scaling relation (3), are not fractal curves. However, many types of fractals (scale-invariant but fractals) have scaling symmetry. Homogeneous functions possess many properties which make them very attractive for the approximate description of real-toms processes and objects.

There are: (1) - positively homogeneous functions for which equality (2) holds only for positive λ (λ> 0), and (2) - absolutely homogeneous functions, for which the following equality:

$$f(\lambda x) = |\lambda|^{\alpha} f(x). \quad (4)$$

Because of the differential properties of homogeneous functions Euler's lemma, we note:

"Homogeneous functions proportional to the scalar product of their gradients to vector-that its variables with a coefficient equal to the degree of homogeneity:

$$\vec{x} \cdot \nabla f(\vec{x}) = \alpha f(\vec{x})". \quad (5)$$

Homogeneous functions play an important role in the description of the thermodynamics of phase transitions in the description of the statistical properties of the percolation in the turbulence in the modern renormalization group theory of critical phenomena, etc. Very often, the universality of a single parcel of fluctuating systems by scaling estimates can be made far-reaching conclusions.

In [13] introduced a special normalized power function

$$f_{\lambda}(t) = \frac{1}{\Gamma(\lambda+1)} t^{\lambda}, \quad t > 0, \quad (6)$$

It called standard power function.

These functions are self-similar (they do not have the characteristic scale, which naturally leads to the concept of fractals); they possess the semigroup property; the zeros of the gamma function G(λ+1) defined as a generalized function, expressed in terms of δ-function and its derivatives $\delta^{(\lambda)}(t)$; Their Laplace transformation also belong to the family of exponential functions with a constant factor; in contrast to the exponential functions which have the property of invariance to within a constant factor, power functions do not possess such a property (here, a property of memory); applicable to them Tauberian theorems that allow the behavior of the Laplace transform in the field of scratch unambiguously determine the asymptotic behavior of these functions $t \to \infty$ in (these theorems are true and provided when the zero and infinity are reversed).

4. Power laws

Among the self-similarity of the material world is very well represented [2, 3]. The mathematical expression of self-similarity is the extent of the law. This law are subject to increase in size as the objects, such as the city and divided into separate fragments, such as stones. The only indispensable condition for the implementation of the power of self-similar law: the lack of this type of objects internal scale. Indeed, there are no real towns with a population of less than 1 or greater than 10^9. Similarly, the size of the stone cannot be smaller molecules or more of the continent. Thus, if the self-similarity and terrestrial, but only in limited areas. The fact that uniform power laws have no natural internal scale leads to another phenomenon - *scaling* or scale invariance.

It can be said that power laws with integer or fractional exponents are the generators of self-similarity. As noted in: "self-similarity in the end, anyway, we have an integer index or not. Often, a fractional index contains important key to solving intricate puzzles. "In mathematics, on the basis of power functions built fractional calculus, introduced the concept of poles and created the theory of residues, to construct a theory of asymptotic expansions, introduced stable distributions.

The cognitive value of probability theory is revealed only limit theorems. Interest in classical studies was limited to the clarification of the conditions of convergence of functions of distributions of sums of independent random variables to a Gaussian law. Therefore, the classical theory of probability studies, only one Limit distributions - Gaussian. In probability theory, in parallel with the completion of the classical perspective the question arose as to which laws, in addition to Gaussian, can be limiting for sums of independent random variables. It turned out that the class of limit laws is not limited to a Gaussian law [2].

The basis of modern probability theory are limit theorems on the convergence of distributions of sums of independent random variables to a so-called stable distributions: Gaussian and non-Gaussian. The first is based on the central limit theorem, and the second (non-Gaussian) - to limit theorem proved BV Gnedenko (1939) and W. Doeblin (1940).

In this case, the limit theorem imposes restrictions on the form of non-Gaussian distributions. Namely: to $F(x)$ distribution law belonged to the domain of attraction of a stable law with characteristic exponent α ($0 < \alpha < 2$), non-Gaussian, it is necessary and sufficient that

1) $$\frac{F(-x)}{1-F(x)} \to \frac{c_1}{c_2} \quad \text{at } x \to \infty, \tag{7}$$

2) for each continuous $k > 0$

$$\frac{1-F(x)+F(-x)}{1-F(kx)+F(-kx)} \to k^{\alpha} \quad \text{at } x \to \infty, \tag{8}$$

where $c_1 \geq 0$, $c_2 \geq 0$, $c_1 + c_2 > 0$, $0 < \alpha < 2$.

To prove (7) and (8) it is necessary and sufficient that for some choice of constants B_n , the following conditions:

$$nF(B_n x) \to \frac{c_1}{|x|^{\alpha}} \qquad (x < 0),$$

$$n[1 - F(B_n x)] \to \frac{c_2}{x^{\alpha}} \qquad (x > 0), \qquad (9)$$

$$\lim_{\varepsilon\to 0}\overline{\lim_{n\to\infty}}\, n\left\{\int_{|x|<\varepsilon} x^2 dF(B_n x) - \left[\int_{|x|<\varepsilon} x dF(B_n x)\right]^2\right\} = 0 .$$

The smaller the value α, the longer the tail of the distribution, and the more it differs substantially from-Gaussian. When 1<α<2 stable laws have expectation; 0<$\alpha \le$1 stable laws have no dispersions nor expectation. Condition (7) - (9) is determined by the so-called Gaussian statistics.

Non-Normal distribution, as well as non-differentiable functions themselves fractals are often much more accurately describe the temporal and spatial natural processes.

5. On the concept of "fractal" in radar

In general, the radar image (RLI) can always be represented as a set of elements X_k, the values of which are proportional to the effective area of the cross section (RCS) k-element resolution radar (RLS) [2]. Fig. 1,*a*, and shows a radar image area obtained at a wavelength of $\lambda = 8{,}6$ mm from the helicopter. Fig. 1,*б* shows radar images of the same terrain sector received radar wavelength of $\lambda \approx 30$ sm. Both images are two-dimensional gray level proportional to the EPR.

Suppose that the radar image is constructed for each surface (Fig. 1c) with the height h, also proportional to the level of gray. Suppose you want to measure the area of the resulting surface. On the RLE corresponding to $\lambda \approx 30$ cm, area received less than RLE $\lambda = 8{,}6$ mm due to the fact, that with decreasing wavelength distinguish more details area.

Probing electromagnetic wave in this case is some "of meter" ruler. At the same time with decreasing wavelength starts to affect more and more the fine structure of space - time signals or fields.

If we now have a radar image obtained in more shortwave RLE range, its area will be more, etc. By reducing the wavelength λ, increasing the value we will get space. Then the question arises: what is actually the surface area from which

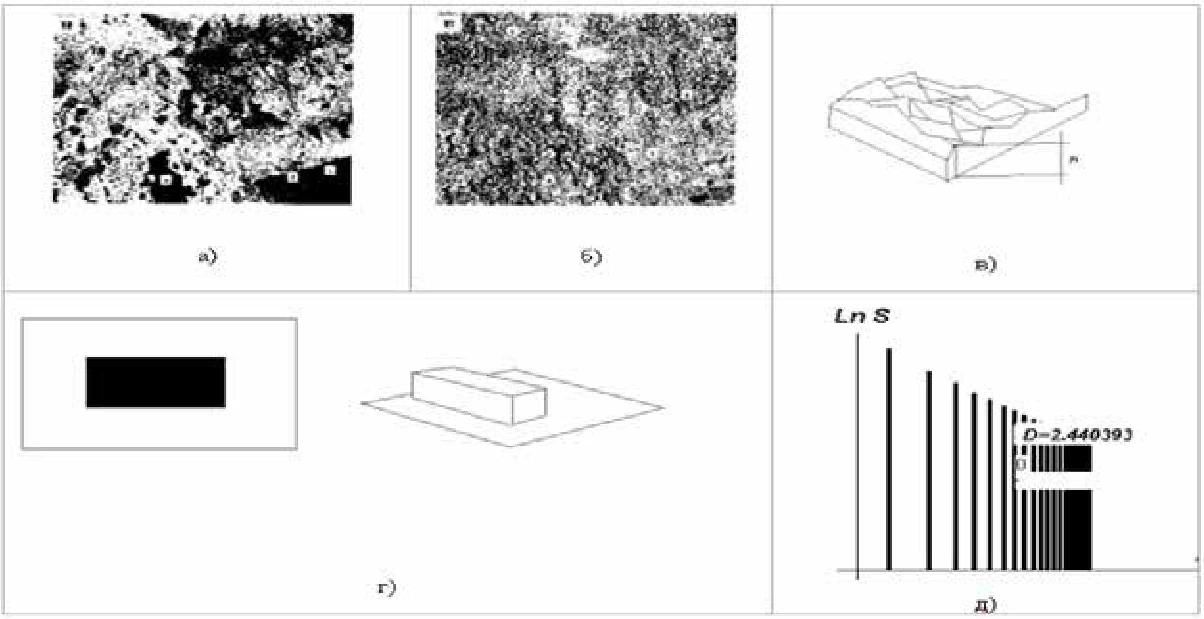

Fig. 1. Examples to explain the essence of the fractal processing (a-d), and fractal spatial signature (d)

obtained RLE? If the surface is covered with simple objects, such as a rectangular elevation (Figure 1, d), and the dimensions of the elevation is much larger than the wavelength, the area of radar images of objects in the short and long waves will be about the same. Then the question could be answered by calculating the number of bins that cover the object. Surface area S in this case would be equal to:

$$S \equiv S(\lambda) = N(\lambda)\delta(\lambda), \qquad (10)$$

where $\delta(\lambda)$ - the area of the element permits RLS; $N(\lambda)$ - the number of bins, required to cover the object; λ - length radar waves RLS. As already noted, for a simple object (Figure 1, d) the value $S(\lambda) = const$.

For RLS in Fig. 1,*a* and 1,*б* can build a relationship $S(\lambda) = f(\lambda)$, and assuming that $\delta(\lambda) = K(\lambda)$, where K - a known function, then build a relationship $S(\lambda) = f(\delta)$. It turns out that the measured surface area S is perfectly described by the formula

$$S(\lambda) = k\lambda^{-D}. \qquad (11)$$

Then, with a simple operation logarithms, we can calculate the parameter D. Addiction $\log S(\lambda) = f(\log \delta)$, defining a fractal signature D (t, f,) RLE, shown in Figure 1, etc. It characterizes the spatial fractal cepstrum image (this concept was introduced by the author in the early 90-ies. The XX-th century). Fractional option *D* $\equiv \dim_H A$ is the dimension of Hausdorff - Besicovitch or fractal dimension [2, 3]. For

RLE objects with simple geometric-sky view (rectangles, circles, smooth curves), this dimension is equal to the topological, those. is equal to the value of 2 for the two-dimensional RLE, and is determined by the angular coefficient of straight lines (11) in double logarithmic coordinates. However, the value of D for most images of real sheets and weather patterns is larger than the topological dimension $D_0 = 2$, underlining the complexity and randomness.

6. Texture and fractal invariants and measures radio physics and radar

Radar observations, together with objects and propagation environment forms the space-time radar sensing channel. When radar probing the useful signal from the target is part of the wave field created by all reflective elements of the observed fragments surrounding the purpose of the background, so in practice the signals from these elements form the interference component. To create a radio system of automatic recognition of the actual non-uniform images of landscapes it is advisable to use the concept of texture [2, 3]. Texture describes the spatial properties of portions of an image the Earth's surface with a locally uniform statistical characteristics. Detection and identification of targets occurs when the target obscures the background portion, changing the texture of the integral parameters.

Many natural objects, such as soil, vegetation, clouds, etc. exhibit fractal properties in some extent [2, 3]. Currently, analysis of natural textures undergone significant changes due to the use of metrics borrowed in fractal geometry. After texture concept of fractals was introduced, ie, signs, the main on the theory of fractional steps for a fundamentally different approach to solving the problems of modern radar.

The fractal dimension D or her signature D (t, f,) in different parts of the Images-reflection surface is a measure of texture, ie, the spatial correlation properties of the scattering of radio waves, from the respective surface areas. In already distant author of the initial stages of the first it was subjected to a detailed study of the concept of texture at the Earth's surface and the radar facilities on their background. In the future, special attention was paid to the development of methods for the detection of texture objects on the Earth's surface background at low signal / background.

7. Fractal signal and image processing intensive interference and noise

When fractal approach, as mentioned above, naturally focus on the description and signal processing radio physical (fields) in a space exclusively measures using fractional scaling hypothesis distribution and universal-divisions with a "heavy-tailed" distributions or stable. The proposed A.A. Potapov classification of fractals was in December 2005 in the United States personally approved by B. Mandelbrot and is shown in Fig. 2, which describes their properties, provided that D0 - topological embedding space dimension.

Developed by the author with his disciples and textural fractal digital methods (Figure 3). [2, 3] allow us to partially overcome the a priori uncertainty in radar problems with using the sample geometry or topology - a one-dimensional or multidimensional.

At the same time become important topological features of the sample, not the average realization of having a different character.

Sample topology. clustering Images

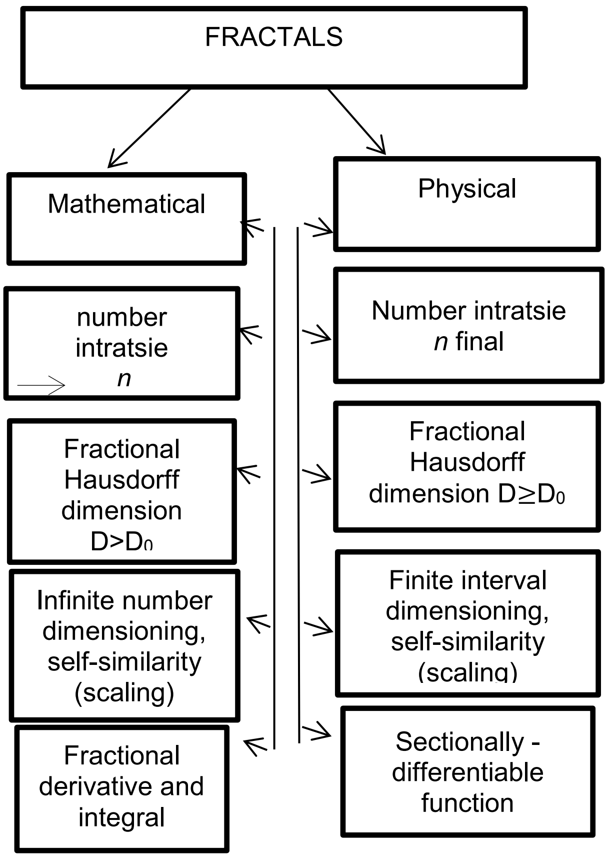

Fig. 2. Author ∞classification fractal sets and signatures

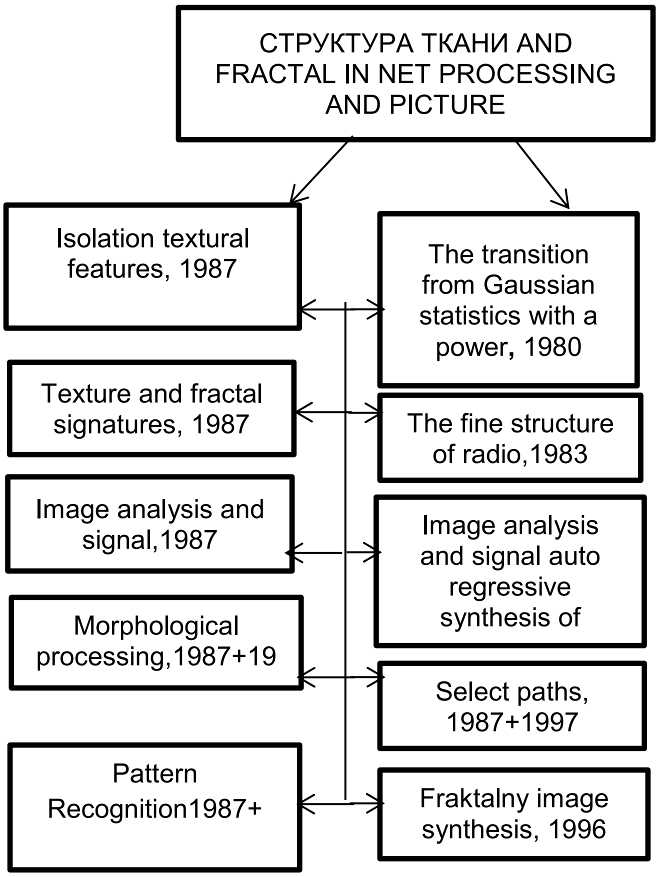

Fig. 3. Texture and fractal methods of processing low-contrast images and ultra-intense signals in the premises-huh

8. Fractal object detection in images taken by SAR and UAVs

Synthetic Aperture Radar (SAR), and unmanned aerial vehicles (UAVs) are widely used in practice, study the Earth's surface. Such radars are a key element of modern and advanced SAR information - technology. The main advantages of data capture systems are simple tastes to the light conditions of the study area and insensitivity to weather conditions in the area of shooting with high spatial resolution. The following will examine the potential of fractal data processing for solving the problems of fractal automatic detection of low-contrast objects on radar data obtained in space and aviation systems.

Initial data for digital fractal processing radar images obtained by satellite synthetic aperture radar (SAR) PALSAR L-band (Japan). PALSAR - the cosmic X-ray diffraction at a wavelength of 23 cm, with a spatial resolution of about 7 m, designed by the Japanese agency JAXA successfully tested on op-bit from 2006 to 2011. Scope PALSAR SAR data includes ice reconnaissance, oceanography, cartography, geology, hydrology, forest research, the decision of problems of agriculture and environmental protection.

As an example, Fig. 4 shows a radar image of the delta of the river Selenga in Trans-Baikal received August 7, 2006 in the high-resolution mode FBS in a coherent horizontal polarization. In the area of the shooting of approximately 60 to 50 km includes forested mountainous area Khamar-Daban (bottom, handed a lighter tone to the character-term "crumpled" structure), flat area of the Selenga River delta (in the middle of the upper part of the picture, transferred to more dark tones) and the black area on the image in the upper left corner - smooth water surface of Lake Baikal. In plain view of the image-HN line structures - the boundaries of agricultural fields, as well as clusters of bright objects - highly reflective elements of buildings and other structures within the settlements. Long meandering dark lines on the plain - numerous branches of the Selenga River.

Conclusion

Fractals were fine before a powerful amalgam of science Island end of the XX century. In the present situation the intellectual debacle suffered attempts to belittle their significance and rely only on classical knowledge.

The purpose of this article does not include a detailed analysis of all the work that successfully could be used to separate monograph. Nevertheless, the general knowledge with research in this area should significantly help a wide range of experts and more accurate way to determine the practical application of the theory of fractals to the decision-fishing radio physics and radar applications.

When the fractal approach is natural to focus on the description and processing of radio physical signals (fields), exclusively in the space fractional-term measures with the use of the scaling hypothesis and the universal distributions "heavy tails" or stable distributions.

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