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THEORY OF CORPUSCULAR RADIO COMMUNICATION SYSTEM

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Keywords: radio communication, particles, corpusculum, radio emissions.

Abstract. When receiving radio signals from remote space sources of radio emissions by means of reflector systems of radio telescopes and radio receivers, there is a task to identify the transfer function of reflector systems in the conversion circuit of space sources of radio emissions – reflector systems – radio receivers – radio signals. To solve this problem, physical and mathematical models of a radio transmission system are required. In this article, we made an attempt to get closer to understanding the physics of processes associated with radio emissions in order to simplify their cybernetic interpretation. As a result, it was possible to present the cybernetic model of the radio transmission system in the form of a pulsed automatic control system and apply standard tools for its analysis and synthesis. For this, the model of radio emissions is presented in the form of streams of corpuscles – neutral (uncharged) radio particles. The radiation sources that left the radiation source are not connected in any way with the electromagnetic field and constitute the totality of material bodies radio particles with constant mass, moving at the speed of light plus the speed of the radiation source and are an independent type of matter. Radio particles, interacting with a substance, induces oscillatory processes in it, similar to the serial shock action of many solid bodies of small mass on a body of large mass. Radio particles knock out electrons with a charge from the substance, and they, in turn, cause processes in the substance, forming signals in the form of voltage, current, electromagnetic field or other physical phenomena that can be measured and estimates of the parameters of the received radio emissions can be obtained. It is believed that all wave processes and effects inherent in the electrodynamic model (interference, diffraction) occur in a substance subjected to radio emission.

ТЕОРИЯ КОРПУСКУЛЯРНОЙ РАДИОСВЯЗИ

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Аннотация. При приеме радиосигналов от удаленных космических источников радиоизлучения с помощью отражательных систем радиотелескопов и радиоприемников возникает задача выявления передаточной функции отражательных систем в схеме преобразования космических источников радиоизлучения – отражательных систем – радиоприемников – радиосигналов. Для решения этой задачи необходимы физико-математические модели системы радиопередачи. В данной статье мы предприняли попытку приблизиться к пониманию физики процессов, связанных с радиоизлучением с целью упрощения их кибернетической интерпретации. В результате появилась возможность представить кибернетическую модель системы радиопередачи в виде импульсной системы автоматического управления и применить стандартные средства ее анализа и синтеза. Для этого модель радиоизлучения представлена в виде потоков корпускул – нейтральных (незаряженных) радиочастиц. Источники излучения никак не связаны с электромагнитным полем и представляют собой совокупность материальных тел радиочастиц с постоянной массой, движущихся со скоростью света плюс скорость источника излучения, и являющются самостоятельным видом материи. Радиочастицы, взаимодействуя с веществом, вызывают в нем колебательные процессы, подобные последовательному ударному воздействию многих твердых тел малой массы на тело большой массы. Радиочастицы выбивают электроны с зарядом из вещества, а те, в свою очередь, вызывают процессы в веществе, формируя сигналы в виде напряжения, тока, электромагнитного поля или других физических явлений, которые можно измерить и получить оценки параметров принимаемых радиоизлучений. Считается, что все волновые процессы и эффекты, присущие электродинамической модели (интерференция, дифракция), происходят в веществе, подвергнутом радиоизлучению.

Introduction

The absence of clear and simple models describing the effect of deformations of the design elements of large radio telescopes (RT) reflector systems on the time and frequency characteristics of received radio signals caused the development of new radio emission (RE) models and radio communication systems based on different physical principles than previously used. First of all, it concerns the physical nature of RE. As a result of intra-atomic processes occurring in a body or from external influences, its energy can be converted to RE, arising from changes in the energy states of a large number of atoms and ions that make up the radiating body.

The answer to the question about the physical nature of the RE, whether the RE is an electromagnetic wave or a stream of radio particles (corpuscles), cannot be convincing without considering the interaction of the RE with a substance (test body) [Dergobuzov].

“The test body is one of the basic concepts of classical field theory, a body that has such a small charge in the case of an electromagnetic field or such a small mass when studying a gravitational field that it neglects the external field negligibly. Additionally, it is assumed that the size of the test body is negligible compared to the characteristic distances for a particular task, that is, taken as a point. A theoretical consideration of fields is an abstraction” [Camilleri and Schlosshauer, 2015].

But the electromagnetic field is generated by the inherent to electrons, and there are no electrons in the RE. According to Maxwell’s theory of electrodynamics, REs are a specific continuous medium propagating in space at the speed of light. According to this theory, radiation sources emitted by a single source can interact in a vacuum, or other medium, with radiation sources emitted by other sources without the aid of charges and matter. And the results of this interaction, such as interference, diffraction, polarization, can be registered by a “test body” or by any element sensitive to this RE. The electromagnetic field of stationary or uniformly moving charged particles is inextricably linked with these particles. With the accelerated movement of charged particles, the electromagnetic field “breaks away” from them and exists independently in the form of electromagnetic waves, not disappearing with the removal of the source (for example, radio waves do not disappear even if there is no current in the antenna that radiated them) [Feynman, 2006].

But the electromagnetic field is created by charged bodies, the potential of which decreases in proportion to the square of the distance, and the RE in the form of a flux of radio particles (RP) propagates to infinity. Consequently, electrodynamics describes the processes of short-range actions of charged bodies creating an electromagnetic field, and radio communication processes are carried out far beyond their interaction. This means that radio communication at remote distances is realized either by the specific electromagnetic environment of Maxwell or by the flux of RP, which are no longer associated with the charges and the field created by them. Therefore, the processes of radio emission and radio reception should be considered separately from the fields created by charged bodies [Maxwell and Clerk, 1865].

Let us list the main physical laws that describe the behavior of an electromagnetic field and its interaction with charged bodies in a local zone, which takes into account its decreasing depending on the distance from these bodies. The listed laws are not fundamentally connected with the processes of radiation, they are experimentally substantiated and are widely used in practice.

– Gaussian law for the electric field, which determines the generation of an electrostatic field by charges.

– The law of closure of magnetic field lines; it is the Gauss law for a magnetic field.

The Faraday induction law, which determines the generation of an electric field by an alternating magnetic field.

– An expression for the Lorentz force, which determines the force acting on a charge that is in an electromagnetic field.

– Joule-Lenz law, which determines the amount of heat loss in a conducting medium with a finite conductivity, in the presence of an electric field in it.

– Coulomb's law – in electrostatics – the law that determines the electric field (intensity and/or potential) of a point charge; the Coulomb's law is also called a similar formula that determines the electrostatic interaction (force or potential energy) of two point charges.

– The Biot–Savart law – in magnetostatics – the basic law describing the generation of a magnetic field by a current (similar in its role in magnetostatics to the Coulomb law in electrostatics).

– Ampere's law, which determines the force acting on the elementary current, placed in a magnetic field.

– The law of conservation of charge – the algebraic sum of the charges of an electrically closed system is preserved.

For the physical interpretation of the effects testifying to the wave nature of light, a theory of RE transformation on the border of two media into processes of a different physical nature inside the substance of sensitive elements was created [Browne, 2013].

The electromagnetic theory of light made it possible to explain many optical phenomena, such as interference, diffraction, polarization, etc. However, this theory did not complete the understanding of the nature of light. Already at the beginning of the 20th century, it became clear that this theory was insufficient to interpret phenomena of atomic scale arising from the interaction of light with matter. To explain such phenomena as blackbody radiation, the photoelectric effect, the Compton effect, etc., the introduction of quantum concepts was required. Science has returned to the idea of corpuscles – light quanta. Moreover, without a test body, it has not yet been proved that these effects, indicating the wave nature of light, occur in space, and not in the substance itself, with which the RE interact.

REs take the greatest simplicity and clear physical meaning when they are represented in the form of a stream of particles (fluence) [https://dic.academic.ru/dic.nsf/ruwiki/1167669].

Fluence – a physical quantity, time integral of the density of a stream of particles or energy. Sometimes the synonymous term “carry” is used.

In the case of a particle ray, the fluence of particles is the ratio of the number of particles that crossed an elementary area perpendicular to the ray over a given period of time to the area of this area. In the case of a diffuse particle field, the fluence at a point is defined as the ratio of the number of particles that have penetrated the elementary sphere with its center at this point to the cross–sectional area of this sphere.

REs that have left the radiation source are in no way connected with the electromagnetic field and constitute the totality of material bodies (RP) having a constant mass, moving at the speed of light plus the speed of the radiation source and are an independent type of matter [Jia et al., 2014]–[Jabs, 2017].

In the middle of the 20th century, quantum electrodynamics was created – one of the most accurate physical theories, which serves as the foundation and model for all modern theoretical concepts in particle physics.

In our opinion, the RE wave properties manifest themselves only in the substance with which it interacts, as in a medium more dense than the RP (radio particle) flux. It is believed that RP are neutral, have no charge, have a constant mass. Due to the small size of the RP, the probability of their collisions is very small, so it is considered that the RP does not interact with each other. The RP flux, interacting with a substance, causes oscillatory processes in it, similar to the serial impact of many solid bodies of small mass on a large mass body. An elementary process of RP interaction with a substance is represented as a model of an oscillator (substance), which is affected by a pulsed signal of a variable duty cycle.

The theoretical basis for the interaction of RP with a substance is the formula $E = hv$, linking the kinetic energy E, n of RP with a total mass $m = m_0 n$, and energy hv, transmitted to an element (pixel) of a substance, proportional to the frequency of irradiation of this pixel $v = n/\tau$, where: m_0 mass of one RP, h – coefficient of proportionality (Planck’s constant), τ – the time it takes for a pixel to drop n RP.

For a mechanical system consisting of one RP, the kinetic energy is $E_0 = m_0 c^2 / 2$, then $m_0 = 2h / c^2$, where c is the speed of light.

Considering that the speed of the RP relative to the source of the RE is constant and equal to the speed of light, we can conclude that the mass of the RP is constant. However, the speed of the RP relative to the receiver may differ from the speed of light if the relative speed of the source and receiver differs from zero. This means that the energy transmitted by the RP pixel may be more or less than E_0.

The physical model of RE interaction with a substance corresponds to the notion that, in a substance on which the RE flux falls, oscillatory processes of temporal changes occur: temperature, RP absorption, secondary RP emission, electron knocking out and other effects, confirmed experimentally.

The simplest mathematical interpretation of the process of interaction between an RE and a substance is an oscillator (oscillating element) model that is affected by a signal as a sequence of pulses, similar to the signal of temporal pulse modulation (TPM), when, in accordance with the RP distribution along the direction of propagation of the RE, the pulses shift along the time axis.

The impact of a separate RP on a substance on the time axis corresponds to a pulse. The pulse width corresponds to the time of impact interaction of RP with matter. Amplitude corresponds to the power of interaction, and the area of the pulse is the kinetic energy of the RP. The period is determined by the distance λ between adjacent RP, i.e. $T = \lambda/c$. At the output of the oscillator, depending on the physical properties of substances, a signal is generated in the form of voltage, current or other physical processes, which can be measured and receive estimates of the parameters of the received PE.

The flow structure of the RE of a point source in a given direction is represented as a sequence of RP (ray) moving one after the other at the speed of light at a distance of step $\lambda = c/v$. According to the terminology adopted in the RE wave theory, λ coincides with the wavelength. Under the wavefront is the geometric location of the points in the form of a sphere or a plane in which the RP are located. The flow of RE in the transverse direction is a ray of rays, the density of which determines the intensity of the RE. Therefore, the statistical concept of the longitudinal and transverse spectral densities of the particle distribution along and across the flow, obeying the statistical laws of distribution, can be applied to the RE. The spectral density of the particle distribution is determined by the properties of the RE source and is of primary interest when identifying spectral parameters and polarizing this source [Browne, 2013], [Berger et al., 2016]–[She and Capasso, 2016].

Rays in a stream can be coherent, i.e. mutual consistency of the location of the RP in each ray. An important characteristic of RE is its polarization. In electrodynamics, the polarization of particles is a characteristic of the state of particles, due to the presence of their own angular momentum – spin. The concept of spin in the exchange interaction of identical particles is taken into account in quantum mechanics and is a purely quantum effect, which disappears when passing to the limit to classical mechanics.

Scientists have discovered particles with spin 0, 1/2, 1, 3/2 and 2. In order to present visually, albeit in a simplified way, the spin as a property of an object, consider the following example.

Let the object have a spin of 1. Then such object will return to its original position when rotated 360 degrees. On the plane, this object can be a pencil, which, after turning 360 degrees, will be in the initial position. In the case of zero spin, with any rotation of the object, it will always look the same, for example, a one–color ball.

For spin 1/2 one needs an item that retains its shape when you turn 180 degrees. It can be all the same pencil, only symmetrically ground on both sides. A spin of 2 will require shape retention when rotated 720 degrees, and 3/2 - 540 degrees [Lisboa and Piqueira, 2016].

In our theory, the polarization of the radio particle itself is absent due to its small linear dimensions. It characterizes not the particles, but the structure of the flow in cross section and determines the degree of its symmetry (or asymmetry) in space. We have assumed that the RE is called polarized if the location of the RP in the cross section of the flow is uneven and there is some preferential direction in which the density of particles in this section per unit area is greater than in other directions. This direction is called the polarization direction. Obviously, polarized REs possess the property that allows one to determine the spectral density of the distribution of particles across the flow in different directions. This is carried out as a result of the interaction of the RE with a certain substance, endowed with such quality or technical device specifically designed to determine the structure of the cross section of the RE.

The effect of RP on a substance (target, test body) is a shock, and the interaction time is much less than the RP response period, therefore, for a single ray, the mathematical model of the process of converting RE into a radio signal is presented in the form of passing through a frequency (band-pass) filter of the delta–pulse sequence (Dirac function). Each RP on the time axis corresponds to a delta pulse with an infinite instantaneous amplitude, and an energy numerically equal to E_0. Influencing an oscillator, this impulse triggers a response at its output in the form of a pulsed transient response. For a pulse sequence, its transient characteristics are added with the time shifts determined by the intervals (periods) of the RP following in the ray. In the general case, the intervals between the RP in the ray are randomly distributed according to a certain statistical model. The sum of the impulse responses at the oscillator output from a single ray forms a useful radio signal, except for noise. Each ray corresponds to a separate oscillator, from the output of which a separate radio signal is taken, and a combination of radio signals forms, conditionally speaking, a “radio image” of an RE source (images on multi–element semiconductor CCD matrices).

The charge–coupled devices that form the basis of modern television technology use the characteristics of “quantum efficiency and quantum efficiency of the CCD array”. The quantum yield is the ratio of the number of photoelectrons formed in or near the semiconductor as a result of the photoelectric effect to the number of photons that fell on this semiconductor. Quantum efficiency is the quantum output of the light-recording part of the receiver multiplied by the photoelectron charge conversion factor into the registered useful signal [Neizvestny and Nikulin, 2019]. CCDs respond to light with wavelengths from a few angstroms (gamma and X-ray radiation sources) to 1100 nm (IR–RE). This huge range is much larger than the spectral range of any other detector known to date.

Such characteristics can be introduced to assess the effectiveness of the interaction of the RE with a substance not only in the operating range of CCD matrices, but also in the radio band after replacing photons at RP and corresponding renormalization of physical quantities.

The main task of the system of reception of radio emissions (RE) is to determine the estimates of their characteristics and parameters. Obtaining such estimates depends on the selected models, methods and tools of the RE observation process. The main elements involved in the observation, and for which a physical and mathematical description is required in explicit form, are:

the received RE flow (RFRE),

the reflector system (RES) of the antenna device (radio telescope) RT,

the guidance system of RT,

sensitive of solid–state multi–pixel element (SE) of the receiving device, which converts the RFRE into a signal. It determines the required estimates by means of a radio receiver (RR).

RES is designed to focus the ray on the plane of the sensitive element to increase their density. In an ideal SE scheme, the rays converge at one point. Deformations of the RT design lead to defocusing, i.e. to the deviation of the lengths of the optical paths of the rays from the ideal. As a result, the focal point on the plane of the sensitive element shifts and “erodes”.

The set of points of intersection of the rays with the SE plane form a region (spot), the position and diameter of which serve as estimates of the effectiveness of the focusing properties of the RES.

At the points of intersection of the rays with the plane of the SE, the substance of which it consists is subjected to a pulsed RP effect with a pulse repetition rate determined by the distances between the RP along the ray.

The difference in the lengths of the optical paths of the rays determines the delay in the arrival of pulses and manifests itself in the phase displacements of the pulsed transient characteristics of the signals taken from the SE and influences their resulting parameters and characteristics.

The proposed approach to calculating estimates of the effect of deformations of the RT structure on the parameters and characteristics of the RFRE makes it possible, by measuring these deformations, to eliminate or reduce their harmful effect.

In Fig. 1 a mathematical model of the RE transmission and reception system is given over a communication channel, which is conventionally one ray. A pulse generator simulates the RE of a sequence of pulses of constant amplitude with a given carrier frequency. The Variable Transport Delay block performs time–pulse modulation of these pulses by the time delay of the informational useful signal fed to the control input. The other block Variable Transport Delay1 carries out a delay of pulses by a constant value proportional to the difference in the lengths of the optical paths of the rays, counted from the front of the RE flow to the points of intersection of the rays of this flow with the surface of the sensitive element of the receiver. All rays have the same structure. The useful signals from each ray after their oscillators are added together, forming the total useful signal [Dubarenko, 2016].

The described approach to estimating the effect of the displacements of the elements of the radio telescope’s reflector system on the characteristics of the received RE was applied to assess the effectiveness of the threereflector RT system with a main reflector diameter of 70 meters. The radiation patterns of the RES RT and the diagrams of the dependence of its transmission coefficients on the displacement of the counter reflector and the main reflector were calculated. The estimates were determined by the time and frequency characteristics of the useful signal.

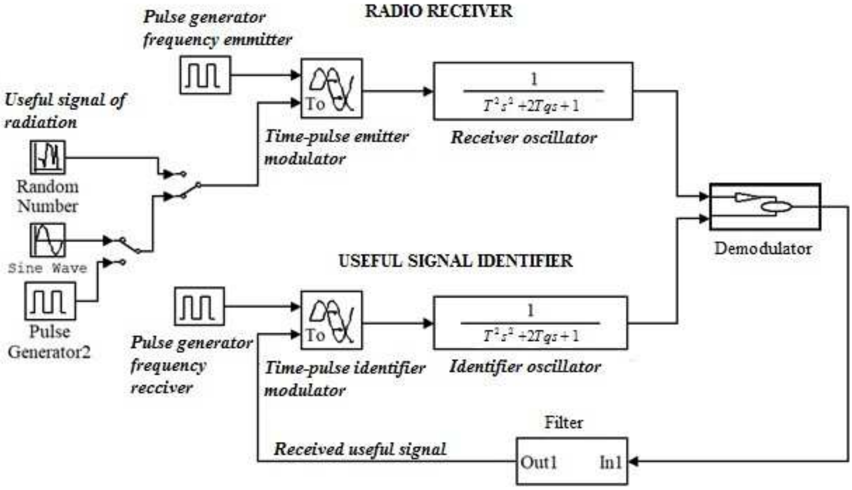


Fig. 1. Simulink block-diagram of the corpuscular model of reception and transmission of radio emissions on one ray

The adoption of a corpuscular model, the basis of which are RP, which do not interact with each other, means the abandonment of the field theory of light and the interpretation of the physical effects associated with it, without the interaction of radioactive substances with matter. The corpuscle-wave dualism was invented in order to eliminate the contradictions associated with the manifestation of light wave properties, which were attributed to light without its influence with matter. In fact, all known effects of the wave properties of light can only be explained by means of a target, a test body, emission, etc. That is, an experiment with light without matter is impossible. Therefore, a point of view is legitimate, and accordingly, a model in which the wave properties are shown not by the radiation source, but by the substance when interacting with it. The expression “photon at a given frequency” loses its meaning, and in the formula $E = mc^2 = h\nu$, m should be understood as the total mass of RP emitted or received per unit time. Essentially, the photon is an RP tuple following each other at a distance $h = c/\nu$ [Muthukrishnan et al., 2008].

The stated interpretation of the processes of reception and transmission of radio emission does not violate the laws of energy conservation in the interaction of RP with matter, but simplifies the calculations of the frequency and time characteristics of radio signals. Significantly simplified are the calculations of estimates of the effect of deviations (or deformations) of structural elements of the antenna reflector systems on the indicated characteristics of useful signals, including on radiation patterns, spectra, instrumentation, etc.

The next step to substantiate the above approach is to conduct experimental studies and compare the results with the results obtained on electrodynamic models.

Obviously, objections of physicists, astrophysicists and astronomers in the form of references to the theory of elementary particles adopted by the scientific community will be against the stated theory of the corpuscular radio broadcasting system: “The standard model is a theoretical construct in elementary particle physics, describing the electromagnetic, weak, and strong interaction of all elementary particles. The standard model is not a theory of everything, because it does not describe dark matter, dark energy and does not include gravity. Experimental confirmation of the existence of intermediate vector bosons in the mid-80s completed the construction of the Standard Model and its adoption as the main one. The need for a slight expansion of the model arose in 2002 after the discovery of neutrino oscillations, and the confirmation of the existence of the Higgs boson in 2012 completed the experimental detection of the predicted Standard Model of elementary particles” (Fig. 2) [https://elementy.ru/LHC/HEP/ SM/beyondSM].

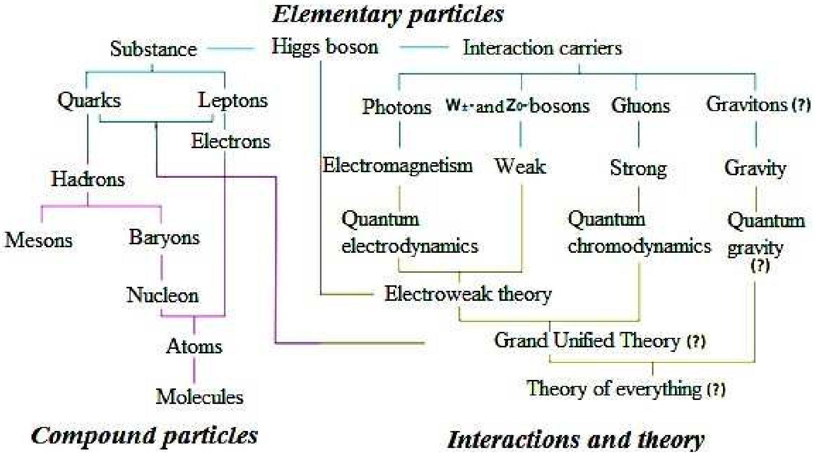


Fig. 2. Block diagram of elementary particles

At present, it is considered proven that a single field uniting all types of interaction can exist only at extremely high particle energies unattainable in modern accelerators. Such large energies particles could have only the very early stages of the Universe, which arose as a result of the so-called Big Bang. Cosmology – the science of the evolution of the universe – suggests that the Big Bang occurred 18 billion years ago. In the standard model of the evolution of the Universe, it is assumed that in the first period after the explosion the temperature could reach $10^{32}K$, and the particle energy $E = kT$ could reach $10^{19}GeV$. During this period, matter existed in the form of quarks and neutrinos, and all types of interactions were combined into a single force field. Gradually, as the universe expanded, the particle energy decreased, and the gravitational interaction first emerged from the single field of interactions (at particle energies $leq10^{19}GeV$), and then the strong interaction separated from the electroweak (at energy order $10^{14}GeV$). At energies of the order of $10^{3}GeV$, all four types of fundamental interactions turned out to be separated. Simultaneously with these processes, the formation of more complex forms of matter – nucleons, light nuclei, ions, atoms, etc. was going on. Cosmology in its model tries to trace the evolution of the Universe at different stages of its development from the Big Bang to the present day, based on the laws of elementary particle physics , as well as nuclear and atomic physics [Camilleri and Schlosshauer, 2015].

Calculation of the Difference Between the Long Optical Paths the Radio Emission Fluxes

The flux of radio emission (RF) will be considered as a combination of individual rays. Due to the large distances from the Earth to the space sources of radio emission (SSR), the incoming front can be considered flat, monochromatic; all the rays in such a RF are parallel to each other, and the intensity of the energy transferred by a RF per unit of time through a unit of area perpendicular to the direction of propagation obeys the laws of fluence [https://dic.academic.ru/dic.nsf/ruwiki/1167669]. In the case of a particle ray, the fluence of particles is the ratio of the number of particles *dN*, that intersect the elementary area *dS* erpendicular to the ray over a given period of time to the area of this area. In the case of a diffuse particle field, the fluence at a point is defined as the ratio of the number of particles that have penetrated into the elementary sphere with its center at this point and the cross-sectional area of this sphere $\Phi_N = dN/dS$.

The fluence of particles (particle flux density) is defined as the time derivative of the fluence accumulated over time t : $P = d\Phi_N/dt$.

Each point of the ray is associated with its own moving coordinate system, the origin of which is determined by the vector relative to the base stationary coordinate system (BCS) of the entire control system. The Z axis is oriented in the direction of the RF propagation, the X axis lies in the RF front parallel to the horizon line. The XYZ coordinate system is right.

When rays hit the reflecting surface, it is considered that the ray is completely, without loss, reflected from the interface between two media. The reflected ray lies in the reflection plane passing through the incident ray and the normal vector to the reflecting surface at the point of incidence. It is assumed that the Snell law is observed, according to which the angle between the normal and the incident ray is equal to the angle between the normal and the reflected ray. The front of the reflected RP is considered to be the locus of the points of the reflected rays with an equal length of optical paths from an arbitrarily chosen initial front along each individual ray.

In the millimeter range, with large sizes, the reflecting surfaces of the RES of the family of reflected rays are tightened almost to points or areas with small linear dimensions.

The main object of study of geometric optics is the ray. A ray is a geometric line along which the energy transmitted by radio emission propagates. Since the medium is homogeneous, the ray is a straight line.

All coordinate systems (CS) that are used in building the model are determined by rotating the BCS by the angles of the simplest rotations s β_i^0, θ_i^0, α_i^0, X-Y-Z sequence and the vector of parallel translation $\mathbf{r}_i^0$ with the coordinate column in the BCS $\mathbf{r}_i^{0,0} = (x_i^{0,0}, y_i^{0,0}, z_i^{0,0})^T$, where the superscript is the identifier of the original CS, and the superscript is the identifier of the new CS, obtained by transferring to this vector, the second superscript denotes the basis of the CS in which the coordinate column is defined.

The transition from CS with index *i* to BCS will be described by a rotation matrix:

$$\mathbf{c}_i^0\left(\beta_i^0,\theta_i^0,\alpha_i^0\right)=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos(\beta_i^0) & -\sin(\beta_i^0)\\ 0 & \sin(\beta_i^0) & \cos(\beta_i^0)\end{bmatrix}\times\begin{bmatrix}\cos(\beta_i^0) & 0 & \sin(\theta_i^0)\\ 0 & 1 & 0\\ -\sin(\theta_i^0) & 0 & \cos(\beta_i^0)\end{bmatrix}\times$$

$$\times\begin{bmatrix}\cos(\alpha_i^0) & -\sin(\alpha_i^0) & 0\\ \sin(\alpha_i^0) & \cos(\alpha_i^0) & 0\\ 0 & 0 & 1\end{bmatrix}.$$

The wavefront has a CS, which will be denoted FCS. In FCS, the direction of propagation of the front rays is parallel to the axis OZ_f and is set by the front guiding vector $\mathbf{e}_f$ with a coordinate column $\mathbf{e}_f^f=(0,0,1)^T$.

We introduce the CS of the incident ray (RCS), obtained by transferring the FCS to the vector of the beginning of the ray $\mathbf{r}_{br}^f$ with the coordinate column $\mathbf{r}_{br}^{f,f}$. The equation of the incident ray in the FCS is given by the equation:

$$\mathbf{R}_{in}^{br,f}=\mathbf{r}_{br}^{f,f}+\mu_{in}\mathbf{e}_f^f,$$

where $\mathbf{R}_{in}^{br,f}$ is vector coordinate column $\mathbf{R}_{in}^{br}$, specifying the position of the point lying on the incident ray; μ_{in} is a parameter characterizing the length of the ray.

The position of the FCS in the BCS is determined by the vector $\mathbf{r}_f^{0,0}$ with the coordinate column and the rotation matrix $\mathbf{c}_f^0(180°+\beta_f^0,0,\alpha_f^0)$ from the angles of orientation of the front β_f^0,α_f^0. The coordinate column of the vector in the BCS is calculated as

$$\mathbf{R}_{in}^{br,0}=\mathbf{c}_f^0\mathbf{R}_{in}^{br,f}+\mathbf{r}_f^{0,0}.$$

In order to determine the position of the main reflector (MR) in space, it is necessary to introduce the following auxiliary CS, due to the design of the RES: AZCS is CS azimuthal axis, whose position in the BCS is characterized by a rotation matrix $\mathbf{c}_a^0(0,0,\alpha_a^0)$ from the azimuth angle α_a^0; EACS is CS of the elevation axis, the position of which in the AZSK is characterized by a vector $\mathbf{r}_{ea}^a$ with a coordinate column $\mathbf{r}_{ea}^{a,a}$; BSCS is CS base, whose position in EACS is characterized by a rotation matrix $\mathbf{c}_b^{ea}(\beta_b^{ea},0,0)$ from the elevation angle β_b^{ea}; from the elevation angle $\mathbf{r}_p^b$ with a coordinate column $\mathbf{r}_p^{b,b}$. To determine the point of incidence of the ray on the MR, it is necessary to write the expression for the ray in the PCS:

$$\mathbf{R}_{in}^{br,p}=\mathbf{c}_b^{ea,T}[\mathbf{c}_a^{0,T}\mathbf{R}_{in}^{br,0}-\mathbf{r}_{ea}^{a,a}]-\mathbf{r}_p^{b,b}=\mathbf{r}_{br}^{p,p}+\mu_{in}\mathbf{e}_f^p=\mathbf{c}_b^{ea,T}\mathbf{c}_a^{0,T}\mathbf{c}_f^0\mathbf{r}_{br}^{f,f}+$$

$$+\mathbf{c}_b^{ea,T}\mathbf{c}_{aa}^{0,T}\mathbf{c}_f^0\mathbf{r}_f^{0,0}-\mathbf{c}_b^{ea,T}\mathbf{r}_{ea}^{a,a}-\mathbf{r}_p^{b,b}+\mu_{in}\mathbf{c}_b^{ea,T}\mathbf{c}_a^{0,T}\mathbf{c}_f^0\mathbf{e}_f^f;$$

$$\mathbf{r}_{sb}^{p,p}=[x_{sb}^{p,p},y_{sb}^{p,p},z_{sb}^{p,p}]^T;\ \mathbf{e}_f^p=(x_f^p,y_f^p,z_f^p)^T. \qquad (1)$$

In the PCS, the paraboloid equation has the simplest form:

$$(x_p)^2+(y_p)^2=2pz_p\,, \tag{2}$$

where x_p, y_p, z_p are coordinates in the PCS of the point lying on the paraboloid; p is a paraboloid parameter.

The parametric paraboloid equation in the PCS will be as follows:

$$\mathbf{R}_p(r_p,\varphi_p)=\left[r_p\cos\varphi_p r_p\sin\varphi_p\,\frac{(r_p)^2}{2p}\right]^T=(x_p,y_p,z_p)^T\,, \tag{3}$$

where $\mathbf{R}_p$ is the coordinate column of the vector defining the point of the paraboloid; r_p is the distance to the projection of the point R_p on the X_pY_p; φ_p is an angle specifying the position of the point on the paraboloid.

The point of incidence $R_{tp}^{p,p}$ simultaneously belongs to the ray and the paraboloid, and $\mathbf{R}_{in}^{br,p}=\mathbf{R}_p=\mathbf{R}_{tp}^{p,p}$, therefore, in order to find it, we substitute equation (1) into (2):

$$\left((x_f^p)^2+(y_f^p)^2\right)(\mu_{in})^2+2(x_f^p x_{br}^{p,p}+y_f^p y_{br}^{p,p}-2pz_f^p)\mu_{in}+(x_{br}^{p,p})^2+(y_{br}^{p,p})^2-2pz_{br}^{p,p}=0\,.$$

Having solved the resulting equation, we find the value of the parameter, and we find $\mathbf{R}_{tp}^{p,p}$.

At the point of incidence we introduce the tangent CS of a paraboloid (TCS) formed by the tangent plane and its normal, the coordinate columns of which are orts $\mathbf{e}_{tp}^x$, $\mathbf{e}_{tp}^y$, $\mathbf{e}_{tp}^z$ in the PCS are defined by the expressions

$$\mathbf{R}_p(r_p,\varphi_p)=\left[r_p\cos\varphi_p,r_p\sin\varphi_p,\frac{(r_p)^2}{2p}\right]^T;$$

$$\mathbf{e}_{tp}^{z,p}=(\mathbf{e}_{tp}^x\times\mathbf{e}_{tp}^y)^p\,;$$

$$\mathbf{e}_{tp}^{x,p}=\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}\Big/\left|\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}\right|;$$

$$\mathbf{e}_{tp}^{y,p}=\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}\Big/\left|\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}\right|;$$

$$\mathbf{e}_{tp}^{x,p}=\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}=[\cos\varphi_p,\sin\varphi_p,\frac{r_p}{p}]\,;$$

$$\mathbf{e}_{tp}^{y,p}=\frac{d\mathbf{R}_p(r_p,\varphi_p)}{dr_p}=[-r_p\sin\varphi_p,r_p\cos\varphi_p,0]^T\,;$$

where $(\mathbf{e}_{tp}^x\times\mathbf{e}_{tp}^y)^p$ is the coordinate column of the vector product of orts $\mathbf{e}_{tp}^x,\mathbf{e}_{tp}^y$ in the PCS. The position of TCS in PCS is determined by a vector $\mathbf{R}_{tp}^p$ and a rotation matrix $\mathbf{c}_{tp}^{p} = [\mathbf{e}_{tp}^{x,p}, \mathbf{e}_{tp}^{y,p}, \mathbf{e}_{tp}^{z,p}]$. We introduce the reflection CS (RCS), the coordinate columns of which are orts $\mathbf{e}_{r}^{x}, \mathbf{e}_{r}^{y}, \mathbf{e}_{r}^{z}$ are determined by the expressions:

$$\mathbf{e}_{r}^{z,tp} = [0,0,1]^{T};\ \mathbf{e}_{r}^{y,tp} = (\mathbf{e}_{f} \times \mathbf{e}_{r}^{z})^{tp};\ \mathbf{e}_{r}^{x,tp} = (\mathbf{e}_{r}^{y} \times \mathbf{e}_{r}^{z})^{tp}.$$

The position of RCS in TCS is determined by the rotation matrix $\mathbf{c}_{r}^{z,tp} = [\mathbf{e}_{r}^{x,tp}, \mathbf{e}_{r}^{y,tp}, \mathbf{e}_{r}^{z,tp}]$. The angle between $\mathbf{e}_{r}^{z}$ and - $\mathbf{e}_{f}$ is defined as $\theta_{r} = \arccos(-\mathbf{e}_{f}^{tp,T} \mathbf{e}_{r}^{z,tp})$, where $\mathbf{e}_{f}^{tp} = \mathbf{c}_{tp}^{p,t} \mathbf{e}_{f}^{p}$.

Then the expression for the reflected ray in the PCS will take the form:

$$\mathbf{R}_{tp}^{tp,p} = \mathbf{R}_{tp}^{p,p} + \mu_{r} \mathbf{e}_{r}^{p},$$

where μ_r is the parameter characterizing the length of the reflected ray.

In order to determine the position of the CR in space, the following auxiliary CSs should be introduced, due to the MR design: CRCS is CS of the CR drive, whose position in the FCS is characterized by a vector $\mathbf{r}_{c}^{b}$ with coordinate column $\mathbf{r}_{c}^{b,b}$ and rotation matrix $\mathbf{c}_{c}^{b}(\beta_{c}^{b}, 0, \alpha_{c}^{b})$. ECS is the CS of an ellipsoid, whose position in the CRCS is characterized by a vector $\mathbf{r}_{e}^{c}$ with a coordinate column $\mathbf{r}_{e}^{c,c}$. To determine the point of incidence of the ray reflected from the MR ray on the CR, it is necessary to write the expression for the ray in the ECS:

$$\mathbf{R}_{r}^{tp,e} = \mathbf{c}_{c}^{b,T}[\mathbf{R}_{tp}^{p,p} + \mu_{r} \mathbf{e}_{r}^{p} + \mathbf{r}_{p}^{b,b} - \mathbf{r}_{c}^{b,b}] - \mathbf{r}_{e}^{c,c} = \mathbf{r}_{tp}^{e,e} + \mu_{r} \mathbf{e}_{r}^{e} =$$
$$= \mathbf{c}_{c}^{b,T} \mathbf{R}_{tp}^{p,p} + \mathbf{c}_{c}^{b} \mathbf{r}_{p}^{b,b} - \mathbf{c}_{c}^{b,T} \mathbf{r}_{c}^{b,b} + \mu_{r} \mathbf{c}_{c}^{b,T} \mathbf{e}_{r}^{p};$$
$$\mathbf{r}_{tp}^{e,e} = [x_{tp}^{e,e}, y_{tp}^{e,e}, z_{tp}^{e,e}]^{T};\ \mathbf{e}_{r}^{e} = [x_{r}^{e}, y_{r}^{e}, z_{r}^{e}]^{T}. \tag{4}$$

In ECS, the paraboloid equation has the simplest form:

$$(z_e)^2 + \frac{a^2}{b^2}(x_e)^2 + \frac{a^2}{b^2}(y_e)^2 = a^2, \tag{5}$$

where x_e, y_e, z_e are coordinates in the ECS point lying on the ellipsoid; a and b are ellipsoid parameters.

The parametric equation of an ellipsoid in ECS is as follows:

$$\mathbf{R}_{e}(\psi_{e}, \varphi_{e}) = (b\cos\psi_{e}\cos\varphi_{e}, b\cos\psi_{e}\sin\varphi_{e}, a\sin\psi_{e})^{T} = (x_{e}, y_{e}, z_{e})^{T}, \tag{6}$$

where $(x_e, y_e, z_e)^T$ is the coordinate column of the vector defining the point of the paraboloid; φ_e, ψ_e are angles that set the position of a point on an ellipsoid.

The point of incidence $\mathbf{R}_{te}^{e,e}$ simultaneously belongs to both the ray and the ellipsoid, and $\mathbf{R}_{r}^{tp,e} = \mathbf{R}_{e} = \mathbf{R}_{te}^{e,e}$, and therefore, to find it, we substitute equation (4) into (5):

$$\left(\frac{a^2}{b^2}(x_r^e)^2 + \frac{a^2}{b^2}(y_r^e)^2 + (z_r^e)^2\right)(\mu_r)^2 + 2\left(\frac{a^2}{b^2} x_r^e x_{tp}^{e,e} + \frac{a^2}{b^2} y_r^e y_{tp}^{e,e} + z_r^e z_{tp}^{e,e}\right)\mu_r +$$
$$+ \frac{a^2}{b^2}\left((x_{tp}^{e,e})^2 + (y_{tp}^{e,e})^2\right) - a^2 = 0.$$

Having solved the resulting equation, we find the value of the parameter, and substituting it into (1) we find $\mathbf{R}_{te}^{e,e}$.

At the point of incidence we introduce the tangent CS of the ellipsoid (ECS) formed by the tangent plane and the normal to it, the coordinate columns of which are orts $e_{te}^{x}, e_{te}^{y}, e_{te}^{z}$ in the PCS are defined by the expressions:

$$\mathbf{R}_e(\psi_e,\varphi_e) = [b\cos\psi_e\cos\varphi_e, b\cos\psi_e\sin\varphi_e, a\sin\psi_e]^T = (x_e, y_e, z_e)^T;$$

$$\mathbf{e}_{te}^{z,e} = (\mathbf{e}_{te}^{x}\times\mathbf{e}_{te}^{y})^e;$$

$$\mathbf{e}_{te}^{x,e} = \frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\psi_e} \Big/ \left|\frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\psi_e}\right|;$$

$$\mathbf{e}_{te}^{y,e} = \frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\varphi_e} \Big/ \left|\frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\varphi_e}\right|;$$

$$\frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\varphi_e} = [-b\cos\psi_e\sin\varphi_e, b\cos\psi_e\cos\varphi_e, 0]^T;$$

$$\frac{d\mathbf{R}_e(\psi_e,\varphi_e)}{d\psi_e} = [-b\sin\psi_e\cos\varphi_e, -b\sin\psi_e\sin\varphi_e, a\cos\varphi_e]^T;$$

where $(\mathbf{e}_{te}^{x}\times\mathbf{e}_{te}^{y})^e$ is the coordinate column of the vector product of orts $\mathbf{e}_{te}^{x}, \mathbf{e}_{te}^{y}$ in ECS. The position of the CECS in the ECS is determined by the vector $\mathbf{R}_{te}^{e,e}$ and the rotation matrix $\mathbf{c}_{te}^{e} = [\mathbf{e}_{te}^{x,e}, \mathbf{e}_{te}^{y,e}, \mathbf{e}_{te}^{z,e}]$. We introduce the reflection CS (RCS), the coordinate columns of the orts $\mathbf{e}_{te}^{x,e}, \mathbf{e}_{te}^{y,e}, \mathbf{e}_{te}^{z,e}$ of which are determined by the expressions:

$$\mathbf{e}_{pe}^{z,te} = [0,0,1]^T; \ \mathbf{e}_{pe}^{y,te} = (\mathbf{e}_r\times\mathbf{e}_{pe}^{z})^{te}; \ \mathbf{e}_{pe}^{x,te} = (\mathbf{e}_{pe}^{y}\times\mathbf{e}_{pe}^{z})^{te}.$$

The position of the RCS in the CCS is determined by the rotation matrix $\mathbf{c}_{pe}^{te} = [\mathbf{e}_{pe}^{x,te}, \mathbf{e}_{pe}^{y,te}, \mathbf{e}_{pe}^{z,te}]$. The angle between $\mathbf{e}_{pe}^{z}$ and - $\mathbf{e}_r$ is defined as $\theta_{pe} = \arccos(-\mathbf{e}_r^{te,T}, \mathbf{e}_{pe}^{z,te})$, where $\mathbf{e}_r^{te} = \mathbf{e}_{te}^{e,T}$.

Then the expression for the reflected ray in the ECS will take the form: $\mathbf{R}_{re}^{te,e} = \mathbf{R}_{te}^{e,e} + \mu_{re}\mathbf{e}_{re}^{e}$, where μ_{re} – is a parameter characterizing the length of the reflected ray.

To find the coordinates of the points of intersection of the rays with the plane of the irradiator, we introduce the irradiator CS (ICS), whose position relative to the CCS is determined by a vector $\mathbf{r}_{ir}^{b}$ with a coordinate column $\mathbf{r}_{ir}^{b,b}$ and a rotation matrix $\mathbf{e}_{ir}^{b}(\beta_{ir}^{b}, 0, \alpha_{ir}^{b})$.

The feed plane in the ICS is set in a parametric form as follows:

$$\mathbf{R}_{ir} = u\mathbf{e}_{ir}^{x,ir} + v\mathbf{e}_{ir}^{y,ir}; \ \mathbf{e}_{ir}^{x,ir} = [1,0,0]^T; \ \mathbf{e}_{ir}^{y,ir} = [0,0,1]^T$$

where u,v are linear dimensions of the feed.

To determine the point of incidence of the ray reflected from the CR ray on the plane of the irradiator, it is necessary to write the expression for the ray in the ICS:

$$\mathbf{R}_{re}^{te,ir} = \mathbf{c}_{ir}^{b,T}[\mathbf{c}_{c}^{b}[\mathbf{R}_{te}^{e,e} + \mu_{re}\mathbf{e}_{re}^{e} + \mathbf{r}_{pe}^{c,c}] + \mathbf{r}_{c}^{b,b} - \mathbf{r}_{ir}^{b,b}]$$

$$= \mathbf{r}_{te}^{ir,ir} + \mu_{re}\mathbf{e}_{re}^{ir} = \mathbf{c}_{ir}^{b,T}\mathbf{c}_{c}^{b}\mathbf{R}_{te}^{e,e} + \mathbf{c}_{ir}^{b,T}\mathbf{r}_{e}^{c,c} + \mathbf{c}_{ir}^{b,T}\mathbf{r}_{c}^{b,b} - \mathbf{c}_{ir}^{b,T}\mathbf{c}_{c}^{b}\mathbf{e}_{re}^{e} + \mu_{r}\mathbf{c}_{ir}^{b,T}\mathbf{c}_{c}^{b}\mathbf{e}_{re}^{e};$$

$$\mathbf{r}_{te}^{ir,ir} = [x_{te}^{ir,ir}, y_{te}^{ir,ir}, z_{te}^{ir,ir}]^{T}\ ;\ \mathbf{e}_{re}^{ir} = [x_{r}^{ir}, y_{r}^{ir}, z_{r}^{ir}].$$

The point of incidence $\mathbf{R}_{t}^{ir,ir}$ simultaneously belongs to the ray and the plane:

$$\mathbf{r}_{te}^{ir,ir} + \mu_{re}\mathbf{e}_{re}^{ir} = \mathbf{R}_{t}^{ir,ir} = u\mathbf{e}_{ir}^{x,ir} + v\mathbf{e}_{ir}^{y,ir}.$$

Having solved the resulting equation, we find the value of the parameter μ_{re}, and substituting it into the equation of the plane we find $\mathbf{R}_{t}^{ir,ir}$.

The concept of the irradiator plane is conditional. It is further assumed that the multi-pixel matrix of the radio receiver is placed in this plane.

The next task is to develop a model of the process of interaction of radio emission with the substance of a sensitive element (pixel).

Suppose an input signal is fed to the input of some linear system. In this case, a signal is observed at the output of this system. The question is how to simulate the work of the “black box” knowing the input and watching the output signals? Since it is possible to choose any input signals, we will feed the delta pulse input:

$$\delta(n) = \begin{cases} 1, \ at\ n = 0, \\ 0, \ else. \end{cases}$$

At the output, we obtain a certain sequence $h(n)$, which is called a response to a single input action, or a pulsed response. Due to the linearity of the system, a change in the scale of the delta pulse will lead to a similar change in the output sequence $h(n)$, i.e. $L[a\delta(n)] = ah(n)$. In this case, any discrete signals can be considered as a sequence of delta pulses with different scales: $x(n)\delta(-n)$. Give the input of the linear system a sequence of delta pulses: $x(n) = \delta(-n)$. Each input signal sample $x(n)$ will generate a shifted sequence $h(n - m)$ (Fig. 3).

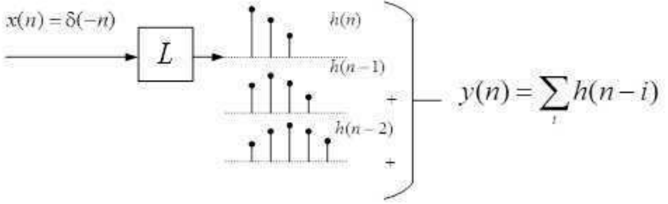


Fig. 3. Formation of the output signal in linear systems with constant parameters

Therefore, with an arbitrary input signal of a linear system with constant parameters, the output will be determined by the expression

$$y(n) = \sum_{k=-\infty}^{\infty} x(k)h(n-k). \tag{7}$$

Thus, the operation of a linear system is completely determined by the impulse response $h(n)$ of this system.

Consider the response of a linear system to an input $x(n) = e^{j\omega n}$, that describes a complex sine wave with a frequency ω. After substitution of the given expression into expression (7), we obtain

$$y(n)=\sum_{k=-\infty}^{\infty}e^{j\omega k}h(n-k)\Big|_{i=n-k}=\sum_{i=-\infty}^{\infty}e^{j\omega(n-i)}h(i)=e^{j\omega v}\sum_{i=-\infty}^{\infty}h(i)e^{-j\omega i}=e^{j\omega n}H(j\omega)\,,(8)$$

where $H(j\omega)$ is the frequency response of the system. Thus, passing the complex sine wave through a linear system, we obtain the same sine wave, but with a modified amplitude and phase $H(j\omega)$.

Frequency response can be written in the following form:

$$H(j\omega)=r(\omega)e^{j\phi},$$

where ϕ is the initial phase;

$$r(\omega)\sqrt{(\mathrm{Im}(H(j\omega))+\mathrm{Re}(H(j\omega)))^2}=|H(j\omega)|.$$

The initial phase can be expressed through the relationship of the imaginary and real parts of the frequency response:

$$\phi=\arctan\frac{\mathrm{Im}(H(j\omega))}{\mathrm{Re}(H(j\omega))}.$$

Since the frequency response $H(j\omega)$ is related to the impulse response $h(n)$ through the Fourier transform, where

$$h(n)=\frac{1}{2\pi}\int_{-\pi}^{\pi}H(j\omega)e^{j\omega n}d\omega. \quad (9)$$

If $|H(j\omega)| = 1$, then complex sinusoids of this frequency pass through the linear system without distortion. Accordingly, if $|H(j\omega)| = 0$, then sine waves of this frequency are not skipped. Using this property of the frequency response, you can filter the signals. For example, with perfect low–pass filtering you can put

$$H(j\omega)=\begin{cases}1, 0\le\omega<\pi,\\ 0, \pi\le\omega<2\pi.\end{cases}$$

From expression (9), the impulse response of such a filter $h(n)$ = sin$c(n)$ is defined on interval $(-\infty;\infty)$. Therefore, in the general case, it is impossible to implement an ideal low–pass filter in practice. A similar expression of the impulse response can be obtained for a high-pass filter, which is also unrealizable.

The convolution calculation (7) can be performed in the frequency domain. It is known that the signal $x(n)$ is associated with its image in the frequency domain by the Fourier transform:

$$X(j\omega)=\sum_{n}x(n)e^{-j\omega n}\ ;\ x(n)=\frac{1}{2\pi}\int_{-\pi}^{\pi}X(j\omega)e^{j\omega n}d\omega.$$

Moreover, if we apply a sequence $X(j\omega)e^{j\omega n}$, to the input of a linear system, then we get a response $e^{j\omega n}X(j\omega)H(j\omega)$. Using the inverse Fourier transform, we obtain

$$y(n)=\frac{1}{2\pi}\int_{-\pi}^{\pi}X(j\omega)H(j\omega)e^{j\omega n}d\omega$$

or in the frequency domain

$$Y(j\omega)=X(j\omega)H(j\omega). \quad (10)$$

Thus, the convolution in the frequency domain is a multiplication of the signal $X(j\omega)$ by the frequency response of the filter $H(j\omega)$.

When receiving radio signals (RS) from remote space sources of radio emission (SSR) by means of reflector systems (RES) of radio telescopes (RT) and radio receivers (RRS), there is the task of identifying the transfer function of the RES in the SSR–RES–RRS–RS transformation chain. To solve this problem requires a physical and mathematical model of this chain of reception and transmission. On the other hand, the RES is an integral part of the RT guidance system (GS), so the task can be formulated differently: how does the GS RT affect the process of receiving and transmitting radio emissions (RE)? The RE model is considered in the form of streams of neutral (uncharged) radio particles (RP). The flow of RP, interacting with substance of the sensing element (SE) of a radio receiver, causes in it oscillatory processes, similar to the serial impact of a multitude of solids of small mass on a large mass body. The elementary process of RP interaction with a substance is represented as a model of an oscillating circuit (substance), which is affected by a pulsed signal of a variable duty cycle [Dubarenko et al., 2019].

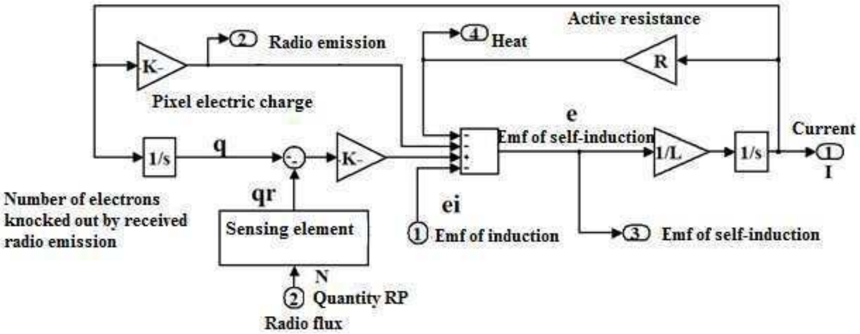


Fig. 4. Mathematical model of the pixel of the matrix receiver of radio emissions

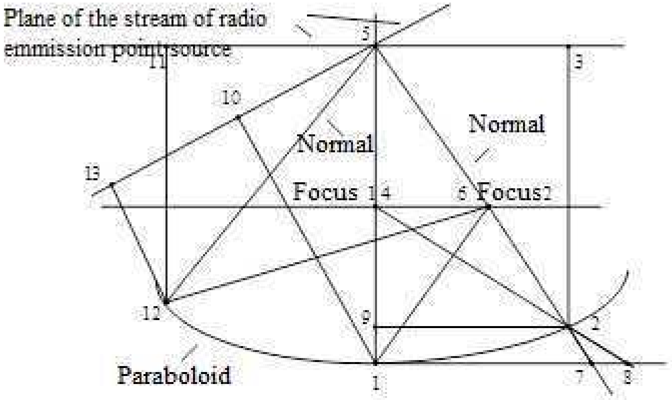
RES is designed to focus the ray on the plane of the sensitive element to increase their density. In an ideal RES scheme, the rays converge at one point. Deformations of the RT design lead to defocusing, i.e. to the deviation of the lengths of the optical paths of the rays from the ideal. The set of points of intersection of the rays with the SE plane form a region (spot), the position and diameter of which serve as estimates of the effectiveness of the focusing properties of the RES. At the points of intersection of the rays with the plane of the SE, the substance of which it consists is subjected to a pulsed RP effect with a pulse repetition rate determined by the distances between the RP along the ray. The difference in the lengths of the optical paths of the rays determines the delay in the arrival of pulses and manifests itself in the phase displacements of the pulsed transient characteristics of the signals taken from the SE and influences their resulting parameters and characteristics. Evaluation of the effect of deformations of the RT design on the parameters and characteristics of the RE flow allows, by measuring these deformations, to eliminate or reduce their harmful effect, that is, to perform automatic control of the reflector system autofocusing. When elements of the RES deviate from their theoretical position and when the focal axis of the main reflector deviates from the direction of the SSR, RP come to the focus spot at different times, or, as applied to the impulse response, the imprint sensitivity of the receiver is in a different phase. The addition of harmonic signals of the same frequency with different phases is equivalent to the conversion to a harmonic signal, the amplitude of which as a function of the phase varies periodically [Goncharova et al., 2017], [Matviychuk, 2016].

In plane 4-6, passing through the focus 1, the matrix of the sensitive element of the radio receiver is usually placed. In the mm-range of the RE and small angles of deviation of the focal axis from the direction to the SSR, the rays from the frontal plane 13-5 converge almost at one point – focus 2. But their optical paths from this plane will be different, that is, they will come to focus 2 different times, with a delay. The difference in the lengths of the optical paths of the rays forms the phase delay of the shock interaction of the corpuscles with the sensitive substance of the matrix. The total interaction of all particles from the plane of the reflector aperture for one oscillation period, in which they excite these oscillations, will depend on the difference in the lengths of the optical paths. And with their significant values, oscillations at the output of the oscillator can come out of phase, zeroing the output signal [Polozov and Rashchikov 2018], [Vladimirova et al., 2018].

The dependence of the radio signal power at the output of the oscillator of the input filter of the radio receiver for one oscillation period on the magnitude of the mismatch between the angular direction to the RES and the direction of the focal axis of the reflector is called the radiation pattern.

Radio Telescope Receiving Antenna Directivity Pattern (RT DP)

RT DP is the most important characteristic of the reflector system of the RES RT, numerically determining its directional properties. In the corpuscular model of radio emission, all the rays of the radio emission flux are parallel to the targeting vector, and the radio particles (RP) in the frontal plane of the flux are coherent. This means that in the ideal case, with a symmetric RES network, when the geometric position of the RES corresponds to the theoretical position, and the vector of the focal axis is collinear to the target designation vector, all particles from the frontal plane of the stream will pass on the multipixel array of the receiver into one focus point (one pixel), forming a single pulse at the entrance to the oscillator, whose amplitude is proportional to the number of rays in the stream. The period of alternation of pulses is inversely proportional to the carrier frequency of the radiation. With the angular mismatch of the target designation vectors and the focal axis, the RP paths along the corresponding rays will be different, that is, the optical paths of the rays will be different. The arrival of each RP per pixel of the receiver matrix is equivalent to the pulse effect on the oscillator, from which output a signal in the form of a pulse transient response is taken. The pulse model is taken as the delta function, and the oscillator model of the pixel sensing element is in the form of an oscillatory circuit tuned to the carrier frequency of the radio emission. The sum of all RP impulse characteristics belonging to one of the planes of the radiation front forms a complex signal in the form of their sum with shifted phases. In a simplified version, this is the sum of the sines shifted in time by the amount of delay. The magnitude of the delay depends on the difference in the lengths of the optical paths of the RP, and they, in turn, on the mismatch between the targeting vectors and the focal axis. Let us find the expression for the sum of sines at the oscillator output for estimating the power of the received signal as a function of the deviation of the focal axis from the direction to the radio source [Dubarenko et al., 2019].



1. The top of the reflector.
2. The point of intersection of the vertically incident ray 3-2 with a parabolic surface.
3. Point on the conditional instantaneous plane of the front of the flux of radio emission (FREF) point of a remote source of radiation.
4. Focus of the first reflector. The point at which all the rays reflected from the paraboloid surface (for example, 2-4, 12-4, 1-4) from vertically incident rays (3-2, 11-12, 5-1) from one remote space source of radio emission (SSR).
5. The point of intersection of the normal 2-5 with the surface of the paraboloid at point 2.
6. Focus of the second reflectors. The point at which all the rays reflected from the paraboloid surface (for example, 2-6, 12-6, 1-6) from obliquely at an angle a of incident rays (5-2, 13-12, 10-1) converge.
7. The intersection point of the normal 2-5 with a horizontal plane passing through the vertex of the paraboloid (point 1).
8. The point of intersection of the reflected ray 2-4 with a horizontal plane passing through the vertex of the paraboloid (point 1).
9. The point of intersection of the focal axis 1-4 with the horizontal plane passing through point 2.
10. Point on the FREF, inclined from the horizontal position at an angle 11–5–13=α.
11. Point on FREF vertically incident ray 11-12.
12. Point on FREF, inclined from the horizontal position at an angle 11–5–13=α, of the ray 10-1, passing through the top of the paraboloid.
13. Point on the FREF, inclined from the horizontal position at an angle 11–5–13=α, of the ray 13-12.

Fig. 5. The path of the rays in a parabolic reflector

To find the amount of the form

$$S_1 = \cos\varphi + \cos(\varphi+\alpha) + \ldots + \cos(\varphi+n\alpha) = \sum_{k=0}^{n} \cos(\varphi+k\alpha)\,, \qquad (11)$$

$$S_1 = \sin\varphi + \sin(\varphi+\alpha) + \ldots + \sin(\varphi+n\alpha) = \sum_{k=0}^{n} \sin(\varphi+k\alpha)\,. \qquad (12)$$

Consider the expression

$$S = S_1 + S_2 \qquad (13)$$

and transform it using Euler’s formula:

$$e^{i\varphi} = \cos\varphi + i\sin\varphi .$$

$$S = \sum_{k=0}^{n} \cos(\varphi + k\alpha) + i\sin(\varphi + k\alpha) = \sum_{k=0}^{n} e^{i(\varphi+k\alpha)} . \tag{14}$$

The right side of the last equation is a geometric progression with a denominator $e^{i\alpha}$. The sum of the members of such a progression is equal to

$$S = \frac{e^{i\varphi}(e^{i(n+1)\alpha} - 1)}{e^{i\alpha} - 1} . \tag{15}$$

Multiply the numerator and denominator of the fraction in the right side of (5) by $(-ie^{i\alpha/2})$. Then the denominator of this fraction becomes real and takes the form

$$-i(e^{i\alpha/2} - e^{-i\alpha/2}) = 2\sin\frac{\alpha}{2} .$$

Then we transform the numerator of the fraction, using the Euler formula:

$$-ie^{i\alpha/2}e^{i\varphi}(e^{i(n+1)\alpha} - 1) = -i(e^{i(\varphi+(n+\frac{1}{2})\alpha)} + e^{i(\varphi-\alpha/2)}) =$$

$$= -i\cos(\varphi + (n + \frac{1}{2})\alpha) - \sin\varphi - \frac{\alpha}{2} + \sin(\varphi + (n + \frac{1}{2})\alpha) - \sin\left(\varphi - \frac{\alpha}{2}\right).$$

Considering that

$$S_1 = \operatorname{Re} S ; \; S_1 = \operatorname{Im} S ,$$

we get

$$S_1 = \frac{\sin(\varphi + (n + \frac{1}{2})\alpha) - \sin(\varphi - \frac{\alpha}{2})}{2\sin\frac{\alpha}{2}} ; \tag{16}$$

$$S_1 = \frac{\cos(\varphi - \frac{\alpha}{2}) - \cos(\varphi + (n + \frac{1}{2})\alpha)}{2\sin\frac{\alpha}{2}} . \tag{17}$$

Using trigonometric identities

$$\sin\alpha - \sin\beta = 2\sin\frac{\alpha-\beta}{2}\cos\frac{\alpha+\beta}{2} ;$$

$$\cos\alpha - \cos\beta = 2\sin\frac{\alpha-\beta}{2}\sin\frac{\alpha+\beta}{2} .$$

transform the sine and cosine differences in the equalities (16) and (17):

$$\sin(\varphi + (n + \frac{1}{2})\alpha) - \sin(\varphi - \frac{\alpha}{2}) = 2\sin\frac{(n+1)\alpha}{2}\cos\left(\varphi + \frac{n\alpha}{2}\right) ;$$

$$\cos(\varphi - \frac{\alpha}{2}) - \cos(\varphi + (n + \frac{1}{2})\alpha) = 2\sin\frac{(n+1)\alpha}{2}\sin\left(\varphi + \frac{n\alpha}{2}\right) .$$

Thus, we have

$$S_1=\sum_{k=0}^{n}\cos(\varphi+k\alpha)=\frac{\sin\frac{(n+1)\alpha}{2}\cos\left(\varphi+\frac{n\alpha}{2}\right)}{\sin\frac{\alpha}{2}};$$

$$S_1=\sum_{k=0}^{n}\sin(\varphi+k\alpha)=\frac{\sin\frac{(n+1)\alpha}{2}\sin\left(\varphi+\frac{n\alpha}{2}\right)}{\sin\frac{\alpha}{2}}. \tag{18}$$

The average power over a gap of length T is calculated by the formula

$$P(t_0,T)=\frac{1}{T}\int_{t_0}^{t_0+T}[x(t)^2]dt\,. \tag{19}$$

If power is considered as a function of time, then it is called time power or simply power. Power can also be represented as a function of frequency. In this case, it is called frequency power or spectral power. Spectral power is often called spectral density or spectrum. The names “temporal power” and “frequency power” although, unfortunately, are rarely used, they more correctly reflect the relationship between the time and frequency representations of the signal compared to the common names “power” (in the case of the temporal representation) and “spectral density” (in the case of frequency representation).

In our case, the ray is characterized by a temporary power. Time interval $T = 1/f_0$ is determined by the carrier frequency of the radio emission f_0. This is the time between two successive fronts of radio emission. A signal S_2 is a function of three arguments:

n is the number of in the frontal plane of the radiation flux incident on the surface of the main reflector;

$n\alpha$ is a phase of maximum time shift pulsed characteristics of the oscillator for a given angle of deviation of the focal axis from the direction to the source of radio emission; $\varphi = 2\pi f_0 t$ is a current angle of the sinusoidal component of the oscillator impulse response.

Only one argument $\varphi(t)$ of these three depends on time. Therefore, the average signal power s_2 over an interval of length T is determined by the expression:

$$P(t_0,T)=\frac{1}{T}\int_{t_0}^{t_0+T}[S_2(t)^2]dt\,, \tag{20}$$

$$P(t_0,T)=\frac{1}{T}\int_{t_0}^{t_0+T}\left(\frac{\sin((n+1)\alpha/2)}{\sin(\alpha/2)}\right)^2(\sin(\varphi+n\alpha/2))^2dt=;$$

$$=\left(\frac{\sin((n+1)\alpha/2)}{\sin(\alpha/2)}\right)^2\frac{1}{T}\int_{t_0}^{t_0+T}(\sin(\varphi+n\alpha/2))^2dt=\left(\frac{\sin((n+1)\alpha/2)}{\sin(\alpha/2)}\right)^2K;$$

$$\frac{1}{T}\int_{t_0}^{t_0+T}(\sin(\varphi+n\alpha/2))^2dt\,; \tag{21}$$

where K is a constant normalizing factor.

RT DP as a function of the mismatch of targeting vectors and the focal axis is determined by the expression

$$DNA = \left(\frac{\sin((n+1)\alpha/2)}{\sin(\alpha/2)} \right)^2 . \tag{22}$$

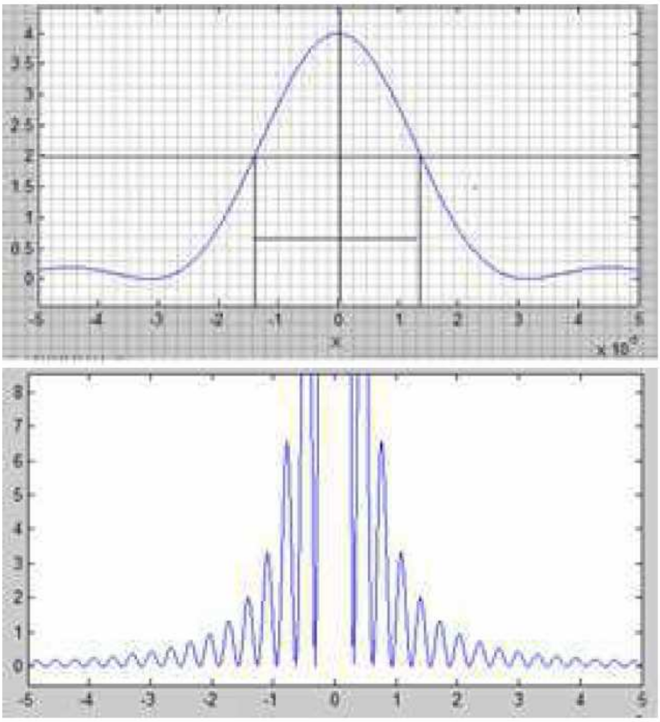


Fig. 6. RT AP as a function of the mismatch of targeting vectors and focal axis

Fig. 6 demonstrates how the shape of the RT AP changes depending on the parameters of the reflector system and the frequency of the radiation source.

The estimate of the phase dependence of the signal at the output of the oscillator on the difference between the optical paths of the rays can be approximately written as follows:

$$e_i = E_i \pm \cdot \sin\left(\omega \cdot t + \frac{2\pi}{\lambda} \cdot (L_i - L_{\min}) + \varphi_i \right);$$

$$\Psi_i = \frac{2\pi}{\lambda} \cdot (L_i - L_{\min}) + \varphi_i \, , \tag{23}$$

where Ψ is a phase, L_i is the optical path length of i ray RE; L_{min} is the minimum length of the optical path of all the rays.

The computational scheme for calculating the optical path length of a ray (radio particle) from the plane of the front of a stream of radio emission in a 3-reflector system of the RT-70 radio telescope constructed according to the Nesmith scheme is shown in Fig. 7:

– the main reflector is a paraboloid of rotation,

– counter reflector is an ellipsoid of rotation,
– periscopic reflector is a plane,
– receiving matrix is a plane.

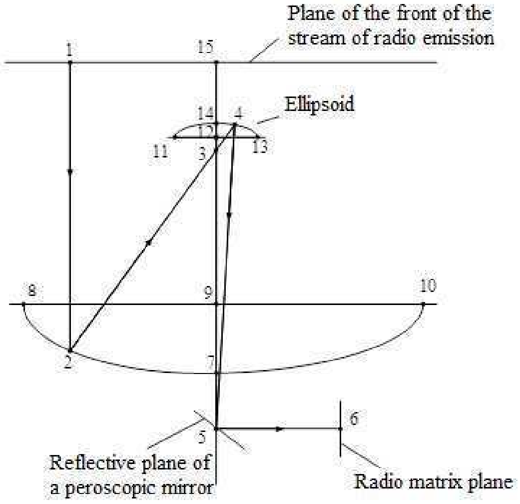


Fig. 7. The optical path of the radio particle in the 3-reflector system of the radio telescope RT-70

The scheme and formula (23) define a simple algorithm for the numerical calculation of the influence of the displacements of RES elements on the characteristics of the total output signal of a receiver carrying useful information about the SSR. To this end, the frontal plane of the radiation flux in the aperture of the main reflector is divided into a given number of rays and, for each ray, the RP optical path is calculated using geometric optics methods. The path is recalculated into the phase, the phases are added up and ultimately, the magnitude of the change in the amplitude of the total radio signal from the factors deviating the RES elements from their theoretical position or deviation from the direction to the SSR (multilobe pattern in estimating signal strength) is determined. If the points of intersection of the rays are not focused in one pixel on the receiving matrix, then the optical path of the smallest length is chosen from all the optical paths of the particles. And the point of intersection of this ray is taken as the phase center. The difference of optical paths is taken into account when calculating the total power of the received radiation. The accuracy of the guidance of the RES RT is provided by the control system, which includes a system for measuring the state vector of the structural elements of the RT relative to the selected coordinate system and compensation for guidance errors [Dubarenko et al., 2014].

Fig. 8 shows the relative intensity of the maximum in the phase center of the secondary focus of the RES with umbrella deformations, lateral displacements of the RC and its displacement.

The intensity distribution in the plane of the irradiator can be approximated by the expression

$$I(\mathbf{e}_{res},\mathbf{q}_{ir},x,y)=A(\mathbf{e}_{res},\mathbf{q}_{ir},x,y)\sin^2(\delta(\mathbf{e}_{res},\mathbf{q}_{ir})\rho(\mathbf{e}_{res},\mathbf{q}_{ir},x,y))/ \\ /(\delta(\mathbf{e}_{res},\mathbf{q}_{ir})\rho(\mathbf{e}_{res},\mathbf{q}_{ir},x,y))^2; \tag{24}$$

where $\mathbf{e}_{res}=(\Delta\alpha_{mr},\Delta\alpha_{mr},\Delta x_c,\Delta y_c,\Delta z_c,\Delta\beta_c,\Delta\theta_c,)^T$;

$\Delta\alpha_{mr}$, $\Delta\beta_{mr}$ are focal axis pointing errors (FA) MR;

Δx_c, Δy_c, Δz_c are linear mismatch foci CR and MR;

$\Delta\beta_c$, $\Delta\theta_c$ are angular mismatch between FA MR and MR CR;

x, y are coordinates defining a point in the plane of the feed;

$\mathbf{q}_{ir}=(\Delta x_{ir},\Delta y_{ir},\Delta z_{ir},\Delta\beta_{ir},\Delta\theta_{ir})^T$ – linear and angular deviations of the irradiator from the adjustment position;

$$\rho^2=(x+\Delta x_{ir}+\delta_1\Delta\alpha_{mr}+\delta_2\Delta\beta_c+\delta_3\Delta x_c+\delta_4\Delta z_c\Delta\theta_c)+ \\ +y(y+\Delta y_{ir}+\delta_1\Delta\beta_{mr}+\delta_2\Delta\theta_c+\delta_3\Delta y_c+\delta_4\Delta z_c\Delta\beta_c);$$

$$\delta=\delta_5-\delta_6(\Delta z_{ir}+\delta_7\Delta z_c+\delta_8\Delta\beta_{ir}+\delta_8\Delta\beta_{ir}+\delta_9\Delta\beta_c\Delta y_c+\delta_9\Delta\theta_c\Delta x_c);$$

$$A=\delta_{10}-\delta_{11}(\Delta y_c(x-\Delta x_{ir})+\delta_{12}\Delta x_c(y-\Delta y_{ir})+\delta_{13}\Delta x_c(x-\Delta x_{ir}))+ \\ +\delta_{14}(\Delta y_c(y-\Delta y_{ir})+\delta_{15}\Delta z_{ir};$$

δ_i is weighting factors are determined during modeling and verified by means of radio holography.

The research results showed that the mm-band radio telescope, by analogy with photo-optical devices, can be considered as a device for obtaining images of remote point and long-range SSRs. In the plane of the irradiator, on which the observed object is projected through the RES, the latter is characterized by the distribution of the intensity of the received radio emission. For RT-70 at a wavelength of 1 mm, the width of the DNA for the point receiver at the half power level was calculated. It is equal to 3 arc.s [Dubarenko et al., 2014].

In the absence of deformations of the structure, the radio image of the point SSR, when its angular position changes, will move along the receiving matrix in the form of a "spot" covering one or several pixels. The size of this spot varies slightly to the periphery. At a wavelength of 1 mm and an angular error of 1 arc.s, the linear displacement of the spot is 2.24 mm. With an aperture size of the receiving array of 50 mm, the field of view of the error will be about 25 arc. s.

One of the main modes of operation of the RT for SSR is the accumulation of a signal during long exposure (up to several hours). Simulation has shown that in this case the use of a single receiver with an aperture area larger than the width DNA, radiation from several sources can get into the receiver, making it difficult to identify them. On the other hand, reducing the area of the aperture of the irradiator will lead to extremely stringent requirements for the accuracy of MR guidance, which is problematic in creating tracking drives and a measuring system. The use of matrix receivers (MRU), which is a package of irradiators packaged in a matrix like a CCD used in optics, is an effective way to compensate for the effects of deformations of the RT design and can significantly reduce the requirements for precision MR and simultaneously increase the resolution by simultaneously receiving a signal several pixels of the receiving array. For the MRU, it is possible to provide a reconstruction of the radio signal from the point SSR using sequential recording of signal frames from the MRU and using information about the likely position of the RES image on the MRU obtained using the model for estimating the effect of guidance errors and deformations of the structure on the ray.

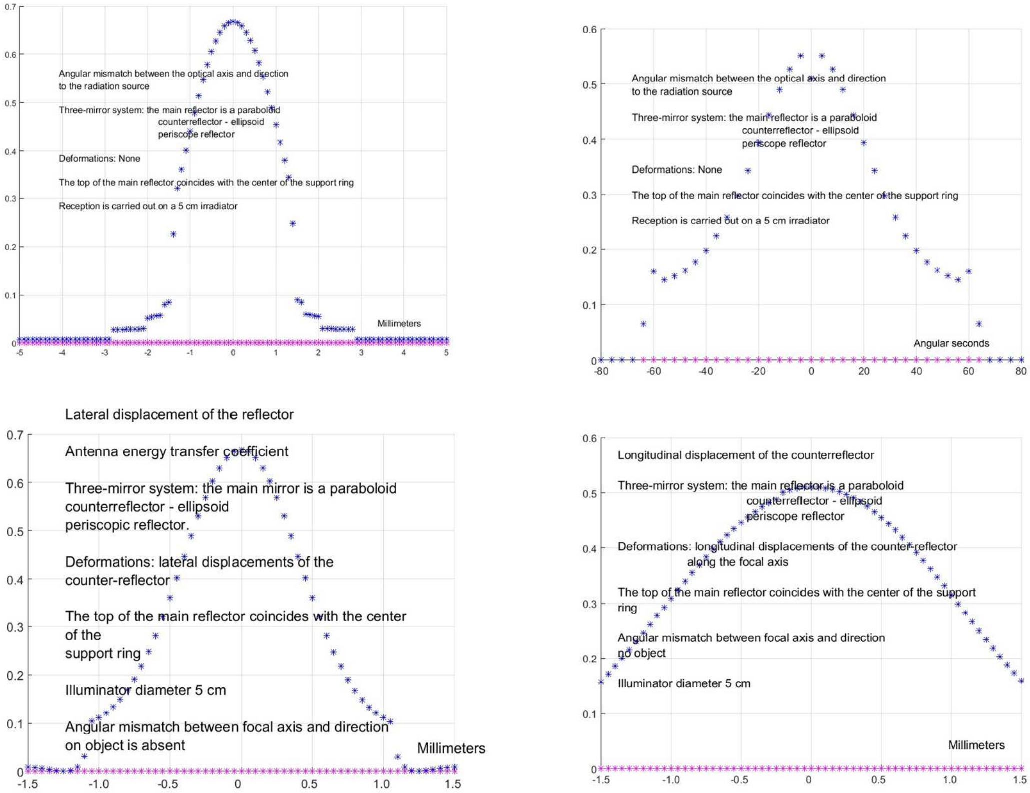


Fig. 8. Dependence of the received signal power in the phase center of the secondary focus of the RES on the MR umbrella deformations, transverse and longitudinal displacements of the CR

To expand the visibility of the SSR, either a multilobe ray or a ray scan with respect to the line of the selected direction to the SSR is required. Below is a description of a conical DP (directivity pattern) scanning system by means of the main guides of the RT-70 telescopic system.

Conclusion

The theory of corpuscular radio communication based on the representation of radio radiation in the form of the flow of radio particles was developed. Impact of particles on the radio receiver in the form of pulse sequence, and the receiver itself in the form of an oscillator were considered. This model of the radio system has made it easier to structure the radio receiver and how to assess radio communications.

The research was carried out over a period of 10 years as part of the “Suffa” research project, involving 15 organisations. The result of the research was a calculated and hardware justification for the modern intellectual system of logical control of RT-70 with an adaptive surfaces. The system has four circuits of control: the main reflector control circuit, the control of its adaptive surface, the hexapod-based counter-reflector circuit, and the control circuit of the third (periscope) reflector. The control system allows, by autofocusing elements of the RT reflector system, using laser, gyroscopic and optical measurements, to provide in the observation mode cosmic objects the following values of angular resolution at a wavelength of 1 mm:

– for single receiver – 3 angular seconds;

– for the matrix multipixel balometric receiver –0.25 angular seconds.

The most important problems that had to be solved were:

– the creation of computer models of RT design dynamics and guidance drives (state identifiers) to obtain estimates of their coordinates not available for direct measurement;

– the creation a system of damping RT’s own mechanical frequencies through gyroscopic angular velocity sensors;

– the creation of a matrix multipixel balometric receiver, the presence of which in the contour of the control system removes the problem of accuracy of the guidance of the optical axis of RT better than 3 angular seconds and opens up the possibility of autonomous control of individual shields of the adaptive surface of the main reflector similar to optical telescopes.

The results of the research were presented three times in 2003, 2012, and 2015 at the Bureau of Energy, Mechanical Engineering, Mechanics and Management Processes of the Russian Academy of Sciences under the direction of the members of the Russian Academy of Sciences V.E. Fortov and A.N. Lagarkov was approved and included in the REPORTS of the Presidency of the Russian Academy of Sciences on Fundamental Research. As part of the project to create the international astronomical observatory “Suffa” published a monograph (Reviewer corresponding member of the Academy of Sciences, D.A. Indeitsev). The monograph lays out the basics of creating and technical implementation of mm frequency antenna systems to detect remote cosmic objects and optimally receiving information from them by increasing the resolution of reception systems devices and the accuracy of reflectorguided systems. The principles of the theory of corpuscular radio communication and the problem of the guidance of radio telescopes on the sources of radio radiation have been tested in the foreign press.

References

1. Dergobuzov, K.A. The interaction of radiation with matter [electronic resource]. http://teachmen.ru/work/interaction (19.12.2018) (in Russian).
2. Camilleri, K. and Schlosshauer, M. (2015). Niels Bohr as Philosopher of Experiment: Does Decoherence Theory Challenge Bohr’s Doctrine of Classical Concepts. Studies in History and Philosophy of Modern Physics, 49, pp. 73-83.
3. Feynman, R.P. (2006) QED: The Strange of Light and Matter. Princeton University Press.

4. Maxwell and Clerk, J. (1 January 1865). A Dynamical Theory of the Electromagnetic Field. Philosophical Transactions of the Royal Society of London.
5. Browne, M. (2013). Physics for Engineering and Science. McGraw Hill/Schaum, New York.
6. Fluence [electronic resource]. https://dic.academic. ru/dic.nsf/ruwiki/1167669 (10.09.2019) (in Russian).
7. Jia, A.A., Huang, J.H., Feng, W., Zhang, T.C., and Zhu, S.Y. (2014). Duality of a single particle with an ndimensional internal degree of freedom. Chin. Phys, 23, pp. 30307-30314.
8. Buscemi, F., Hall, M.J.W., Ozawa, M., and Wilde, M.M. (2014). Noise and disturbance in quantum measurements: an information-theoretic approach. Phys. Rev. Lett, 112, 050401.
9. Coles, P., Kaniewski, J., and Wehner, S. (2014). Equivalence of waveparticle duality to entropic uncertainty. Nat Commun, 5, 5814.
10. Jabs, A. (2017). A conjecture concerning determinism, reduction, and measurement in quantum mechanics. Quantum Studies: Mathematics and Foundations, 3(4), pp. 279-292.
11. Berger, M.J., Hubbell, J.H., Seltzer, S.M., Chang, J., Coursey, J.S., Sukumar, R., Zucker, D.S., and Olsen, K. (2010). XCOM: Photon Cross Section Database (ver. 1.5) [electronic resource]. Retrieved March 30, 2016. http://physics.nist.gov/xcom (12.10.2019).
12. Bettini, A. (2016). A Course in Classical Physics. Waves and Light. Springer, 4, pp. 95-103.
13. She, A. and Capasso, F. (2016). Parallel Polarization State Generation. Scientific Reports, 6, 26019.
14. Lisboa, A. C. and Piqueira, J. (2016). Relativistic quantum control theory. Cybernetics and Physics, 5(1), pp. 12-15.
15. Neizvestny, S.I. and Nikulin, O.Yu. Charge coupled devices. Device and basic principles of work [electronic resource] http://www.vrsystems.ru/stati/pribori_s_zaryadovoi_svyazyu_ustroistvo_i_osnovnie_principi_raboti.htm (15.10.2019) (in Russian).
16. Dubarenko, V. (2016). Corpuscular Model of Radio Emission. Int. J. Mech. Eng. Autom. Amanda, Editors Departament IJMEA, USA Ethan Publishing Company, 3(1), pp. 40-45.
17. Muthukrishnan, A., Marlan O., Scully, M., and Zubairy S. (2008). The Concept of the PhotonRevisited/ The Nature of Light What is a Photon? Edited ByChandra Roychoudhuri, A.F. Kracklauer, Kathy Creath/ First Published, 2008 eBook Published 19 December 2017, Pub. location Boca Raton Imprint CRC Press.
18. Beyond the Standard Model. https://elementy.ru/LHC/HEP/SM/beyondSM (25.10.2019) (in Russian).

19. Dubarenko, V.V., Kuchmin, A.Yu., Artemenko, Yu.N., and Kornyushin, A.M. (2019). Control of the RT-70 radio telescope with an adaptive surface in the millimeter range. Transactions of IPA RAS, 48, pp. 29-33. (in Russian).
20. Goncharova, E., Samsonyuk, O., and Staritsyn, M. (2017). Dynamical systems with states of bounded pvariation: A new trend in impulsive control. Cybernetics and Physics, 6(4), pp. 208-214.
21. Matviychuk, O. (2016). Ellipsoidal estimates of reachable sets of impulsive control systems with bilinear uncertainty. Cybernetics and Physics, 5(3), pp. 96-104.
22. Polozov, S. and Rashchikov, V. (2018) Longitudinal motion stability of electrons inside the plasma channel of LPWA. Cybernetics and Physics, 7(4), pp. 228-232.
23. Vladimirova, L., Rubtsova, I., and Edamenko, N. (2018). Electrostatic potential calculation by application of walk-on-spheres method. Cybernetics and Physics, 7(3), pp. 152-160.
24. Dubarenko, V.V., Kuchmin, A.Yu., Artemenko, Yu.N., and Shishlakov V.F. (2019). Milimeter-wave radio telescopes with adjustable reflective surfaces. SPb., SUAI. (in Russian).
25. Dubarenko, V.V., Kuchmin, A.Yu., and Artemenko, Yu.N. (2014). Radio telescopes. SPb., Polytechnic Publishing House University. (in Russian).

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