Georgian Technical University

Investigation of Statistical Characteristics of Scattered Electromagnetic Waves in the Earth's Ionosphere and Lower Atmospheric Layers Using Designed Unique Measuring Equipment

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Project Summary

Basic research. A new statistical model of the turbulent diffusion of passive impuruty transfer in lower atmospheric layers will be proposed. The effective turbulent diffusion coefficient will take into account both molecular and turbulent diffusions. Isolines and two-dimensional pictures of passive impurity transfer at different distances from a source and in various meteorological conditions will be constructed. The algorithm of video presentation will be patented. In numerical calculations we will use ESA, NASA database and observation data of meteorological-ionospheric ground based stations. New features of the "compensation" and "double-humped" effects, along with statistical characteristics of multiple scattered electromagnetic waves in turbulent anisotropic magnetized collisional plasma taking into account both electron density and external magnetic field fluctuations (in magnitude and direction) will be investigated. The results will be valid for arbitrary correlation functions of fluctuating plasma parameters in near and far zones from a plasma slab. We will propose an algorithm determining propagation directions ("compensation angle") of the original wave in magnetized collisional anisotropic turbulent plasma with electron density irregularities at which the damping is weakened. Video presentation of the qualitative evaluation of the phase portraits of scattered radiation in anisotropic collisional magnetized plasma caused by directional fluctuations of an external magnetic field will be provided and its algorithm will be patented for different non-dimensional linear parameters characterizing geometry of the task. The video material makes it possible to restore or forecast different phenomena arising during magnetic storms, earthquakes and other disasters. The results may be used in ecology, in establishing the principles of remote sensing of ionospheric and cosmic plasma by radio using the translucent method.

Applied research. The development of new methods, design and manufacture of new multichannel equipment and implementation of new investigation of the amplitude and phase progression fluctuations at microwave propagation in opened links in relation to changes of meteorological and geomagnetic environment will be proposed. The well developed and patented by authors method of amplitude and phase progression measurements will be used during the Project implementation. The methods of measurements have no analogues and it will have great practical and commercialization interest. This equipment will not have analogues and based on the homodyne method measuring of amplitude, phase progression and the angle-of-arrival fluctuations of the scattered microwaves at propagation along the open links. The approaches to equipment design and measurements were patented by authors of project. The equipment operating frequency will be 10 GHz. The unique equipment for phase synchronization of reference oscillators, placed at opposite sides of testing microwave link will be modeled, designed and manufactured. This equipment is of need for implementing of phase progression measurements. The equipment is unique and anywhere in the world earlier was not applied. Methods of phase progression measurements and synchronization of reference oscillators are supported by series of patents. Experimental investigations of microwave propagation will have exclusive uniqueness as multi-channel measurements of microwaves phase progression were never carried out over opened links. Unique equipment will permit: to measure the meteorological, geomagnetic, and electrical values in different places of the communication link in bottom atmosphere layers; to estimate and to storage obtained data in computer memory; to experimental investigate the microwave propagation. New measuring equipment will allow carry out the certification of opened links of telecommunication system revealing "dead zones" and so on. All measuring data will be registered periodically in the computer memory with corresponding minute mark. The obtained information will be preliminary processed using specialized controllers. Developing of Multiple-Input, Multiple-Output (MIMO) conception, recommendations and its application for organization of new telecommunication system will be offered in this Project. The obtained results will have high demand for: telecommunication systems designers and users; mobile communication organizers; wireless computer network organizers; telemetry, radio navigation, radar and remote sensing.

I. Basic Research

The overall objective of this project is the investigation of statistical characteristics for scattered electromagnetic waves propagating in the lower turbulent atmospheric layers and in the anisotropic inhomogeneous magnetized ionospheric plasma on different altitudes of the Earth ionosphere. This project will solve important tasks of the global problem "Propagation in turbulent absorptive media". Combined efforts involving experimental, numerical, and theoretical studies are the key to the advancement of the field.

1. Introduction

It is well known that earthquakes, volcanic eruptions are very dangerous phenomena in the world and its population. These processes lead to the perturbation of meteorological parameters in the lower atmosphere, electron density perturbations in the upper atmosphere and ionosphere, fluctuations of geomagnetic field and hence, climate change. The ionosphere is a dispersive, time-varing, turbulent, and random medium, with irregularities frequently permeating the background ionosphere. Global research of wave processes in the atmosphere on different altitudes above the Earth surface and investigation of statistical characteristics of scattered electromagnetic waves in turbulent plasma layers are very actual for today and have practical applications in both natural and laboratory plasma [1-3].

We investigated wave processes in the atmosphere applying both deterministic and statistical methods. Deterministic scientific research is devoted to the generation and propagation of different type waves and vortex structures in the ionospheric *D*, *E* and *F* layers [4-19]. **The deterministic models** used in some studies allow electromagnetic propagation through the ionosphere to be analysed in detail, but they do not serve to allow the performance to be predicted accurately enough for compensation. These errors must be treated as random variables. **Statistical scientific research** substantially differs from previous' one in content and in the application of mathematical and numerical methods [20-23] bearing in mind problems which include randomness of the media. Presently the features of light propagation in random media have been well studied. Many review articles and monographs related to the statistical characteristics of scattered electromagnetic waves in the ionosphere with isotropic irregularities have been published [24,25]. In reality anisotropic irregularities exist permanently in the ionosphere having different nature at various altitudes above the Earth surface and mainly elongated along the geomagnetic field [26].

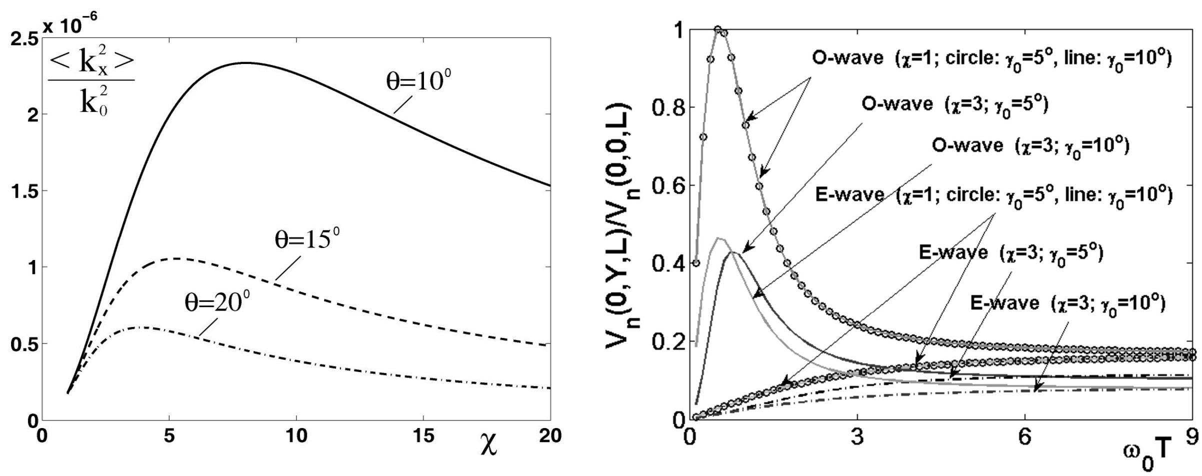
Turbulence in the atmosphere leads to the scattering of incident radiation, the transformation of spectral and energetic characteristics: intensity, energy density, and a power spectrum. Random fluctuations of electron density cause radio waves to be scattered, producing random variations in received signal amplitude and phase. Ionospheric effects were discussed on space-based radar systems (SBRs), especially on ground-looking space-based radar systems (SARs). **Two family of effects were involved here**. One is those of the background ionosphere (non-turbulent), such as dispersion, group-path delay, refraction, Faraday rotation, and phase shift. The other is those due to ionospheric irregularities, such as refractive index fluctuation, phase perturbation, angle-of-arrival (AOA) fluctuation, pulse broadening, clutter, and amplitude scintillation [27,28]. The ionosphere have significant effects on the propagation of radio waves. Disturbances due to **mean or very large-scale** ionization include attenuation, absorption, phase shift, time delay, dispersion, polarization rotation, refraction, and multipaths. Additionally, relatively **small-scale** ionospheric structure in the propagation medium can cause signal scintillation, which comprises essentially random fluctuations in the received signal phase, amplitude, AOA, and other signal properties. The refractive index of the ionosphere is determined by the local electron density; hence it will vary along the propagation path. An essentially radio wave may be specified in terms of **five parameters**: amplitude, direction of propagation, phase, frequency, and polarization, together with their time and spatial variations. At frequences below 1 GHz the ionosphere may affect any or even all of the five basic parameters defining the radio wave. Thus, the amplitude of the received radio wave may be affected by absorption, or by large-scale focusing effects, or by small-scale diffraction effects. The AOA may be changed by refraction or diffraction. The instantaneous frequency of the radio wave may be affected by fluctuations in the received phase, and the polarization of the radio wave may be changed by the magnetoionic splitting and subsequent differential absorption, refraction, and phase changes. The temporal and spatial variations of these five basic parameters may be affected by ionospheric irregularities of various sizes and, for a moving source, even by a smooth, non-turbulent ionosphere. Theories for wave propagation and scattering in random media are the bases for radio communications (one-way propagation) and radar systems (two-way propagation) including ground based and SBRs. The distortion introduced by the ionosphere includs dispersion, Faraday rotation, and scintillation [29-32]. **Generally, three kinds of effect from the ionosphere should be considered. The first** is actually a family of effects: group delay, dispersion, and Faraday rotation. They are grouped together because they all depend on the integral of the electron density along the ray path (or total electron content, TEC) through the ionosphere. The Faraday effect is the most prominent resulting from birefringence. When a linearly polarized radio wave enters an ionized medium in the presence of an external magnetic field, the radio wave splits into two oppositely rotating circularly polarized waves, travelling with slightly different velocities and along slightly different ray paths [33]. An electromagnetic wave with linear polarization, travelling in anisotropic media, such as ionospheric plasma in the presence of a geomagnetic field, is split into two characteristic waves. In the ionosphere, the characteristic polarization depends on the propagation angle relative to the direction of the steady magnetic field. When the propagation is longitudinal, the two characteristic polarizations are circular, of opposite sense. When the propagation is transverse, the two characteristic polarizations are linear but orthogonal. Linearly polarized electromagnetic waves transversing through the ionosphere are generally elliptically polarized with opposite senses of rotation, and travel independently with different phase velocities. In the northern hemisphere, the sense of rotation of the wave as it travels towards the satellite is anticlockwise and as it travels towards the Earth it is clockwise. The observer is located at the transmitter end. The Faraday rotation angle is directly proportional to the TEC along the path, to the magnetic field strength at the height of the ionosphere, and to the cosine of the angle between the satellite-to-ground path and the magnetic field lines. Polarization rotation is inversely proportional to the square of the operating frequency. The phenomenon of Faraday rotation seriously affects any space communication or radar systems that use linear polarization. **The second effect** of concern is clutter resulting backscattering by electron density irregularities on the finest scales. Such backscattering occurs frequently at high latitudes and occasionally (under conditions of geomagnetic disturbance) at middle latitudes. **The third effect** is really another family of effects occuring under the name scintillation [34], which relate to spatial and temporal fluctuations in any signal parameter, such as amplitude, phase, AOA, and polarization, caused by narrow-angle forward scattering in intermediate-scale (tens of metres to tens of kilometres) structures. Scintillation is one of the most likely threats of SBR performance, especially at low frequencies and /or low grazing angles with respect to the ionosphere (or the elongation area of the scattering structures). According to the latitude, **scintillation can be devided into two groups**: one occiring at low latitude and the other at high latitude. At low latitude, the most important scintillation source is F-spread. It is caused by rod-shaped, magnetic field-aligned bubbles, which are formed in the F-layer. F-spread is centred at the magnetic equator and has two peaks at plus and minus ten degrees latitude. At high latitude, the aurora effect is caused by solar wind and coupling of the Earth's magnetic field with the magnetic field of the sun.

ERC project overall is devoted to the integrated study of statistical characteristics of multiple scattered electromagnetic waves and its second order moments in turbulent, anisotropic, collisional, magnetized ionospheric plasma taking into account both electron density and external magnetic field fluctuations (on magnitude and in direction). The obtained results will have: **practical application** in communication, radio-sighting and navigation; in establishing the principles for remote sensing of ionospheric and cosmic plasma by radio using the translusent method; in ecology, observing distribution of pollutant ingredients and their transfer trajectories in the atmosphere at earthquakes, volcanic eruptions, magnetic storms. The influence of directional fluctuations of the geomagnetic field combining with anisotropy of randomly varying plasma parameters on statistical characteristics of scattered radiation not considered comprehensive till now as far as the problem is complicated and requires complex knowledge of **different disciplines**, and therefore **will open new horizons for science**. In this project **we will calculate** statistical characteristics of scattered frequencies (< 1 GHz) electromagnetic waves encounters ionospheric influences such as dispersion, Faraday rotation, group delay, refraction, phase and amplitude fluctuations, AOA perturbations, and scintillation.

2. Statistical characteristics of scattered electromagnetic radiation in magnetized turbulent plasma

The interaction between the Earth's magnetic field and the free electrons produces anisotropy in the permittivity of the ionosphere. It has been established that the absorption of electromagnetic waves in a turbulent collisional magnetized plasma due to particle collisions leads not only to a decrease in their amplitudes, but also to a substantial distortion in the angular distribution of a scattered field. That manifests itself most vividly when waves propagate at a great angle with respect to the external magnetic field. In this case, the angular spectrum maximum is substantially displaced with respect to the primary direction of wave propagation and an anomalously fast increase in the spectral width takes place due to absorption. When a plane wave is incident at a small angle on the interface between an isotropic collisional turbulent plasma and vacuum, the width of the angular spectrum of the scattered radiation increases monotonically with distance from a plasma boundary and approaches a certain asymptotic value (the so-called deep penetration regime). At sufficiently large angles of incidence of radiation, some new effect appear:

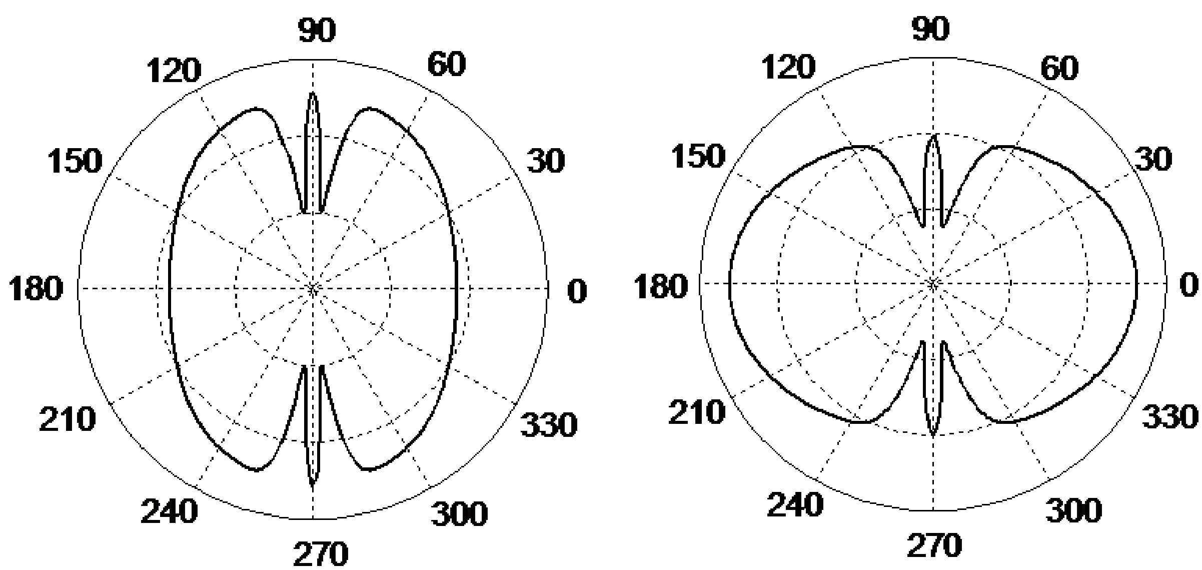
the maximum of the angular spectrum shifts toward the normal to the plasma boundary. However, as the distance from the boundary increases, the spectrum width changes nonmonotonically. When the absorption is sufficiently strong, there exists an interval of distances from the boundary within which the spectrum width substantially exceeds its asymptotic calue. Within this interval, as well as near the plasma boundary, the width of the angular spectrum increases with the absorption coefficient, all other conditions being the same (**the so-called anomalous broadening**). Moreover, within this interval of distances from the plasma boundary, the angular spectrum is highly asymmetric with respect to its maximum (the third central moment is essentially nonzero). These effects are a consequence of **the asymmetry of the problem**. Such an asymmetry occurs not only in the case of oblique incidence of radiation on a plasma-vacuum interface; it can also be an intrinsic property of the plasma in an external magnetic field. **Angular power spectrum** (APS) of scattered radiation is equivalent to brightness [35,36] entering a radiation transfer equation. It has great practical application and is experimentally observed. It can be obtained by a Fourier transform of correlation function of scattered field [1,36]. In turbulent collisionless magnetized plasma with electron density fluctuations the features of statistical characteristics of the APS (broadening and displacement of its maximum) have been considered on the basis of the stochastic eikonal equation numerical simulations were carried out using the Monte-Carlo method. Additionally external magnetic field variations were taken into consideration [37-39].



a) Dependence of the normalized broadening of the APS versus anisotropic factor for different values of refraction angle θ in XOZ plane; b) Normalized correlation function of scattered ordinary and extraordinary waves for different parameters anisotropy and angle of inclination of prolate irregularities of electron density fluctuations with respect to the external magnetic field.

First inovative aspect of the project is the investigation of the statistical characteristics of the APS for multiple scattered electromagnetic waves in collisional, magnetized, anisotropic ionospheric plasma taking into account both electron density and external magnetic field fluctuations (on magnitude and in direction). Following **different disciplines will be applied**: radio physics, plasma physics, atmosphere physics, geophysics, meteorology, theoretical aspects of partial differential equations and mathematical physics. **We will investigate analytically and**

numerically: correlation functions of the phase and amplitude fluctuations of scattered ordinary and extraordinary waves including polarization coefficients, AOAs in the principle and perpendicular planes, scintillation index, Stokes parameters, depolarization coefficients, Faraday angle and the wave structure functions for different spectra. **These statistical characteristics of scattered radiation will include:** geometry of the task, thickness of a slab, absorption coefficient, angle of incidence, angle between the direction of an external magnetic field and the normal to the layer boundary; also the anisotropy of irregularities (anisotropy factor - ratio of longitudinal and transverse characteristic linear scales of electron density irregularities and their inclination angle with respect to the external magnetic field). Two and three dimensional portraits of phase and amplitude correlation functions of scattered radiation caused by the external magnetic field directional fluctuations will be constructed for different non-dimensional parameters characterizing the geometry of the task. The obtained results will be valid for the arbitrary correlation functions of fluctuating parameters of collisional magnetized anisotropic plasma slab in near and far zones. We will investigate **Faraday rotation** phenomenon for the ordinary and extraordinary waves (including polarization) and its affect on space communication or radar systems taking into account both anisotropy of electron density and external magnetic field fluctuations (on magnitude and in direction) on different altitudes of the ionosphere; calculate Faraday rotation angle. Numerical simulation will be carried out for different spectral functions characterising ionospheric regions. We will calculate **scintillation index** S_4, extremely useful parameter, characterizes the depth of fading for the ordinary and extraordinary waves in anisotropic turbulent magnetized plasma [41]; the value of S_4 depends on geometry, frequency, and the ionization irregularity structure. Scintillations, play an important role in the influence of the ionosphere on the synthetic aperture radar system. We will obtain the value of the scintillation index as a function of the radar transmission frequency, geometry ionospheric conditions, and time of day. This investigation will also be useful in communication in the upper atmosphere. **Numerical calculations** will be carried out for different

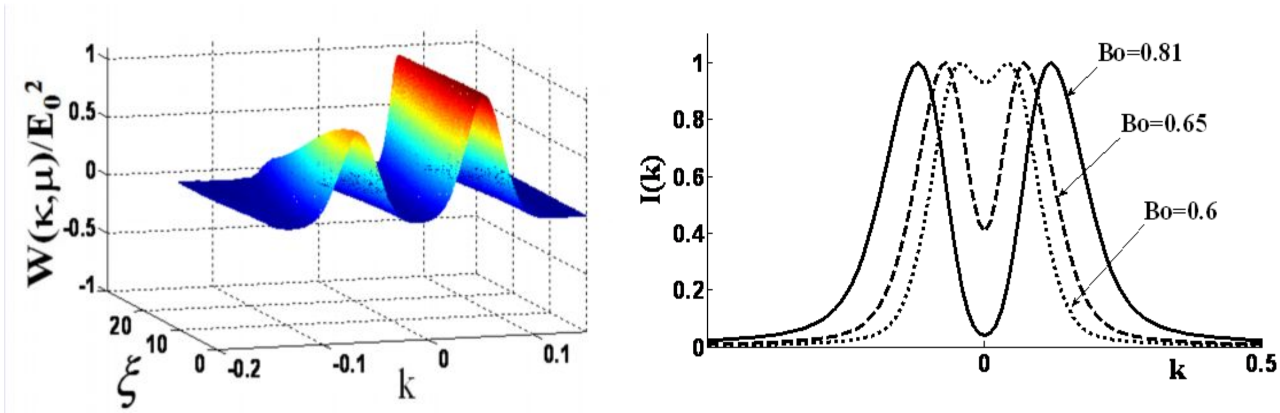


Phase portraits of the normalized phase correlation function of scattered ordinary electromagnetic waves caused by directional fluctuations of an external magnetic field spectral functions of electron density irregularities characterising these ionospheric regions, and external magnetic field fluctuations. This model will be useful in establishing principles for remote sensing of ionospheric and cosmic plasma by radio using the translusent method. Video of the qualitatively evaluation of the phase portraits of scattered radiation in anisotropic collisional magnetized plasma caused by directional fluctuations of an external magnetic field will be presented for different non-dimensional parameters characterizing the problem. **Video presentation** makes possible to restore or forecast different phenomena arising at magnetic storms, earthquakes and other disasters. **The algorithm of the phase portraits will be patented** keeping the Intellectual Property Rights during the project implementation. Experimental measurements of scattered radiation in the upper and lower turbulent atmosphere will be carried out. We will publish the results in refereed scientific journals and submit joint reports in international conferences.

3. "Double humped effect"

Second aim of the project is an investigation of a new "double humped effect" arising at inclined incidence of electromagnetic wave on the anisotropc turbulent collisional magnetized plasma with electron density and external magnetic field fluctuations using the smooth perturbation method, and taking into account diffraction effects. This effect will have practical application in communication, information trasfer and investigation new wave processes at different alititudes of the atmosphere. Following **different disciplines will be applied**: radio physics, plasma physics, atmosphere physics, hydrodynamics, theoretical aspects of partial differential equations and statistical physics. **Anisotropy irregularities have different nature**. For example characteristic length of molecules of thermotropic liquid crystals is about 20 angstrom and the ratio of their longitudinal to transverse sizes equal $4 \div 8$. Larger structures are formed in lyotropic systems, where the ratio may exceed 15. Chloroplasts of algae and plants are ellipsoidal in shape with a diameter $1 \div 5\ \mu m$ and length of $1 \div 10\ \mu m$. Prolate irregularities are oriented along a certain direction in lyotropic liquid crystals with hexagonal structure under the influence of an external electric field. Moreover, polymer macromolecules in a flow of liquid are oriented along velocity gradient. Randomly internal waves exist in the ocean, the irregularities highly elongated along the direction of the Earth's magnetic field [42-45]. Obtained results could also find extensive practical application in propagation of short-wavelength radio waves in the Earth's ionosphere, where random plasma inhomogeneities are aligned with the geomagnetic field. 2D non-absorptive medium with random irregularities extended along a direction of propagation of an initial wave has been studied on the bases of Fokker-Planck equation for the probability density of coordinates and angles of ray-propagation. Numerical solve of the equation shows that the angular distribution function has a double-peaked shape with a dip along the prolate irregularities [46-48]. Numerical simulation of the angular distribution of the intensity of an electromagnetic wave incident on a thick layer of a randomly statistically anisotropic medium with prolate inhomogeneities of the refractive index oriented along the normal to the medium boundary by the Monte-Carlo method shows that a gap is detected and the angular spectrum has a double-peaked shape. An analytical investigation of the features of the spatial power spectrum (SPS) of multiple scattered waves at oblique illumination of a boundary of randomly-inhomogeneous medium with prolate irreguarities by smooth perturbation method show that the SPS has a double-peaked shape. **A double-peaked cross section curve is**

formed due to dominant presence of scattering not only in the direction close to the incident wave but also in mirror direction. As a result the angular distribution of one-time scattering intensity



a) 3D picture of dependence of SPS of scattered electromagnetic waves versus non-dimensional parameter k in non-magnetized plasma; b) Dependence of SPS versus non-dimensional parameter k of scattered extraordinary wave in the anisotropic magnetized plasma (incident radiation has a finite width).

under oblique illumination of inhomogeneities has a conic shape. The last mentioned effect is well known among practical researchers of the ionospheric inhomogeneities. It could be observed for example in the case of ionospheric inhomogeneities exposure to radio waves with satellites. The surface thickness of wall of the cone under oblique illumination is essentially determined by the transverse scale of refractive index inhomogeneities; height of the wall is essentially determined by the longitudinal one. A double peaked shape of the cross section of the angular power distribution of the initially plane wave is observed, even in the case of $\vartheta_0 = 0$ (ϑ_0 being the angle formed by an incident plane wave wavevector and the inhomogeneities axis), at distances from the boundary of the random medium where the average field is small in comparison with the scattered one. Angular distributions of radiation power at different distances from the boundary (depths), derived by Monte-Carlo simulation shows that with increasing distance, the wave angular distribution obtains a double-peaked shape quickly, and the gap increases considerably with the distance. At first ordinary widening of the angular spectrum takes place and only after that it does gain a double-peaked shape. Moreover the last effect takes place at considerably great distances. The point is that the angular spectrum of a one-time scattered wave has a maximum, but in the spectrum of a doubly scattered field, for which the radiation initially has a non-zero angular spectrum width, a relatively small gap arises in the centre. As a result, in the case of relatively great multiple scattering, the spectrum cross-section gains a double-peaked shape. If the angular power distribution has a non-zero width already on entry into the medium then the gap in the spectrum arises and increases faster. **The ionosphere is immersed in a magnetic field and exhibits the following properties**: a) Dispersive: its index of refraction is a function of the frequency, and the group velocity is not necessarily equal to the phase velocity; 2) Absorptive: the ionospheric refractive index is complex, having real and imaginary parts. The absorption is always dissipative and represents a conversion of the wave energy into heat through the collision process; 3) Birefringent: the index of refraction has two distinct values, owing to the presence of the uniform geomagnetic field and free electron mobility. This property suggests the possibility of two ray paths, each characterized by different phase and group velocities; 4) Anisotropic: each of the two indices of refraction is a separate function of the orientation of the normal to the surface of constant wave phase with respect to the background (uniform) geomagnetic field. Properties (1) and (2) will exist even in the absence of the Earth magnetic field. The presence of the geomagnetic field leads to the last two properties, birefringence and anisotropy. In the ionosphere anisotropy of the shape of irregularities is connected with the difference of diffusion coefficients in the field align and field perpendicular directions. Because plasma diffusion along the magnetic field lines proceeds far more rapidly than across the magnetic field, structures orthogonal to the field in the lower ionosphere are maintained at all altitudes, giving the ionosphere a tube-like structure. Polarization fluctuations are attributed to scintillation caused by small-scale irregularities (scale sizes $\leq 10-200$ m at 140 MGz). The temporal and spatial properties of ionospheric inhomogeneities and the associated phase and amplitude scintillations are of utmost relevancy. The irregularities producing scintillations are predominantly in the F-layer at altitudes ranging from 200 to 1000 km with the primary disturbance region for high and equatorial latitude irregularities between 250 and 400 km. The absorption of radio waves in the ionosphere arises from the collision of the electrons (which are oscillating under the influence of the incident radio wave) with the neutral and ionized constituents of the atmosphere. **They are several kinds of absorption:** regular D-region absorption, auroral absorption events, polar cap absorption event, and F-region absorption. Influence of the absorption caused by collision of electrons with other plasma particles on the APS of scattered radiation substantially depends on the direction of an incident wave and external magnetic field. New effects arise increasing angle of incidence of electromagnetic wave on a slab: angular spectrum monotonically broadens and its maximum displaced to the normal. At big external magnetic fields the influence of medium anisotropy substantially exceeds the effects caused by an incline incidence. In the contrary, if external magnetic field is weaker or absent, the effects connecting with the incline incidence previle over the phenomena caused by the anisotropy. In this case scattering effects of radiation in plasma are the same as in isotropic media. More interesting effects are realized if medium anisotropy and incline incidence of wave are the same order.

The "double-humped effect" was considered analytically and numerically for ordinary and extraordinary waves in collisionless magnetized plasma with anisotropic electron density irregularities at inclined incidence of electromagnetic wave on plasma slab boundary taking into account diffraction effects. Investigation shows that the SPS for both waves has a double-peaked shape. External magnetic field narrows a SPS of the ordinary wave. The width of the SPS broadens travelling long distance by extraordinary wave in turbulent collisionless magnetized plasma, location of maxima insignificantly varies and a gap increases along the direction of prolate irregularities. A double-humped shape and anomalous broadening of the angular spectrum of a multiple scattered wave is a reason of statement of the asymmetry of the problem. In an asymmetric case, there are two preferential directions in an absorbing medium; the propagation direction of the original plane wave and the direction along which the wave propagates a given distance from the plasma boundary being damped to the smallest extent. As the radiation propagates away from the plasma boundary it deviates progressively from its original direction due to multiple scattering (preferential through small angles) by random smooth inhomogeneities [49,50]. Nevertheless a relatively small portion of the scattered waves occur in a narrow angular interval along the direction of weakest damping. When the absorption is sufficiently strong the amplitude of these waves decreases far more gradually than the amplitudes of other waves so a second peak can form in the angular power spectrum. Under such conditions, the width of the angular spectrum is anomalously large in comparison to that of a similar nonabsorbing medium. If the original wave propagation direction coincides with the direction of weakest dumping, then the problem is symmetric and the absorption does not lead to anomalous effects.

At investigation of the "double-humped effect" **we will consider** an evaluation of the gap of the SPS for different anisotropic spectra of electron density fluctuations including anisotropy factor taking into account angle of inclination of prolate irregularities with respect to the external magnetic field and fluctuations of geomagnetic field. As far as the influence of the absorption caused by collision of electrons with other plasma particles on the APS of scattered radiation substantially depends on the direction of an incident wave and external magnetic field, we expect that the "double-humped effect" in the magnetized ionospheric plasma **will have practical application** determining fluctuating plasma parameters in the upper atmosphere.

4. "Compensation effect"

Third inovative aspect of the project is investigation of new features for the "compensation effect" in both ionospheric anisotropic collision magnetized plasma and absorptive lower atmospheric layers using the ray- (optics) approximation and smooth perturbation method. This investigation includes **different disciplines**: radio physics, plasma physics, meteorology, and atmosphere physics. The obtained results will have practical application in radio sighting and radio navigation. We will give recommendations of their practical applications. "Compensation effect" has been revealed at investigation of statistical characteristics of the APS of multiple scattered radiation in collisional magnetized plasma with electron density fluctuations [51,52]. The geometrical optics approximation at incidence of a small-amplitude plane electromagnetic wave on a semi-infinite slab of a collisional turbulent plasma in an external uniform magnetic field have shown that for particular values of the different plasma parameters (electron density, magnetic field induction and collision frequency of electrons with other plasma particles) the oblique refraction and anisotropy compensate each other. Statistical simulation by the Monte-Carlo method shows that for a fixed collision frequency between particles, the degree to which the absorption influences the angular spectrum of the scattered waves depends strongly on the propagation direction of the original incident wave with respect to the plasma boundary and also on the strength of the external magnetic field, as well as on its inclination angle (i.e. the angle it makes with the plasma boundary). **The compensation angle defines** the direction of scattered electromagnetic waves along which neither anomalous broadening of the APS nor displacement of its center of gravity may take place. In this project compensation parameter **will be calculated containing three asymmetric factors:** oblique angle of incidence of wave, absorption coefficient and medium anisotropy. All these factors have a substantial influence on the APS but their joint action will not lead to broadening or a substantial deformation of this spectrum. Numerical calculations will be carried out by well developed methods and algorithms for different nondimensional spatial parameters using **ESA. NASA databases** and the observation data of meteorological ground based stations. **We propose an**

algorithm for determining those propagation directions of the original wave in magnetized collisional anisotropic turbulent plasma with electron density irregularities at which the absorption is weakened. Knowledge of the compensation angle is very important for the information transfer at great distances with minor losses in the lower and upper atmospheric layers. **I will patent new features of the "double-humped" and "compensation" effects** keeping the Intellectual Property Rights during the project implementation. The shift of the centroid position of the peak in the angular power distribution of the radiation scattered in the Earth's ionosphere **is a measurable quantity**. We guess that the "compensation effect" **may be detected in a quite ionosphere**.

5. Turbulent diffusion and passive impurities transfer in lower atmospheric layers

At present there are no generalized physics-mathematical models describing diffusion processes in the atmosphere. **Forth aim of the project** is elaboration of new theory of the turbulent diffusion of passive impurities transfer in lower atmospheric layers. Investigation includes **different disciplines**: radio physics, hydrodynamics, hydrology, theoretical aspects of partial differential equations and atmosphere physics. The obtained results will have wide practical applications in ecology, volcanic eruptions, radiation transfer from atomic power stations observing distribution of pollutant ingredients and theirs transfer trajectories in the atmosphere and will be useful for theoreticians and experimentators working in oceanology, meteorology and atmosphere physics.

Transfer of impurities and heat in low atmospheric layers, liquids and gases occurs by two distinguishing mechanisms. **On the one hand** molecular diffusion process is caused by variations of temperature, density and velocity vector fields leading to the molecular heat transfer, ordinary and ambipolar diffusions. **On the other hand**, laminar and turbulent motions cause redistribution of the temperature and density in the atmosphere, seas and oceans. In this case attention should be devoted to the joint action of both molecular and convective diffusions on the impurities transfer. Admixture concentration in liquids and atmosphere depends on the source power and medium features. Eruptive impurities from a source transfer in the atmosphere by different scale turbulent vortices permanently existing in the low atmospheric layers. Small scale vortices lead to instantaneous pulsations of wind flow velocity, medium-sized vortices - to the smooth variations of the velocity, large-scale vertex structures – to the substantial variations of velocity during a long time interval. These three-dimensional liquid and air structures randomly move from one place to the other one with random velocities and substantially depend on their excitation mechanism: instability, temperature gradient, heat convection, density gradients and so on. **In new theory** description of passive impurities dynamics will be based on the solution of stochastic parabolic type set of differential equations taking into account corresponding boundary conditions. Analytical expression for effective turbulent diffusion coefficient will be obtained taking into account both molecular and turbulent diffusions. Transversal and longitudinal diffusion coefficients (with respect to the stream motion) will be calculated for the different unsteady lower atmospheric layers. In this section we also will investigate wave structure functions and the influence of medium absorption on the statistical characteristics of scattered space-bounded radiation in the lower inhomogeneous atmospheric layers. The wave structure function is dominated by the phase structure function, and phase fluctuations are generally considered to be a large scale phenomenon. Isolines, three dimensional pictures and **video presentation** of passive impurities transferred on different distances from a source and at various meteorological conditions will be offered. **The algorithm of video presentation will be patented** keeping the Intellectual Property Rights during the project implementation. Transfer trajectories in the atmosphere at different meteorological conditions will have wide practical applications in ecology, at radiation transfer from atomic power stations, earthquake, volcanic eruptions, magnetic storms, and other disasters observing the distribution of pollutant ingredients. **We will carry out experimental measurements** in the upper and turbulent lower atmosphere **in Davos** in different seasons of the year looking at the evaluation of statistical characteristics caused by fluctuating meteorological parameters and geomagnetic field. At numerical calculations we will use also the **ESA, NASA databases** and the observation data of meteorological ground based stations.

6. Methodology

We will investigate statistical characteristics of scattered lower frequencies (< 1 GHz) electromagnetic waves propagating in lower turbulent atmospheric layers and anisotropic inhomogeneous collisional magnetized plasma on different altitudes of the Earth ionosphere applying various statistical methods. Analytical and numerical methods include randomness of media, that is, all parameters are random functions of the spatial coordinates. Application of different statistical methods: perturbation method, complex ray (-optics) method, smooth perturbation method, Monte-Carlo simulation, approximation of Markov processes and other one substantially depends on the ratio of the wavelength and linear scales of inhomogeneities characterising random media and formulation of the problem. Statistical scientific research is based on the solution of stochastic differential and integral equations taking into account boundary conditions characterizing given task. Combined efforts involving experimental, numerical, and theoretical studies are the key to the advancement of the field. **First inovative aspect of the project** is a new theory of the turbulent diffusion of passive impurities transfer in lower atmospheric layers using stochastic hydrodynamic and the effective dielectric permittivity method. New statistical model will be based on the solution of parabolic type stochastic set of differential equations taking into account boundary conditions. **The algorithm of video presentation** of passive impurities transfer on different distances from a source **will be patented** keeping the Intellectual Property Rights during the project implementation. The obtained results will have wide practical applications in ecology, earthquake, volcanic eruptions, magnetic storms, and other disasters observing the distribution of pollutant ingredients and their transfer trajectories in the atmosphere at different meteorological conditions. **At numerical calculations** we will use the **ESA, NASA databases** and the observation data of meteorological ground based stations. **Second aim of the project** is investigation of the statistical characteristics of the angular power spectrum for multiple scattered electromagnetic waves in collisional, magnetized, anisotropic ionospheric plasma taking into account both electron density and external magnetic field fluctuations (on magnitude and in direction). **We will investigate analytically** correlation functions of the phase and amplitude fluctuations of scattered ordinary and extraordinary waves including polarization coefficients, angles of arrivals in the principle and perpendicular planes, scintillation index, Stokes parameters, depolarization coefficients, Faraday angle and wave structural functions using complex geometrical optics approximation and smooth perturbation method. The phenomenon of Faraday rotation for the ordinary and extraordinary waves can be applied in space communication or radar systems that use linear polarization; at investigation of the behaviour of the polarization of radar signals in the space-time-frequency domain having an important bearing on radar design, as well as influencing radar techniques and signal interpretation. Faraday rotation information obtained by auxiliary systems is useful; this is typically based on measurements of satellite signals. Scintillations, play an important role in the influence of the ionosphere on the synthetic aperture radar system. We will calculate scintillation index characterizing the depth of fading for the ordinary and extraordinary waves in anisotropic turbulent magnetized plasma; its value will depend on the ionospheric conditions, radar transmission frequency, and the irregularity structure. This investigation will be useful in communication in the upper atmosphere. **Video presentation** of the qualitatively evoluation of the phase portraits of scattered radiation in anisotropic collisional magnetized plasma caused by directional fluctuations of an external magnetic field will be offered for different non-dimensional linear parameters characterizing geometry of the problem. **Video presentation makes possible to restore or forecast** different phenomena arising at magnetic storms, earthquakes and other disasters. The algorithm of the phase portraits **will be patented** keeping the Intellectual Property Rights during the project implementation. **ESA, NASA databases**, and observations data of meteorological-ionospheric ground based stations will be applied at numerical calculations using spectral functions of electron density irregularities and external magnetic field fluctuations on different altitudes above the Earth surface. The obtained results will be useful also in establishing principles for remote sensing of ionospheric and cosmic plasma by radio using the translusent method. **Third and fourth inovative aspects of the project are** investigations of a new "double humped effect" and "compensation effect" in anisotropc turbulent collisional magnetized plasma with electron density and external magnetic field fluctuations. **Analytical calculations** will be carried out using Markov approximation, the ray- (optics) approximation, and smooth perturbation method taking into account diffraction effects. **The compensation angle contains three asymmetric factors**: oblique angle of incidence of wave, absorption coefficient and medium anisotropy (anisotropy factor and angle of inclination of prolate irregularities with respect to the external magnetic field). All these factors have a substantial influence on the APS but their joint action will not lead to broadening or a substantial deformation of this spectrum. Compensation angle defines the direction of scattered electromagnetic waves along which neither anomalous broadening of the APS nor displacement of its center of gravity may take place. **We will propose an algorithm** for determining those propagation directions of the original wave in magnetized collisional anisotropic turbulent plasma at which the absorption is weakened. Knowledge of the compensation angle is very important for the information transfer at great distances with minor losses in the lower and upper atmospheric layers. We guess that the "compensation effect" may will be detected in a quite ionosphere. We expect that the "double-humped effect" in the magnetized ionospheric plasma will have practical application determining fluctuating plasma parameters in the upper atmosphere and communication. The shift of the centroid position of the peak in the angular power distribution of the radiation scattered in the Earth's ionosphere is a measurable quantity. **We will patent** new features of the "double-humped" and "compensation" effects keeping the Intellectual Property

Rights during the project implementation. **Numerical calculations** will be carried out by well developed methods and algorithms for different nondimensional spatial parameters using **ESA, NASA databases**, and the observation data of meteorological ground based stations.

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II. Applied Research

1. Introduction

All of radio engineering systems suppose the radiation and the reception of **radio waves**. State-of-art approach to radio engineering system design assumes the ubiquitous use of **microwaves** for information transfer. So, often, this peculiarity determines the system bottleneck because the microwave propagation takes place in opened links and nature processes in bottom atmosphere layers **disturb the microwave propagation**. Modern radio engineering systems widely use the **phase method** of obtaining of its **improved features** and **phase characteristics** of communication channel must be taken into account. Especially it concerns to telecommunication systems where the certain kinds of phase modulation are used for high system efficiency obtaining. There is no secret; the microwave link often does not ensure the proper communication even at line-of-sight and enough energy of the link. Especially such situation takes place at evaporation processes, presence of essential temperature gradients in bottom atmosphere layers, and so on. The channel capacity falls in several times in these cases and the right prediction of behavior of atmosphere communication channel lets to implement the adoptive radio engineering system. Besides the telecommunication tasks the operation of navigation and radar technique depends on microwave propagation directly. The accuracy of target detection can be improved taking into account the knowledge on microwave propagation. Separately, the microwave propagation can be used in a task of ecological monitoring. Rather vice versa, the reverse task can be solved. The direct electrical measurements of parameters of electromagnetic field in microwave frequency band let us obtain the data regarding the changing in environment.

So, the detail studying of microwave propagation in atmosphere bottom layers is actual and very important task. The adequate model of microwave propagation in opened link lets to improve the efficiency of any radio engineering system itself and obtain certain indirect usefulness e.g. ecological monitoring, earthquake monitoring, and so on.

Despite the microwave propagation in opened links is well studied today, certain problems at operation of telecommunication, radar, and navigation systems take place. Detail analysis of obtained worldwide theoretical and experimental results shows the essential part of these investigations is absent. First of all it concerns to investigation of phase progression at microwave propagation in opened links. Theoretical studies of microwave propagation in bottom atmosphere layers are fulfilled quite enough today. But experimental investigations **of phase progression measurements** at microwave propagation **absented** till recently as the adequate method and equipment for these measurements was not developed. The functioning of obsolete radio engineering systems did not need in these investigations as their technical characteristics were weak. But modern radio engineering systems widely use the phase method of obtaining of its improved features and phase characteristics of communication channel must be taken into account. Especially it concerns to telecommunication systems where the certain kinds of phase modulation are used for high system efficiency obtaining. The **amplitude** and **phase fluctuation** at microwave propagation **disturbs** the system **operation** and **decreases** its **efficiency**.

The phase fluctuations at microwave propagation in an opened link are caused by various reasons. The **structure** of the medium at bottom **atmosphere layers** affects the microwave propagation first of all. The dependence of atmosphere refractivity from **meteorological factors** leads to casual phase fluctuations of propagated microwave what, in turn, leads to **decreasing** of radio engineering system operation **efficiency**. **Another dependence** of characteristics of microwave propagation is weakly studied today. It’s the dependence of system operation efficiency from fluctuations of **magnetic field of the Earth**. The only thing we can affirm today the radio engineering **systems failure** at the occurrence of **geomagnetic storm**.

All of mentioned above stipulate the following: the microwave propagation in opened links and its dependence from mentioned disturbing factors must be studied in detail.

The development of **new methods,** design and manufacture of **new multichannel equipment** and implementation of **new investigation of amplitude and phase progression fluctuations** at microwave propagation in opened links in relation to changes of **meteorological and geomagnetic environment** is one of the **main goals** of this Project.

None theory has no practical value without experimental proving. The experimental investigations **of phase progression measurements** at microwave propagation **absented** till recently as the adequate method and equipment for these measurements was not developed. The well developed and **patented** by authors **method** of amplitude and phase progression measurements will be used during the Project implementation. The methods of measurements **have no analogues** and it will have great **practical and commercialization interest**. In a frame work of Project the **unique** multi-channel equipment for measurement of amplitude and phase progression of microwave signal propagating along the open links taking into account turbulences in the bottom atmosphere layers and turbulences of magnetic field of the Earth will be made. **This equipment will not have analogues and** based on the **homodyne method** measuring of **amplitude**, phase **progression** and the **angle-of-arrival** fluctuations of the scattered microwaves at propagation along the open links. The approaches to equipment design and measurements were **patented** by authors of project. The equipment operating frequency will be 10 GHz. **The uniqueness of the method and equipment consists** in implementing of the phase progression measurements while the number of phase cycles of microwave phase progression fluctuations varies in large intervals at the changes of propagation conditions. Fluctuations of phase progression of scattered microwaves on short links (up to 100 m for wave length in 3 cm) will not exceed the value of one phase cycle. The accuracy of microwave signal phase progression measurement within one phase cycle will be 1.4° (8 binary digits). This is the instrumental resolution of phase meter of equipment and there is no need in its increasing. This resolution is quite enough for mentioned above investigations. Increasing the length of the links the number of phase cycles can reach several units. Equipment will allow calculating the number of phase cycles. The calculated number of phase cycles can reach arbitrary value, but according to obvious reasons the number of phase cycles will not exceed the value in 10 at the link length up to 1 km for wave length mentioned above. Amplitude measurements will be carried out in dynamic range in 80 dB with accuracy in 0.5 dB.

The unique equipment for phase synchronization of reference oscillators, placed at opposite sites of testing microwave link will be modeled, designed and manufactured. This equipment is of need for implementing of phase progression measurements. **The mentioned measuring equipment is developed and partially made. The equipment is unique and anywhere in the world earlier was not applied. Methods of phase progression measurements and synchronization of reference oscillators are supported by series of patents.**

Developing measuring equipment will be characterized by: possibilities of synchronous measurements of multichannel electrical, meteorological, and geomagnetic characteristics. “Electrical” one assumes the measurements of amplitude and phase progression (electrical link length) of microwave signals at its propagation in an opened link. The electrical measurements are characterized with **high accuracy** and **high stability** at multichannel equipment implementation. Patented multichannel measurement method allows direct measuring of parameters of scattered microwave and obtaining its very important characteristic: **angle-of-arrival** (**AOA**). The **interferometer base** can be changed **freely** in wide range, even while the measurements are carrying out. The microwave interferometer units are not connected each with another with hard microwave feeder.

Experimental investigations of microwave propagation **will have exclusive uniqueness** as multi-channel measurements of microwaves phase progression were **never** carried out over opened links. **Unique equipment will permit:** to measure the meteorological, geomagnetic, and electrical values in different places of the communication link in bottom atmosphere layers; to estimate and to storage obtained data in computer memory; to experimental investigate the microwave propagation. **New measuring equipment will allow** carry out the certification of opened links of telecommunication system revealing “dead zones” and so on. All measuring data will be registered periodically in the computer memory with corresponding minute mark. The obtained information will be preliminary processed using specialized controllers.

Mathematical model of the microwave propagation will be elaborated in a framework of this Project. Obtained models will permit substantially shorten the time of telecommunication link testing and **therefore these models have commercial advantage.** These models will take into account as turbulence of bottom atmosphere layers as well as turbulences of magnetic field strength of the Earth. **Developing of** Multiple-Input, Multiple-Output (**MIMO) conception, recommendations and its application for organization of new telecommunication system will be offered in this Project. The obtained results will have high demand** for: telecommunication systems designers and users; mobile communication organizers; wireless computer network organizers; telemetry, radio navigation, radar and remote sensing.

Basic research of the project **is devoted to investigation of:** peculiarities of electromagnetic waves propagation and scattering in turbulent atmospheric layers at different altitudes above the Earth surface.

The obtained results **will be published** in refereed scientific journals and international symposium keeping all Copyrights Agreements.

Main goals of the Project are: Elaboration of method of measurement of **amplitude** and **phase** progression at microwave propagation on opened links. **Elaboration** of method of **angle-of-arrival** measurement at microwave propagation in opened links. **Elaboration** of the generalized mathematical model of homodyne microwave converter adequately describes the processes of signal transformations in various parts of equipment which will be designed. Great attention at this elaboration will be paid to excluding the influence of disturbing factors on accuracy and stability of signal transformation. **Simulation** of homodyne microwave converter operation for minimization of influence of disturbing factors. **Synthesis** of real homodyne microwave converter on the basis of its generalized mathematical model at equipment design. **Elaboration** of processing algorithms for adequate synchronous measurement and storage of electrical, meteorological, and geomagnetic environment data in computer memory. Electrical data will be the amplitude and the phase progression of microwave signal at its propagation in opened link. Electrical data will be fixed at various points of reception which allows obtaining important information regarding microwave angle-of-arrival. Meteorological data will be the air temperature, humidity, atmospheric pressure, speed and 3D direction of wind in a place of reception of microwave signals. Geomagnetic data will be 3D magnetic field strength of the Earth in a place of reception of microwave signals. All of mentioned above data will be obtained in real time measurements with certain periodicity which adequately represents the real processes in bottom atmosphere layer and magnetic field of the Earth. **Manufacture** of the equipment for multichannel electrical, meteorological, and geomagnetic measurements and data storage. Multichannel electrical measurements assume the **creation** of microwave and low-frequency processing units of equipment. Microwave units of equipment are not connected with hard feeder and let implement the measurements of **AOA**, changing the interferometer base freely. **Elaboration** of computer programs for obtained data processing and results presentation. **Elaboration** of theoretical model of microwave propagation in bottom atmosphere layer. **Experimental investigations** of microwave propagation in atmosphere bottom layer in relation of meteorological and geomagnetic environment. More precise **definition** of model of microwave propagation in bottom atmosphere layer. **Forming of guidance** on radio engineering systems design taking into account the particularities of microwave propagation in bottom atmosphere layers.

Project participants have scientific **experience** on investigation and elaboration of similar measuring equipment**.** The **results of project** implementation will have **commercialization interest** for**:** manufacturers of microwave equipment having different special purposes, manufacturing planners developing of radio engineering systems of various purposes, users of radio engineering systems of various purposes, scientists in microwave propagation, geosciense, and remote sensing.

Designers and manufacturers of microwave equipment are interested in low-cost microwave measuring devices which possesses high metrological characteristics (Scientific production association “Svetlana,” Sankt-Peterburg, Russia; Scientific production company “Micran,” Tomsk, Russia; Research institute “Orion,” Kiev, Ukraine; Scientific production association “Saturn,” Kiev, Ukraine; Limited company “Kvant-efir,” Kiev, Ukraine), Concern “TeleRadioTransmission,” Ukraine. **Designers, manufacturers, and users of telecommunication equipment** interested in the acquisition of parameters of opened telecommunication links. **Manufacturers** of equipment for mobile communication: Huawei Technologies Ltd company, Nokia-Siemens-Network company, Samsung Electronics Co. Ltd, Motorola inc., company, Worldwide, Mobile operators, Internet operators, Worldwide, Concern “TeleRadioTransmission,” Ukraine, “Ukrtelecom,” Ukraine. **Operators** of mobile telecommunication, such as: “MTS,” “Astelit,” and so on. **Designers, manufacturers, and users of radar and navigation equipment** (Scientific production association S.A. Lavochkin, Khimki, Russia; Design office “Yuzhnoe”, Dnepropetrovsk, Ukraine), **National cosmic agencies of different countries (**NASA, USA; Russian Cosmos, Russia; Ukraine Cosmos, Ukraine).

2. Overview

Obviously, the opened communication channel of radio engineering system plays important role at system operation. Mostly all of quality system parameters directly depend from the stability of this channel. So, the careful study of radio wave propagation in communication channel of radio engineering system is very important. Random variations of turbulent atmosphere parameters have a substantial influence on radio communication quality. The influence of destabilizing factors (humidity, temperature) on the refractive index increases in the low atmospheric layers. Radio telecommunications realizing in the low atmospheric layers demand elaboration of effective communication methods. Amplitude fluctuations and power degradation at the reception point are caused due to scattering and dumping of radio waves. For this reason signal/noise ratio becomes worse in the input radio-receiver equipment causing communication glitch, the decrease of communication range, the distortion of the received information and so on.

As it was mentioned above the microwave propagation in opened links is well studied today. However, detail analysis of obtained worldwide theoretical and experimental results of researches shows, the essential part of these investigations is absent. It concerns to investigation of phase progression at microwave propagation in opened links. Regular radio engineering systems use simple modulation technique and have weak technical characteristics. So, the investigation of phase progression is out of interest for the system characteristic improving. But modern radio engineering systems widely use phase methods of obtaining of its improved features and, obviously, phase characteristics of communication channel must be taken into account. Especially it concerns to telecommunication systems where the certain kinds of phase modulation are used for the obtaining of high system efficiency. In this case any amplitude and phase fluctuations at microwave propagation disturb the system operation and decrease its efficiency.

As to amplitude fluctuation at microwave propagation with regard to environment properties we can affirm: all or quite all is well known today. But fluctuation of phase progression at microwave propagation is not studied enough. Moreover, the fluctuations of phase progression can generate the amplitude fluctuations, which we often mistaken assume due to its own nature of origin.

Theoretically, fluctuations of phase progression at microwave propagation (Tatarsky, Rytov, a.o.) were preliminary investigated long ago. However, the experimental investigations in this field were not carried out because the adequate method and the equipment for phase progression measurements both were absent till today.

Author of Project preliminary elaborated the method of phase progression measurements at microwave propagation in an opened link. Corresponding equipment was made and preliminary experimental results on phase progression fluctuations in a couple with amplitude fluctuations with regard to meteorological changes were obtained recently. These experimental data are very promising. The equipment let us to investigate the thin structure of electromagnetic field in a point of reception. The equipment for amplitude measurements only does not “see” the detail changes of environment; disturbing factors are mostly hidden. So, mostly, we cannot adequately describe and clarify the failure of modern radio engineering system in a case of its occurrence.

As a derivation of mentioned method the method of determination of angle-of-arrival of scattered microwave was elaborated as well. This method allows further expanding our knowledge on microwave propagation because more data of thin structure of electromagnetic field are obtained in this case.

Mentioned methods were patented by authors recently.

According to these methods the initial microwave oscillations are the heterodyne signal for microwave passing twice the investigated path. Such approach to heterodyne signal forming is well known and it is named as homodyne detection. Microwave signal at first is received by transponder. Low-frequency shift is added to the initial received microwave signal. This frequency shift keeps the microwave signal phase which contains the initial phase of microwave signal plus phase shift due to the microwave propagation. Realization of the frequency shift is possible by monotonous increasing (decreasing) of the phase in received microwave oscillations. Similar operations are equivalent to the Doppler frequency shift. Speed of microwave signal phase change determines the value of the frequency shift. This phase shift was obtained under controlling low-frequency signal. For practical realization of such system it is expedient to replace linearly increasing of phase shift by the discrete one. It was shown that the discrete number of phase shifts is expedient be equal to four or eight, which is equivalent to the realization of two or three phase shifter sections. Phase shift of each section is assumed under binary law. After frequency transformation the initial phase of the microwave signal contains the added initial phase of the controlling low-frequency signal. Then the transformed microwave signal is reradiated back in a direction of primary radiated microwave. After the secondary receiving of microwave signal, the initial microwave signal and the secondary frequency-transformed microwave signal are multiplied in a mixer. In this case the low-frequency combination is selected. The frequency and the initial phase of microwave signal are subtracted from the argument. Argument of the selected harmonic signal contains only low-frequency signal. Initial phase of this low-frequency signal contains the phase shift due to microwave propagation plus initial phase of the controlling low-frequency signal. We should only ensure phase coincidence of the low-frequency oscillations in both parts of testing link. This problem was solved by synchronization of the VHF and low-frequency signals modulation. This modulated signal is transmitted and received. This problem was well investigated by Project participants.

Microwave phase variations depend on the geometry, turbulences, and other conditions in the lower atmospheric layers. In any case this phase shift substantially exceeds 2π at investigation of the phase characteristics along testing link. In reality it is possible measuring only two signals phase difference varying between 0 and 2π. At the same time, it is possible measuring the relative variation in a dynamic range substantially exceeding 2π. Such variations are revealed at weather changing conditions, at pollution of the atmospheric layer, at presence of turbulence, at variations of geometry of the microwaves propagation path, and at, possibly, geomagnetic storms. On the other hand it is possible to estimate the length of measuring links and to calculate the number of phase cycles. Combination of these methods allows obtaining more reliable processes data being along the link of microwave propagation.

Project participants have practical experience of measuring of parameters along short links. In authors' papers the influence of turbulence in the lower atmospheric layers on the amplitude and phase of the received microwave signal were considered. In these investigations electrical measurements were accompanied by meteorological one. For relatively long links it is necessary to solve both: energetic problems (transmitter power, antenna amplification and the receiver sensitivity) and oscillator frequency stabilization which is very important at phase progression measurements. There is no problem to ensure mentioned requirements at investigation of microwave propagation. The methods and devices for amplitude and phase measurements at the microwave propagation are supported by numerous authors' patents.

The design and manufacture of the improved experimental equipment for the measuring of amplitude and phase progression fluctuations at microwave propagation with synchronous meteorological measurements and 3D measurements of magnetic field of the Earth is some of the goals of this Project.

The uniqueness of the measuring equipment is defined by the possibility of measurement of microwave signal phase progression on an open link of radio-waves propagation with possibility of calculation of phase cycles number arising at fluctuations of signal phase progression, caused by changes of electric link length. The number of digits of instrument for phase difference measurements within one phase cycle can reach 14, that causes hardware accuracy of measurement of phase progression up to $360°/16384=0.022°$, however such accuracy of measurement can be realized only on short links when frequency instability of the microwave oscillator does not lead to errors of the phase measurement, exceeding the specified value. On such links the fluctuation of phase progression of a signal will not exceed the value of one phase cycle. On rather extended links the number of digits of phase difference measuring instrument within one phase cycle is expedient for choosing equal to 8, causing thus accuracy of measurement of microwave signal phase progression in value 1.4°. On such links at the change of microwave propagation conditions the value of fluctuations of its phase progression can exceed one phase cycle. The general number of digits of the measuring instrument of fluctuations of full phase progression of a microwave signal is chosen equal to 16. Thus depending on realized microwave oscillator frequency instability and measuring link length the specified number of digits of the measuring instrument is redistributed between the phase difference measurer within one phase cycle and the counter of phase cycles number.

Separate task had to be solved in a framework of project is the investigation of the system of phase synchronization of reference oscillator, placed at opposite sites of the link under the test. This system is of need for implementation of phase measurements of microwave signals. Separate VHF channel is used for this purpose. The simple kind of modulation of radio frequency carrier by the low frequency signal is used for this purpose achieving. Mentioned low frequency signal is used for phase synchronization of reference oscillators.

The mentioned measuring equipment is developed and partially made. The equipment is unique and anywhere in the world earlier was not applied. Methods of phase progression measurement are supported by series of patents. Preliminary results of the researches, related to aspects of equipment construction and some preliminary measurements, were repeatedly reported at the international conferences and always caused certain interest of an audience.

2. Expected Results and Their Application

The development of **new methods,** design and manufacture of **new multichannel equipment** for **electrical**, **meteorological**, and **geomagnetic** measurements and **data storage**, implementation of **new investigation of amplitude and phase progression fluctuations** at microwave propagation in opened links in relation to changes of **meteorological** and **geomagnetic environment** is one of the **main goals** of this Project.

The methods of phase progression measurements at microwave propagation in an opened links and the method of determinations of scattered microwave angle-of-arrival are **patented** by authors of Project. This equipment has **no analogues** as it cannot be designed on the basis of the standard measuring equipment. **New** microwave measuring equipment will be characterized by: **high accuracy**, **high stability**, **low cost**, **small dimensions** and **weight**. The solution of this problem will allow carrying out **continuous** multichannel electrical, meteorological, and geomagnetic measurements during **several seasons** on selected opened link.

The results of researches are of interest for: manufacturers of microwave equipments having different special purposes, manufacturing planners developing of radio engineering systems of various purposes, users of radio engineering systems of various purposes, scientists in microwave propagation, geoscience, remote sensing, and so on.

Main goals which should be solved during the Project implementation: 1. Elaboration of method of measurement of amplitude and phase progression at microwave propagation on opened links. **2. Elaboration** of method of angle-of-arrival measurement at microwave propagation on opened links. **3. Elaboration** of the generalized mathematical model of homodyne microwave converter adequately describes the processes of signal transformations in various parts of equipment which will be designed. Great attention at this elaboration will be paid to excluding the influence of disturbing factors on accuracy and stability of signal transformation. **4. Simulation** of homodyne microwave converter operation for minimization of influence of disturbing factors. **5. Synthesis** of real homodyne microwave converter on the basis of its generalized mathematical model at equipment design. **6. Elaboration** of processing algorithms for adequate synchronous measurement and storage of electrical, meteorological, and geomagnetic environment data in computer memory. Electrical data will be the amplitude and the phase progression of microwave signal at its propagation in opened link. Electrical data will be fixed at various points of reception which allows obtaining important information regarding microwave angle-of-arrival. Meteorological data will be the air temperature, humidity, atmospheric pressure, speed and 3D direction of wind in a place of reception of microwave signals. Geomagnetic data will be 3D magnetic field strength of the Earth in a place of reception of microwave signals. All of mentioned above data will be obtained in real time measurements with certain periodicity which adequately represents the real processes in bottom layer of atmosphere and magnetic field of the Earth. **7. Manufacture** of the equipment for multichannel electrical, meteorological, and geomagnetic measurements and data storage. Multichannel electrical measurements assume the **creation** of microwave and low-frequency processing units of equipment. Microwave units of equipment are not connected with hard feeder and let implement the measurements of **angle-of-arrival**, changing the interferometer base freely. **8. Elaboration** of computer programs for obtained data processing and results presentation. **9. Elaboration** of theoretical model of microwave propagation in atmosphere bottom layer. **10. Experimental investigations** of microwave propagation in atmosphere bottom layer in relation of meteorological and geomagnetic environment. **11. More precise definition** of model of microwave propagation in atmosphere bottom layer. **12. Forming of guidance** on radio engineering systems design taking into account the particularities of microwave propagation in atmosphere bottom layers. New multi-channel measurement method of the amplitude and phase of the microwave signals at propagation in opened links **will be developed in a framework of the Project**. **The design and manufacture of the new experimental equipment for** multi-channel measurements of amplitude and phase progression fluctuations at microwave propagation **is offered in this Project**. **Designed new equipment will be based on the uniquely elaborated and improved homodyne method** measuring **amplitude**, **phase** progression and the **angle-of-arrival** fluctuations of the scattered microwaves. **The mentioned measuring equipment is developed and partially made. The equipment is unique and anywhere in the world earlier was not applied. Methods of phase progression measurement are supported by series of patents. The uniqueness of the measuring equipment is** defined by the possibility of measurement of microwave signal phase progression on an open link of microwaves propagation with possibility of calculation of phase cycles number arising at fluctuations of signal phase progression, caused by changes of electric link length. Fluctuations of phase progression of scattered microwaves on short links will not exceed the value of one phase cycle. The number of digits of instrument for phase difference measurements within one phase cycle can reach 14, that causes the hardware accuracy of measurement of phase progression up to 360°/16384=0.022°. This is the instrumental resolution of phase meter of equipment and there is no need in its increasing. This resolution is quite enough for mentioned above investigations. Increasing the length of the links the number of phase cycles can reach several units. Equipment will allow calculating the number of phase cycles.

Synchronously with the electrical measurements the meteorological measurements of the turbulent bottom atmosphere layers and measurements of geomagnetic environment **will be carried out in the framework of this Project**.

New measuring equipment contains several parts. First part represents processing equipment of the measuring information. It will contain several (at leas two) independent microwave oscillators, microwave directional couplers, microwave directional transmitting/receiving antennas, microwave mixers, low-frequency processing unit, low-frequency oscillator combining with VHF transmitter and computer. Other parts of this equipment will be represented by transponder. Transponder will be independent unit containing microwave antenna(s), frequency converter and the local low-frequency oscillator combining with the VHF receiver. **The system of phase synchronization** of reference oscillators **will be developed and manufactured** in a framework of Project.

New meteorological equipment will carry out: measurements of the air temperature, humidity, atmospheric pressure, speed and 3D direction of wind in a place of reception of microwave signals. **New geomagnetic equipment** will carry out the measurements of 3D magnetic field strength of the Earth in a place of reception of microwave signals. Microwave signal amplitude will be measured in the dynamical range in 80 dB with the accuracy of 0,5 dB; microwave signal phase will be measured in $256 \cdot 2\pi$ range with the accuracy varied from 1,4° up to 0.022°. All measuring data will be registered periodically in the computer memory with corresponding minute marks. The obtained information will be preliminary processed using specialized controllers. The data from the central computer memory of the measuring equipment periodically will be transferred into other computer for statistical processing.

Simulation of the communication channels will be carried out at radio waves propagation. **Mathematical model** of the microwave propagation will be elaborated in a framework of this Project. This model will take into account as turbulences in bottom atmosphere layers at microwaves propagation as well as the changes of geomagnetic environment. Simulation of the equipment units for multi-channel measurements of the receiving microwave signal amplitude and phase will be carried out. **Microwaves propagation models** on the basis experimental investigations will be elaborated. Recommendations of antennas design and application of a certain design modulation of the telecommunication systems taking into account the particularities of microwaves propagation on the basis of theoretical and experimental **investigations will be developed in this Project. Recommendations** of communication channels creation in the telecommunication systems and their application in difficult conditions will be justified in this Project. These investigations will predict some features of radio communication systems, to design optimal communication systems taking into account obstacles, turbulences in bottom atmosphere layers, geomagnetic storms etc. **Developing of MIMO conception,** recommendations and its application for organization of new telecommunication system will be offered in this Project.

The obtained results **will be published** in refereed scientific journals and reported in the international symposiums.

2.1. Sustainability Implementation Plan

2.1.1. Results to be promoted

New equipment which will have much demand in the market of the modern technology and investors will be realized in this project. Namely:

- **New multi-channel equipment** for measurements of amplitudes and phase progressions of the microwave signals propagating along the opened links in bottom atmosphere layers will be designed. New measuring equipment will allow carry out the **testing of communication links** of radio engineering systems at given location and orientation of the transmitting and receiving antennas. Equipment will allow implement the investigations of microwave propagation in relation of environment changes. Equipment will allow determining of microwave **angle-of-arrival at arbitrary interferometer base**.
- **New equipment for meteorological** observations, synchronous with electrical measurements, will be designed. New meteorological equipment will implement the measurements of air temperature, humidity, atmospheric pressure, speed and 3D direction of wind in a place of reception of microwave signals.
- **New equipment for geomagnetic** observations will be designed. Equipment will allow measuring of 3D strength of magnetic field of the Earth in a place of reception of microwave signals.
- **New equipment for data storage** in computer memory will be designed. Equipment will allow to storage all of obtained electrical, meteorological, and geomagnetic data in computer memory synchronously.
- **New models** of microwaves propagation in the lower atmospheric layers will be elaborated and **the recommendations** of radio engineering (especially telecommunication) systems design for different purposes will be offered. These models will permit substantially shorten the testing time of radio engineering system operation and therefore they will have **commercial interest.** New models of microwave propagation will be of **interest of scientists** in related areas.

2.1.2. Uniqueness of results

Uniqueness of the equipment design, implemented in a framework of this project is:

- **The test of the links of radio engineering systems having various special purpose designations (radar, cosmic communication, television, cellular communications and so on).**

Equipment will allow solving important application task: **direct measurements of parameters of opened microwave links** of radio engineering system communication channel in relation to environment changes. The measurements of fluctuations of **phase progression never had been implemented** before. The use of **state-of-art kinds of phase modulation** of modern radio engineering systems **had no been tested** regarding the influence of **meteorological** and **geomagnetic changes** of environment.

- **Multi-channel measuring equipment will not have analogues**; the equipment design is based on the **homodyne method** of amplitude and phase progression measurements at microwave propagation along open links having arbitrary configuration. Developed by authors measuring methods are supported by series of patents. **New additional innovation applications will be given during the Project implementation**. Theoretical investigations of amplitude and phase progression microwave measurements using homodyne method **will be unique also**. Experimental investigations of microwave propagation in opened links **will have exclusive uniqueness** as multi-channel measurements of microwaves phase progression were **never** carried out over opened links

early till now all over the world. **Unique method** of microwave **angle-of-arrival** measurements, supported by patents, will be used during project implementation. Uniqueness of the method consists in the possibility of **freely changing of interferometer base** of measuring equipment because the microwave units of equipment **are not connected** each with another by **hard microwave feeder**.

2.1.3. Demand for results

Potential demand on the Project results is very high from the certain manufacturer groups (see below) engaging in exploitation and elaboration of radio engineering systems having different spatial-purposes in microwave band; and also from education institutions and separate radio-amateurs. The list of potential demands is listed below.

2.1.3.1. Designers and manufacturers of microwave chains and communication networks are interested in low-cost microwave measuring devices, such as:

- Scientific production association “Svetlana” Sankt-Peterburg, Russia,
- Scientific production company “Micran”, Tomsk, Russia,
- Research institute “Orion”, Kiev, Ukraine,
- Scientific production association “Saturn”, Kiev, Ukraine,
- Limited company “Kvant-efir”, Kiev, Ukraine.

2.1.3.2. Designers and manufacturers of the space technology interested in the acquisition of space communication system microwave chains parameters, such as:

- Scientific production association S.A. Lavochkin, Khimki, Russia,
- Design office “Yuzhnoe”, Dnepropetrovsk, Ukraine.

2.1.3.3. National cosmic agency of different countries, such as:

- NASA, USA,
- Russian Cosmos, Russia,
- Ukraine Cosmos, Ukraine.

2.1.3.3. Manufacturers of mobile communication systems including the equipments of the ground-based stations and mobile telephones interested in the adaptation of the communication systems to changing environment, taking into account the use of state-of-art multi parameters kinds of modulation. Manufacturers are:

- Huawei Technologies Ltd company , China,
- Nokia-Siemens-Network company, Finland, Germany,
- Samsung Electronics Co. Ltd, South Korea,
- Motorola inc., company, USA

2.1.3.4. The obtained results will have high demand from

- telecommunication systems designers and users; mobile operators: “MTS,” “Astelit,” and so on;
- wireless computer network operators; telemetry users,

2.1.4. Expected income

The expected income depends on the volume and nomenclature of the realized production. At profitability for product unit 30% expected profit rate will be from 5,000 USD up to 20,000 USD.

At annual volume from 20 till 200 pieces profit will make from 100,000 USD up to 4,000,000 USD.

Estimation of the expected profit is possible selling measuring equipment. Modern network analyzers carrying out similar measurements are very expensive, from ten and hundred thousand USD. Cost of the designed measuring equipment will not exceed 10,000 USD **which will be profitable for consumers**. At profitability for product unit 20% profit rate will be about 2,000 USD. At annual volume (300 items) profit rate will be 600,000 USD.

Additional profit from the invention within a scope of this Project is related with the certification of opened microwave links. Mobile operators spend millions dollars for networks design which are not always optimum. Certification of the specified links will allow separate enterprises to receive a profit of 1,000,000 USD.

2.1.5. Plan of implementation

2.1.5.1. Planning of the business plan on the basis of the results obtained in the framework of the Project.

2.1.5.2. Search of the investor for realization of the business plan.

2.1.5.3. Marketing researches of the market specifying potential consumers and volume of production.

2.1.5.4. Sign the contracts with potential consumers, specification of the technical characteristics and possible prices on the product.

2.1.5.5. Compilation of the technical elaboration task taking into account Project results and consumers requirements.

2.1.5.6. Formation of the Project management, designer group, financial and economic blocks.

2.1.5.7. Elaboration of the technical documents.

2.1.5.8. Calculation of the production price and realization of the cost taking into account profit rate.

2.1.5.9. Placement of orders for manufacturing of separate components of the product.

2.1.5.10. Area facilities for final assemblage of the product.

2.1.5.11. Start of the product manufacture.

2.1.5.12. Supply contracts and realization of deliveries.

2.1.5.13. Formation of a dealer network, escalating of manufacture volumes.

III. Supporting Information

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