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TROPOSCATTER COMMUNICATION LINK MODEL BASED ON RAY-TRACING

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Background. At present, the demand in tropospheric over-the-horizon communication systems determines the inherent advantages of these systems over satellite and radio-relay systems of direct visibility, especially in combat and emergency situations. Although the fundamentals of the theory of tropospheric scattering were developed as early as the middle of the last century, the development of over-the-horizon systems requires constant refinements of known theoretical positions in accordance with new data on the nature of tropospheric scattering, atmospheric inhomogeneities, capabilities of new methods for calculating and estimating radio propagation.
Objective. The aim of the work is to develop a radio link model of a trans-horizon tropospheric communication to study the possibility of controlling (improving) attenuation on such a route by changing the electrophysical characteristics of the environment, in particular atmospheric turbulence, or using artificial formations in the atmosphere.
Methods. The created model is based on the Ray-tracing method.
Results. A model of radio link losses in the over-horizon tropospheric communication (long-range tropospheric propagation) was developed, based on the ray-tracing technique in two versions: simplified, with homogeneous layers, and full, with a combination of blocks of structures of scattering spheres in each of the layers. A study of the possibility of improving attenuation along the tropospheric scattering pathway by regulating changes in the electrophysical parameters of inhomogeneities and artificial formations in the atmosphere was conducted.
Conclusions. The convergence of the results of the simulation with the data obtained by known / traditional analytical models for calculating the losses on the tropospheric scattering path confirms the adequacy of the proposed model to the statistical data of the real losses in tropospheric scattering. The obtained results indicate that, for practical purposes, the accuracy of calculations of the loss characteristics is sufficient and that they can be used to form a tropospheric dispersion route with significantly reduced loss values by artificially adding a certain liquid or solid substance to the atmospheric heterogeneity.
Keywords: troposcatter communication; troposcatter link model; over-horizon tropospheric communication; atmospheric turbulence; artificial formations in the atmosphere

I. Introduction

At present, the demand in over-horizon troposcatter communication determines the inherent advantages of these systems over satellite and radio-relay of line-of-sight systems, especially in conditions of combat and emergency situations [1]-[4]. The main problem of troposcatter communication is that most of the transmitting energy emitted is dissipated in the atmosphere (about 80% of power is lost), which makes this kind of wireless communication less effective than, for example, a radio-relay of line-of-sight [5].

All known traditional methods of increasing capacity and noise immunity of over-horizon troposcatter communication focusing on improving equipment efficiency, responsible for forming, processing and direct signal transmission between two ground stations [6]-[8].

The radical solution to the problem presented in non line-of-sight conditions is proposed in two ways: the use of a radio-signal of artificial formations in the atmosphere (rebinding of a signal from artificial formations) and the use set of (constellation) airborne drones that will perform a passive or active retransmission of a signal. Grouply coordinated application of drones can significantly improve the performance of relay processes and the possibility of implementing broadband radio access multi-station within the boundaries of such a constellation.

As artificial formations, various passive obstacles can be used, which is the result of scattering of electromagnetic waves by foil, dipole, angular and lens reflectors, reflecting antenna arrays, ionized media and aerosol formations.

Although the fundamentals of the tropospheric scattering theory were developed in the middle of the last century, however, the development of over-horizon communication systems requires constant refinement of the known theoretical positions in accordance with new data on the nature of tropospheric scattering, atmospheric heterogeneities, the possibilities of new methods for calculating and estimating the propagation of radio waves [9].

If earlier, to predict the radio waves propagation during tropospheric scattering, only statistical methods of accumulation and analysis of experimental data and large-scale integral models of tropospheric scattering volume were used, then being more widely used deterministic methods, especially based technology ray-tracing [10]-[13]. In this technique, the rays are geometrically traced from the transmitter to the receiver, taking into account the interaction with the surrounding structures (reflection, diffraction or transmission). Characteristics of the radio waves propagation are predicted based on information about the rays, such as electric field strength, angles of incidence and reflection, path length. Here, there is a correlation between the accuracy of prediction and the required computing time. For high precision forecasting is necessary to trace the ray tracing of a higher order that undergo many interactions, while taking into account as many surrounding structures. This increases the number of intermediate processes and computing time. The main problem of this technique when tracking rays is acceleration of the calculation process.

So, in [14]-[17], using the technique of ray tracing, an analytical model of the ring scattering ring (RSM) was developed that allows us to estimate the correlation of fading in tropospheric systems, depending on spatial, frequency and angular diversity. This model can use the results of real measurements of water and steam, taking into account air turbulence fluctuations. In addition, there was a comparative impact of the diversity methods that are suitable for tropospheric communications, and various spatial-frequency techniques by obtaining their distribution of achievable data rates. However, the model uses the whole volume integral scattering cross-section of the differential scattering, determined using the Rayleigh scattering spectrum Kolmogorov (variation of refractive index) and defined for this volume of distribution of heterogeneities in the atmosphere. All this considerably limits the use of the model, especially for the study of the influence of electrophysical parameters and artificial formations on tropospheric scattering, and requires the development of a new, smaller-scale model of tropospheric scattering based on the technology of beam tracing, taking into account the scattering of radio waves on individual inhomogeneities and atmospheric formations.

The purpose of this work is development of the radio link of the over-horizon troposcatter communication to study the possibility of controlling (improving) attenuation along such link by changing the electrophysical characteristics of the environment, in particular atmospheric turbulence, or the use of artificial formations in the atmosphere. On the basis of the developed model, investigate the specific laws of tropospheric scattering on inhomogeneities and artificial formations in the atmospheric, the electrical parameters of which can be regulated, and determine the limits of the possible application of artificial passive obstacles in the troposphere for the directed reflection of the radio signal of the ground station with the possibility of creating an effective long length relay radio-line.

II. LINK MODEL OF THE TROPOSCATTER COMMUNICATION

In the proposed model, the volume of tropospheric scattering is presented in the form of a multilayer structure, limited by the size of atmospheric turbulence or heterogeneity. According to the modeling of the layers, there are two variants of the representation of the propagation of radio waves through the trace of tropospheric scattering: 1) simplified - each individual layer is homogeneous with single electrophysical parameters; 2) complete - each layer is a complex structure of blocks of spherical diffusers with different electrophysical parameters.

In a simplified version of the Wolf-Bragg model, which is observed in the diffraction of X-rays in crystalline bodies, at a given angle of the scattering of the tropospheric path θ_{rez} (the tracks of a certain length) and the wavelength λ effective scattering in the direction of the point of admission is created only by those scatters which separated from each other vertically at a distance $L=\lambda/2\sin(\theta_{rez}/2)$. The distance L between parallel idealized layers of the atmosphere, which houses a source of scattering of equal size or heterogeneity of atmospheric turbulence. It is a spatial period of repetition of inhomogeneities in the troposphere. In a turbulent atmosphere, the swirling of different sizes. Additional phase shift between such layers will be $\Delta\varphi = 4\pi L \sin(\theta_{rez}/2) / \lambda$.

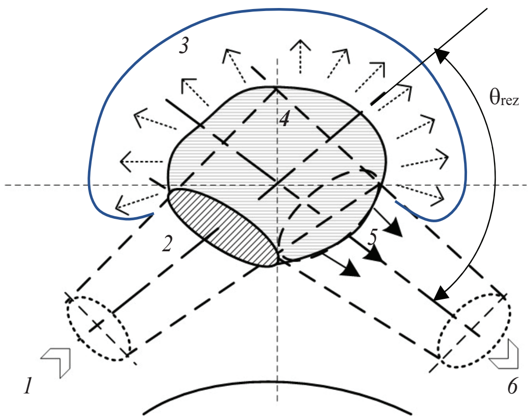

Fig. 1. Representation of tropospheric scattering volume: 1 - radiation pattern from the transmitter antenna; 2 - cross-sectional area of the radiation pattern of the transmitter antenna with a scattering volume; 3 - rays dispersed in directions that do not coincide with the radiation pattern of receiver antenna; 4 - scattering volume; 5 - cross-sectional area of the radiation pattern of receiver antenna with the scattering volume; 6 - Radiation pattern of the receiver antenna

In the case of a complete model, a complete trace of all the rays that can fall to plane 5 (Fig. 1) is performed. Each layer of the atmosphere heterogeneities is represented in the form of independent block structures (*A* and *Б*) with spherical diffusers [18] whose electrophysical parameters are described by the complex dielectric constant ε and the conductivity σ (Fig. 2). Block structures can be shifted to each other by δ_2, and spherical diffusers form a quadrature grid with a displacement δ_1. The formation of the tree of the trace occurs at several sublevels according to the structures *A* and *Б* itself - large-scale and small-scale. The technique of tracing the rays used is similar [19-20].

The result of the preprocessing of the building database is a tree structure containing start source point of transmission, secondary source points and stopped points of the prediction area, as indicated in fig. 3 in an example. In this tree every branch symbolizes a visibility relationship between two elements.

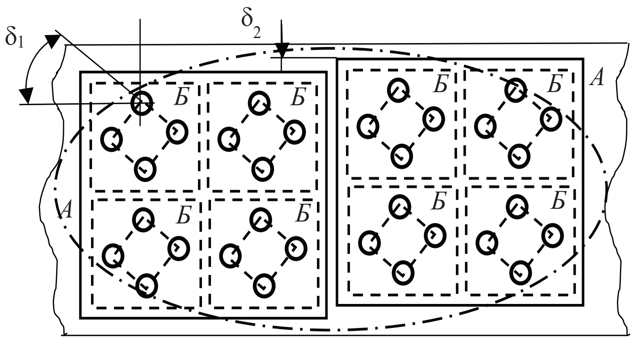

Fig. 2. Representation of a single layer of the atmosphere heterogeneities in the form of independent block structures with spherical diffusers

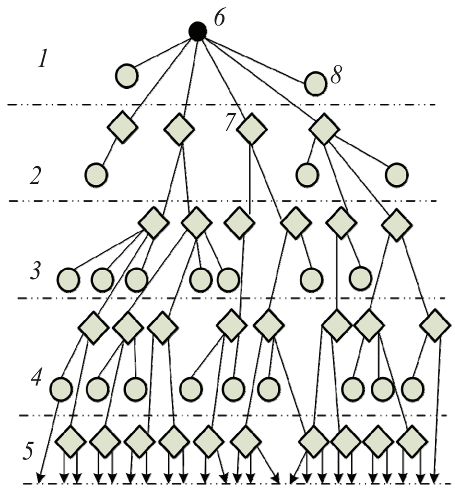

Fig. 3. The tree structure for determination of ray paths:
1, 2, 3, 4, 5 – interactions of direct ray; *6* – start source point of transmission; *7* – secondary source points; *8* – stopped points

The limiting conditions for further tracing of the ray in the scattering volume (that is, its exclusion from the calculations) are:

- the instantaneous value of the power of the electromagnetic wave at the arrival point of the ray $P_м$, taking into account the value of losses in the free space $g_м$, calculated from the arrival point of the beam to the position of the receiver antenna with the gain coefficient $G_{прм}$ in the direction to the arrival point of the beam, less receiver sensitivity of the ground station P_{ch}, that is, $P_м\ G_{прм} / g_м < P_{ch}$;
- the additional phase shift of the beam exceeds the limiting phase shift, which corresponds to the coherent bandwidth of the receiving channel;
- the direction (vector) of the beam on the boundary volume loop has a direction other than the direction to the antenna direction diagram of the receiver of the ground station (this condition may be disconnected).

The following should be noted. Any model that describes propagation through the earth's troposphere will require some description of the state of the propagation medium. The simplest propagation model may simply assume a global average atmosphere. But global and temporal variations can be large, and any model that aims to take account of this variability will need a way of representing the variability of the meteorological data.

The ITU-R community has developed a number of methods to do this. Global variability is generally described by maps and for the troposphere the key ITU-R references are Recommendation P.453 for refractive index effects and Recommendation P.837 for the effects of rain. Digital versions of these maps are available from the ITU-R Study Group 3 Website. Recommendation P.453 provides maps of various gradient and duct statistics that were derived from radiosonde measurements and numerical weather models. Some account of seasonal differences and time-variability of surface layer gradients is given.

In some cases, the method uses a combination of maps and modelling to provide the necessary data. For example, the calculation of rain attenuation in ITU-R P.837 takes three parameters that are geographically defined by means of maps and uses these in formulae that specify the time-dependence of the rain attenuation. In other cases, a simple formula has been found adequate to express the geographical variability of a meteorological parameter.

III. SIMULATION RESULTS

The calculations were made for a radio path with the following characteristics: the height above the Earth's surface of the lower point of the dispersion volume (the appearance of turbulence and heterogeneity) is 8 km; the distance from the ground stations to the lower point of the scattering is the same as their angles (the distance diagonally to the point is $d = d1 = d2$), the operating frequency of the radio waves is 4.7 GHz, the height of the location of the antennas above the Earth's surface is 5 m, mirror diameter parabolic antenna 1.8 m. The model of the plane surface of the Earth, the conditions of the standard atmosphere, the atmospheric turbulence of the Middle-European latitudes of the summer period (the dimensions of turbulence up to 500 m), the angles of the slope of the spherical structure of the volume of scattering in relation to the plane of the horizon varied to 5 degrees. For spheres of scattering as a material, water was received, and the distribution of the number of drops per cubic meter of air was determined by the Gamma drop size distributions.

Calculations of supporting median losses on the tropospheric scattering line were carried out in accordance with [9]. Support losses were used to conduct a comparative analysis of the correspondence of the results obtained with the proposed model with the reference loss data. Also, according to the reference losses, the calibration of the model was performed because it has certain components of simulation (selection δ_1, δ_2, ε, spheres size, followings of blocks *А* and *Б*, height and shape of turbulence, required number of branches of the tree of ray tracing, restriction of iterations in the layer of heterogeneities of the atmosphere and the angles of inclination of such a layer to the horizontal plane).

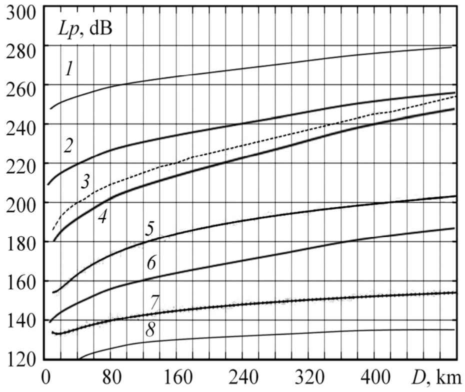

Fig. 4. The dependence of median path losses of radio waves *Lp* by the distance between ground stations *D*: 1 - model of the full version with insertion into the spheres of the imaginary component ε"= 0.035; 2 - model of the simplified version; 3 - tropospheric scattering support; 4 - model of the full version; 5 - model of the full version with dilution of the dispersion volume in the first three layers (in block *A* only one block *B* with proportional scaling of the spheres); 6 - model of the full version with a increase of ε spheres; 7 - path loss in a free space of 2*d* length; 8 - model of the full version with the insertion into the spheres of conduction σ = 10^{-3} S/m (water vapor with smog) of 10 m^2

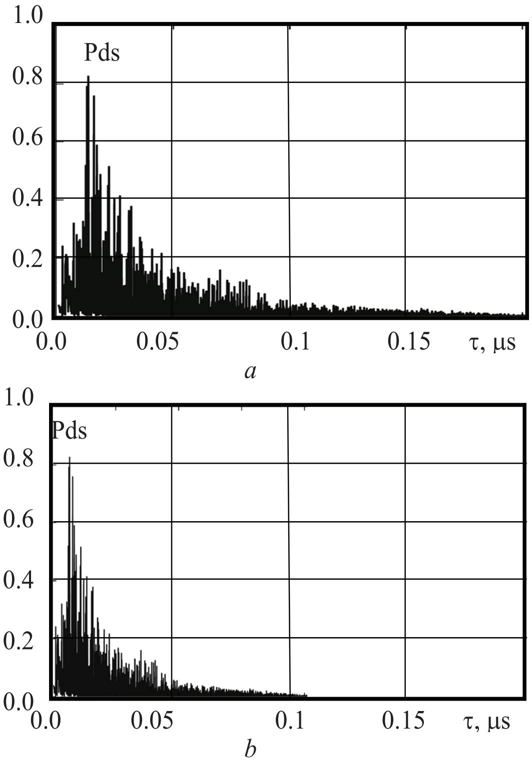

Fig. 4. Power delay spectrum Pds for a 140-km troposcatter link for 4.7 GHz: *a* - model 5 in Fig. 3; *b* - models 8 in Fig. 3

The simulation results using the proposed path loss model are shown in Fig. 4. The obtained results testify to the adequacy of the proposed model to the real experimentally obtained path losses in the tropospheric scattering (curves 2, 3, 4). The insertion of additional fading ε" to scattering spheres leads to almost linear increase in tropospheric scatter loss without changing the slope of the loss curve (curve 1). The growth of the actual part ε leads to a decrease in losses (curve 6), but to a certain value ε_{lim}, after which losses begin quite the value of ε_{lim} depends on many factors, such as all the angles of the slope of the spheres and layers structures, the angles of the location of the aerials of the ground stations, the length and height of the turbulence. The great effect on the loss of tropospheric scattering is given by the combination of *A* and *B* with a proportional scaling of the position of the spheres (especially their inclination) (curve 5). This combination can simulate almost any atmospheric turbulence. Insertion into the conduction fields dramatically reduces the path losses on the radio path (curve 8), with the greater the conductivity, the less than the layers of the dispersion volume takes part in the formation of the radio path, due to the fact that the lower layers are practically shielding the upper, reaching the effect of passive retranslation from the plane having conductivity. Practically here the process of reflection from artificial reflectors is simulated: dipoles made of aluminum foil; angle reflectors; Lüneberg lenses, representing a dielectric layer with a variable refractive index; Van-Atta antenna ray.

Fig. 4 shows the obtained values of the Power delay spectrum for two cases (link 140 km): models 5 and 8 in Fig. 3.

IV. Conclusions

The model of path losses on the radio link of the over-horizon tropospheric communication (long-range tropospheric propagation or tropospheric scattering) is developed, which is based on the technique of ray tracing in two variants: simplified with homogeneous layers and complete with combination of blocks of scattering sphere structures in each of the layers.

The study of the possibility of improving the attenuation along the link of tropospheric scattering by controlling the change in the electrophysical parameters of inhomogeneities and artificial formations in the atmosphere was carried out.

The possibility of using artificial passive formations in the troposphere for the directed reflection of the radio signal of the ground station with the possibility of creating an effective relay radio-line of large length is presented.

The convergence of the results of the simulation carried out with the data obtained by known/traditional analytical models for calculating the path losses on the tropospheric scattering path confirms the adequacy of the proposed model with statistical data of real losses during tropospheric scattering.

The obtained results indicate that the accuracy of calculations of the characteristics of path losses and the possibility of their use for forming the tropospheric scattering trail with a significantly reduced value of losses by artificially introducing into the atmospheric heterogeneity of a certain liquid or solid substance are sufficient for practical purposes.

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Модель втрат радіолінії тропосферного зв'язку на основі трасування променів

Проблематика. На даний час затребуваність в тропосферних системах загоризонтного зв'язку визначають притаманні цим системам переваги перед супутниковими і радіорелейними системами прямої видимості, особливо в умовах бойових дій та надзвичайних ситуацій. Хоча основи теорії тропосферного розсіювання були розроблені ще в середині минулого сторіччя, однак розвиток систем загоризонтного зв'язку потребує постійних уточнень відомих теоретичних положень відповідно до нових даних про природу тропосферного розсіювання, атмосферних неоднорідностей, можливостей нових методів розрахунку та оцінювання поширення радіохвиль.

Мета. Метою роботи є розробка моделі радіолінії загоризонтного тропосферного зв'язку для дослідження можливості регулювання (покращення) затухання на такій трасі шляхом зміни електрофізичних характеристик оточуючого середовища, зокрема атмосферних турбулентностей, або задіяння штучних утворень в атмосфері.

Методи. Створена модель базується на методі трасування променів Ray-tracing.

Результати. Розроблено модель втрат на радіолінії загоризонтного тропосферного зв'язку (дальнього тропосферного поширення чи тропосферного розсіяння), що базується на техніці трасування променів у двох варіантах: спрощеному з однорідними шарами і повному з комбінуванням блоків структур сфер розсіювання в кожному із шарів.

Проведено дослідження можливості покращення затухання на трасі тропосферного розсіювання шляхом регулювання зміни електрофізичних параметрів неоднорідностей і штучних утворень в атмосфері.

Висновки. Збіжність отриманих результатів проведеного моделювання із даними, отриманими відомими/традиційними аналітичними моделями, щодо розрахунку втрат на трасі тропосферного розсіювання підтверджує адекватність запропонованої моделі статистичним даним реальних втрат при тропосферному розсіянню. Отримані результати свідчать про достатню для практичних цілей точність розрахунків характеристик втрат та можливість їх використання для формування траси тропосферного розсіювання із значно зменшеними значеннями втрат шляхом штучного внесення в атмосферну неоднорідність певної рідкої чи твердої субстанції.

Ключові слова: тропосферне розсіяння; модель радіолінії; загоризонтний тропосферний зв'язок; атмосферні турбулентності; штучні утворення в атмосфері.

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Модель потерь радиолинии тропосферной связи на основе трассировки лучей

Проблематика. В настоящее время востребованность в тропосферных системах загоризонтной связи определяют присущие этим системам преимущества перед спутниковыми и радиорелейными системами прямой видимости, особенно в условиях боевых действий и чрезвычайных ситуаций. Хотя основы теории тропосферного рассеяния были разработаны еще в середине прошлого века, однако развитие систем загоризонтной связи требует постоянных уточнений известных теоретических положений в соответствии с новыми данными о природе тропосферного рассеяния, атмосферных неоднородностей, возможностей новых методов расчета и оценки распространения радиоволн.

Цель. Целью работы является разработка модели радиолинии загоризонтной тропосферной связи для исследования возможности регулирования (улучшения) затухания на такой трассе путем изменения электрофизических характеристик окружающей среды, в частности атмосферной турбулентности, или задействования искусственных образований в атмосфере.

Методы. Созданная модель базируется на методе трассировки лучей Ray-tracing.

Результаты. Разработана модель потерь на радиолинии загоризонтной тропосферной связи (дальнего тропосферного распространения), основанная на технике трассировки лучей в двух вариантах: упрощенном с однородными слоями и полном с комбинированием блоков структур сфер рассеяния в каждом из слоев.

Проведено исследование возможности улучшения затухания на трассе тропосферного рассеяния путем регулирования изменения электрофизических параметров неоднородностей и искусственных образований в атмосфере.

Выводы. Сходимость полученных результатов проведенного моделирования с данными, полученными известными/традиционными аналитическими моделями, по расчету потерь на трассе тропосферного рассеяния подтверждает адекватность предложенной модели статистическим данным реальных потерь при тропосферном рассеянии. Полученные результаты свидетельствуют о достаточной для практических целей точности расчетов характеристик потерь и возможности их использования для формирования трассы тропосферного рассеяния со значительно уменьшенными значениями потерь путем искусственного внесения в атмосферную неоднородность определенной жидкой или твердой субстанции.

Ключевые слова: тропосферное рассеяния; модель радиолинии; загоризонтная тропосферная связь; атмосферные турбулентности; искусственные образования в атмосфере.