Loss of radio waves energy on radio lines satellite-earth station

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Abstract. The main contribution of this paper is to study the influence of various natural factors on the conditions for the radio signals propagation on the satellite - Earth links. It is shown that the ionosphere practically does not interfere with satellite radio communications at frequencies above 5 GHz. The mathematical model is proposed for the numerical determination of the attenuation of the radio signal depending on the optical visibility during dust storms along the communication path.

1. Introduction
Signals propagating on radio links between spacecraft and earth stations are weakened by both deterministic and stochastic properties of radio channels. This leads to losses of energy potential on communication lines. Due to the numerous and different properties of radio channels, there are many reasons for the occurrence of energy losses during signal transmission. They are determined both by the properties of the radio channel and by the geography and topology of the radio link. Depending on the orbit of spacecraft (SC), their radio links with earth stations (ES) have certain features. For example, due to the high flight speed of near-Earth spacecraft (spacecraft flight altitude less than 2000 km), Doppler frequency shifts occur and the elevation angle of spacecraft and ES antennas changes continuously. The elevation angle of the ES antennas changes over time when working with a spacecraft moving in elliptical orbits. And the magnitude of the elevation angle of the antennas affects many parameters of radio channels and, as a consequence, the magnitude of the energy potential losses.

The most complete consideration of the properties of satellite radio channels is contained in numerous recommendations of the International Telecommunication Union [1-3]. These recommendations were developed by scientists all over the world, but on the basis of experimental data obtained in certain geographic and climatic conditions, mainly in Europe, America and Russia.

The analysis of the problem shows that at present there is no unified generally accepted method for assessing the energy potential losses arising during the propagation of a signal on radio lines from a spacecraft. There are several methods for calculating the energy of SC-ES radio lines [4-6], but some factors influencing the attenuation of radio signals have remained unaccounted for in these methods [7]. The peculiarities of the climate, for example, of Africa with tropical rains, or the Middle East with dust and sand storms, are not taken into account in the known methods for calculating the energy potential of SC-ES radio links. Therefore, we will consider the features of the propagation of radio waves on the SC-ES radio lines, taking into account such natural phenomena.
2. Loss of energy potential on satellite - Earth radio links

When transmitting information with a certain quality, the required transmission rate and the bit error probability are specified. Therefore, it is required to analyze the physical processes during the propagation of a radio signal and determine, and, if possible, analytically evaluate their impact on the loss of energy potential.

A significant reserve of energy potential of satellite communication systems is required due to the large distances between the transmitting and receiving stations. This loss is called free space attenuation. They are determined by the well-known expression [1]

\[ L = 20 \log \left( \frac{4\pi R(t)}{\lambda} \right) = 32.4 + 20 \log f + 20 \log R(t), \quad (dB), \]

where \( \lambda \) is the wavelength (km); \( f \) - frequency (MHz); \( R(t) \) - distance to satellite (km).

2.1. Influence of the ionosphere

Passing through the Earth’s radiation belts, radio waves are weakly affected by turbulently moving ionized particles caused by the solar wind and chemical processes in a rarefied atmosphere [8]. In the ionosphere, radio waves overcome the already highly ionized layers of a rarefied atmosphere. When radio waves pass through the ionosphere, Faraday rotation of the plane of polarization occurs due to the interaction of the wave with the ionized medium along the communication line. The magnitude of the Faraday rotation of the plane of polarization is determined by the expression for the angle of rotation of polarization [9]

\[ \varphi = 2.36 \cdot 10^{-14} \frac{B_a \cdot N_T}{f^2} \quad (\text{radian}), \]

where \( B_a \) is the average level of the Earth’s magnetic field (Tesla); \( N_T \) - total content of electrons (e/m²); \( f \) - frequency (GHz).

Average value of the electron content in the ionosphere (e/m²). The magnitude of the Faraday rotation of the polarization, determined on the basis of expression (2), is shown in figure 1. It can be seen from the figure that at frequencies above 10 GHz, the influence of the ionosphere on the change in the polarization of the propagating radio wave can be neglected due to its weak influence.

The median value of the polarization rotation has a regular value depending on the season, time of day and solar activity. In practice, it is compensated by adjusting the antenna polarization tilt angle. Deviations from expression (2) are possible during intense geomagnetic storms and cannot be predicted in advance. Such deviations are rare and are also not difficult to compensate for.

![Figure 1. Change in the polarization of radio waves in the ionosphere [9].](image)
It is known that charged particles slow down the propagation of radio waves by forming a group delay of the signal $t$. The group delay of the signal negatively affects the synchronization of the systems and should not be neglected. This delay is calculated in accordance with the following expression [10].

$$t = 1.345 \frac{N_r}{f^2} \cdot 10^{-7} \text{ (s)},$$ \hspace{1cm} (3)

The results of calculating the group delay of the signal in the ionosphere are shown in figure 2. At satellite communication frequencies above three gigahertz, the value of the group delay of the signals is negligible. Figures 1 and 2 show that the ionosphere actively affects the propagation of radio waves through it at frequencies below 5 GHz, and only for spacecraft using frequencies below 3 GHz can have a tangible effect on the change in polarization and signal delay.

![Figure 2. Dependence of the group delay of the signal in the ionosphere on the frequency](image)

Passing through the ionosphere, the radio signal is subject to fluctuations, which are caused by stochastic changes in the ionization density of small-scale irregularities. Such fluctuations were called ionospheric scintillations. The scintillation of the ionosphere leads to changes in the angle of arrival, amplitude and phase of the received radio signal. Interference of fluctuating signals $U$ at the input of the receiving antenna leads to fading. The full range of fading can be described by the empirically obtained expression given in the recommendations [9]

$$P = 27.55 S^{1.36} \text{ (dB)},$$ \hspace{1cm} (4)

where $S = \sqrt{\frac{\langle U^2 \rangle - \langle U \rangle^2}{\langle U \rangle^2}}$ is the scintillation index; $\langle x \rangle$ - average for the ensemble; $U$ is the intensity of the signal.

The scintillation index varies in the range from 0.1 to 1.5 depending on the signal frequency, solar activity, geography of the place and other factors. For $S = 1$, the distribution of the signal intensity $U$ is described by the Rayleigh distribution, which is most often encountered in practice. Deeper fading occurs less frequently when the scintillation index exceeds one. The deepest fading is observed in equatorial regions with high solar activity and at frequencies up to 5 GHz, their full swing can exceed 10 dB [10]. The intensity of ionospheric fading fluctuates not exceeding 1 Hz [11].

2.2. Attenuation of signals on SC-ES radio links in the atmosphere

When crossing the atmosphere, the radio signal undergoes additional attenuation. Radio waves are scattered by turbulences in the troposphere, reflected from layers of the atmosphere of different
temperatures, and attenuated in clouds, in rain, and in other hydrometeors. Reflection from atmospheric boundaries and scattering by turbulences create additional fading in the amplitude and phase of the propagating signal.

Signal fading due to the ionosphere and atmosphere is most rigorously described by multivariate probability distributions, such as the m-parametric Nakagami distribution or the four-parameter distribution [5]. The Nakagami distribution is difficult to apply in practice and it is easier to use the four-parameter distribution [12]. The four-parameter differential distribution of the transfer function of the radio channel can be described by the following expression

\[
\omega(\gamma) = \frac{\gamma}{\sigma_x \sigma_y} \exp\left(-\frac{\gamma^2}{2\sigma_x^2} - \frac{m_x^2 \sigma_y^2 + m_y^2 \sigma_x^2}{2\sigma_x^2 \sigma_y^2}\right) \times \\
\times \sum_{k=0}^{\infty} \sum_{s=0}^{\infty} \frac{(2k + 2s - 1)! (\sigma_y^2 - \sigma_x^2)^k}{k!(2s)! \sigma_y^{2k} + 4s m_k + s} \frac{m_x^2 \sigma_y^2}{2 k + 4sm_k + s} \times \\
\times \gamma^{k + s} I_{k + s} \left(\frac{m_x^2}{\sigma_x^2} \gamma\right),
\]

where: \( \gamma \) is the transfer function of the radio channel; \( I_{k+s}(z) \) - modified Bessel function of order \( k + s \); \( \sigma_x, m_x, m_y, \sigma_y \) - parameters of the four-parameter law of probability distribution.

The four-parameter law of probability distribution is quite simple to model. Depending on the value of its parameters, it is transformed into other probability distributions [12]. For example, at, the four-parameter distribution degenerates into a one-parameter Rayleigh distribution, and at, into a two-parameter truncated-normal distribution, which has been repeatedly detected experimentally, with deeper fading than with the Rayleigh distribution.

In addition to attenuating radio waves by fading, they are absorbed by the gases of the atmosphere itself. The absorption of electromagnetic waves in atmospheric gases, depending on the frequency, has a pronounced nonlinear character, as shown in figure 3. At the same time, attenuation emissions are observed at certain frequencies. Attenuation surges can be explained by resonance phenomena in oxygen and water molecules at these frequencies.

\[\text{Figure 3. Specific attenuation of radio waves in atmospheric gases.}\]
At frequencies above 5 GHz, atmospheric signal attenuation is strongly influenced by rain and other hydrometeors. Even ordinary clouds in the Ku band attenuate the satellite radio signal by almost 0.1 dB/km. Therefore, for areas with heavy seasonal rains, the methods recommended by the International Telecommunication Union for calculating the loss of energy potential in rains [3] required correction [12].

The known methods for calculating satellite radio links practically do not take into account such natural phenomena as dust and sand storms. However, they occur in many parts of the world, lasting from several hours to several days. Carried by high winds, they can occupy a height in the atmosphere of up to several kilometers. Figure 4 shows a photo of a dust storm in Russia in 2021.

In [14], a formula was determined for assessing the visibility V depending on the concentration of aerosols in the atmosphere

\[
V = \frac{5.5 \times 10^4}{N r^2},
\]

where \( N \) is the number of particles in one cubic meter of atmosphere [particles/m³]; \( r \) - average radius of particles (m)

![Aerial view of a dust storm in Russia in 2021](image)

**Figure 4.** An impending dust storm (June 2021)

When analyzing the influence of hydrometeors on a propagating radio signal, an expression is often used to estimate the attenuation of a radio signal along a path of one kilometer, that is, the linear attenuation of the signal [15].

\[
L_g = 4.343 \cdot 10^3 \cdot N \cdot \frac{\lambda^2}{2\pi} \cdot \left(\frac{2\pi r}{\lambda}\right)^3 \cdot C \quad (\text{dB/km}),
\]

where \( \lambda \) is the wavelength [m]; \( C \) is the coefficient determined by the value of the dielectric constant of aerosols.

In [16], the value of the coefficient \( C \) is defined as

\[
C = c_1 + c_2 \left(\frac{2\pi r}{\lambda}\right)^2 + c_3 \left(\frac{2\pi r}{\lambda}\right)^3,
\]

and the coefficients \( c_1, c_2, c_3 \), which depend on the values of the real \( e_{\text{re}} \) and imaginary \( e_{\text{im}} \) parts of the dielectric constant \( e \) in the aerosol atmosphere, are determined as follows:
\[ c_1 = \frac{6e_{\text{im}}}{(e_{\text{Re}} + 2)^2 + e_{\text{Im}}^2}; \]

\[ c_2 = e_{\text{im}} \left( 1,2 \left[ \frac{7(e_{\text{Re}}^2 + e_{\text{Im}}^2) + 4e_{\text{Re}} - 20}{(e_{\text{Re}} + 2)^2 + e_{\text{Im}}^2} \right] + \frac{1,67}{(2e_{\text{Re}} + 3)^2 + 4e_{\text{Im}}^2} + 0,07 \right); \]

\[ c_3 = \frac{4\left( (e_{\text{Re}} - 1)^2 \cdot (e_{\text{Re}} + 2) + \left[ 2(e_{\text{Re}} - 1) \cdot (e_{\text{Re}} + 2) - 9 \right] + e_{\text{Im}}^4 \right)}{(e_{\text{Re}} + 2)^2 + e_{\text{Im}}^2}. \]

By measuring the visibility \( V \) and substituting into expression (7) the value of the concentration of aerosols in the atmosphere from expression (6) as

\[ N = \frac{5,5 \cdot 10^{-4}}{V r^2}, \]

and the value of the coefficient \( C \) from expression (8), taking into account (9), we obtain the value of the linear attenuation of the radio signal with the frequency \( f \) [GHz] = 0.3 / \( \lambda \) [m] depending on the measured value of visibility \( V \) and on the average radius of aerosol particles \( r \) with real \( e_{\text{Re}} \) and imaginary \( e_{\text{Im}} \) parts of the dielectric constant of aerosol in the atmosphere, shown in table 1.

With increasing altitude, visibility changes and this must be taken into account. The elevation angle of the antennas determines the length of the signal propagation path in a dusty environment and this must also be taken into account. Taking into account the magnitude of the elevation angle of the antennas \( \Theta \) and the height of the dust storm \( h \), we obtain an expression for estimating the attenuation of the radio signal in a dust storm in the form of the following expression

\[ L = \frac{4,5 \cdot C \cdot f \cdot r \cdot h}{V \cdot \sin \Theta} \text{ dB}, \]

where the components have the following dimensions: \( f \) (GHz), \( h \) (km), \( V \) (km), \( r \) (m).

**Table 1.** Real and imaginary parts of the dielectric permeability of coarse aerosols in the atmosphere.

| Frequency Band | \( e_{\text{Re}} \) | \( e_{\text{Im}} \) | Reference |
|----------------|------------------|------------------|-----------|
| S              | 4.56             | 0.25             | [17]      |
| X              | 5.73             | 0.42             | [18]      |
| Ku             | 5.5              | 1.3              | [19]      |
| Ka             | 4.0              | 1.33             | [19]      |

The obtained expression (11) makes it possible to determine the attenuation of microwave signals during dust and sand storms on the communication lines of satellites with ground stations. It should be noted that the dust density along the path of radio wave propagation is different, which determines the attenuation fluctuations and additionally stimulates interference fading at the receiver input. It should also be noted that when the elevation angle of the antennas \( \Theta \) approaches zero, the attenuation \( L \) tends to infinity, since the path actually runs along the Earth's surface.

**3. Conclusion**

On the SC-ES radio lines, energy potential losses occur for a number of reasons. Due to the scintillation of the ionosphere, in addition to polarization distortions due to Faraday rotation and the group delay of
the radio signal, fading occurs. This occurs at frequencies up to 5 GHz and the total fade swing can exceed 10 dB.

In the atmosphere, signal attenuation is affected by atmospheric gases, rain and other hydrometeors, as well as dust and sandstorms. Turbulence in the atmosphere, its layering, hydrometeors and aerosols cause interference fading of the signal at the inputs of the receiving antennas. The transfer function of the radio channel under such conditions is successfully described by the four-parameter law of the probability distribution observed on the spacecraft.

The radio channel under such conditions is successfully described by the four-parameter law of the probability distribution observed on the spacecraft.

It is proposed in the methods for calculating the energy potential of satellite communication lines to take into account the attenuation introduced into radio channels by dust and sand storms, often observed in areas with a hot, sharply continental climate. An expression is obtained that makes it possible to estimate the attenuation of radio signals introduced by dust storms depending on the height of the dust storm, on the elevation angle of the ES antennas and on the dielectric constant of the dust.

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