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Electromagnetic Accessibility of Starlink User Terminals

Sergei V. Dvornikov, practicdsv@yandex.ru

Saint Petersburg State University of Aerospace Instrumentation,
St. Petersburg, 190000, Russian Federation
Military Academy of Communications,
St. Petersburg, 194064, Russian Federation

Abstract: *The results of assessing the electromagnetic accessibility of radio emission sources of the Starlink satellite communication system are presented. The features of the organizational and technical structure of the system are considered. Its main technical capabilities for organizing the provision of telecommunications services to users of subscriber terminals are analyzed. The technical features of the infrastructure of the Starlink satellite communication system, which are essential for the electromagnetic accessibility of its sources, have been studied. The possibility of radio links for transmitting information content in the upstream and downstream channels of the Starlink satellite communication system was assessed. The main stages of the developed methodology for assessing the electromagnetic accessibility of sources are presented. Analytical expressions are given for calculating the probability of detection and attenuation of signals. The requirements for the sensitivity of the receiving equipment of monitoring equipment are substantiated. Dependences of the level of signal attenuation on the distance of control equipment were obtained.*

Keywords: *assessment of electromagnetic accessibility of radio emission sources, Starlink satellite communication system, probability of correct signal detection, level of signal attenuation, sensitivity of receiving devices*

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Электромагнитная доступность абонентских терминалов Starlink

Сергей Викторович Дворников, practicdsv@yandex.ru

Санкт-Петербургский государственный университет аэрокосмического приборостроения,
Санкт-Петербург, 190000, Российская Федерация
Военная академия связи им. С.М. Буденного,
Санкт-Петербург, 194064, Российская Федерация

Аннотация: *Представлены результаты оценки электромагнитной доступности источников радиоизлучений спутниковой системы связи Starlink. Рассмотрены особенности организационно-технического построения системы. Проанализированы основные ее технические возможности по организации предоставления телекоммуникационных услуг пользователям абонентских терминалов. Исследованы технические особенности инфраструктуры спутниковой системы связи Starlink, существенные для электромагнитной доступности ее источников. Оценена возможность радиолиний по передаче информационного контента в восходящих и нисходящих каналах спутниковой системы связи Starlink. Представлены основные этапы разработанной методики оценки электромагнитной доступности источников. Приведены аналитические выражения для расчета вероятности обнаружения и затухания сигналов. Обоснованы требования к чувствительности приемной аппаратуры средств контроля. Получены зависимости уровня затухания сигнала от удаленности средств контроля.*

Ключевые слова: *оценка электромагнитной доступности источников радиоизлучений, спутниковая система связи Starlink, вероятность правильного обнаружения сигнала, уровень затухания сигнала, чувствительность приемных устройств*

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General information about the Starlink Satellite Communications System

The development of the project began in 2015, and already in February 2018, the launch of two experimental spacecraft (SC) Tintin-A and Tintin-B into low-Earth orbit, located at an altitude of about 1150 km, was successfully completed. Initially, their task was to test the developed data transmission technologies in the Ku and Ka-bands under the Starlink program [1].

By April 2019, based on the results of the test tests, the need to change the initially planned orbits was justified by reducing their altitude to 550 km and organizing spacecraft flights in 24 orbital planes with an inclination of 53 ° (https://www.eoportal.org/satellite-missions/starlink , https://habr.com/ru/post/652467).

The first test version of the full-scale operation of SSC Starlink, the grouping of which included 60 SC Starlink version 1.0, was tested by November 2019. And in October 2020, SpaceX announced its readiness to provide communication services throughout the Earth (https://www.comnews.ru/content/209438/2020-10-07/2020-w41/enciklopediya-starlink). At the same time, the emphasis was on providing high-speed access (up to 500 Mbit/s, in the absence of other subscribers in this cell) to the Internet up to an unlimited amount of traffic with a delay of no more than 20-40 ms. In August 2022, SpaceX announced a project developed jointly with mobile communications company T-Mobile to provide mobile communications services based on SSC Starlink. As a result, by the beginning of September 2022, the number of SSC Starlink users exceeded 500,000 subscriber numbers (https://en.wikipedia.org/wiki/Starlink). As the main service, the Starlink Business communication package was provided at Internet access speeds from 150 to 500 Mbit/s (https://naked-science.ru/article/tech/starlink-perehvat), [2]. As of December 2022, the number of users exceeded more than 1 million, and by May 2023 it reached 1.5 million subscribers and reached 2 million subscribers by September 2023.

Initially, it was planned that the implementation of the project would provide subscribers with telephone communications in areas not covered by terrestrial cellular networks, for which an additional set of PCS (personal communications service) equipment, presumably of the IMT-2000 standard, was installed on the Starlink spacecraft. This approach made it possible, at a speed of 2 to 4 Mbit/s, to organize the simultaneous operation of about 2000 voice calls and more than 1 million short text messages in the SSC Starlink coverage area. However, later it was decided that it was necessary to work together with standard cell phones, for which IP traffic was organized.

Currently, SSC Starlink communication services are provided in 70 countries (including Ukraine) (https://en.wikipedia.org/wiki/Starlink_in_the_Russo-Ukrainian_War). Between February 2018 and February 2023, SpaceX successfully launched 4,002 Starlink satellites into orbit, including prototypes and satellites that later failed or deorbited before entering service (https://www.eoportal.org/satellite-missions/starlink). Spacecraft are placed in orbits at an altitude of 540-570 km. Data on the general development prospects of SSC Starlink are presented in Table 1 (https://naked-science.ru/article/tech/starlink-perehvat).

TABLE 1. General Planned Composition of SC SSC Starlink Orbital Constellation of the 1st Phase

Generation of satellites	Orbital titude, km	Orbital inclination, degrees	Number of orbital planes	Number of SC in plane	Total SC in this group
Group 1	550	53	72	22	1584
Group 2	570	70	36	20	720
Group 3	560	97,6	6	58	348
Group 4	540	53,2	72	22	1584
Group 5	560	97,6	4	43	172
Total in the 1st phase of the orbital constellation					4408

And if half of the entire satellite constellation was deployed at the beginning of March 2022, then the full deployment is planned to be completed by the end of March 2027.

Further development of SSC Starlink involves a gradual transition to the second phase of deployment of the orbital constellation using SC Starlink versions 1.5 and 2.0. The main payload of SC Starlink is 2 antenna complexes for communication with gateway stations (GS) (gateways) and user terminals (UT).

The antenna complex for communication with the GS (or feeder line) is a parabolic antenna, aimed during the flight at the point on Earth where the GS is located. The system operates in the Ka-band (18/30 GHz). The characteristics of SSC Starlink communication channels are presented in Table 2 [1]. Each SC has at its disposal a frequency resource of 2100 MHz allocated in the direction from the gateway station to the SC, and a frequency resource of 1300 MHz allocated in the reverse direction. When used on left- and right-polarized lines (in the case of using circularly polarized antennas), it becomes possible to transmit traffic in a common band of 4200 MHz from GS to SC and 2600 MHz in the opposite direction.

Communication between UT and SC is carried out in the Ku-band (https://en.wikipedia.org/wiki/Starlink). In this case, a frequency band of 2000 MHz can be used to transmit information from SC to UT, and only 500 MHz from UT to SC. Taking into account the possibility of using two polarizations, the frequency range for transmitting SC traffic will be 4000 MHz for downstream transmission, and 1000 MHz for reception.

It should be noted that on board the SC there is a set of equipment for organizing the operation of the commandradio link and telemetry transmission, using a 150 MHz band in the Ka and Ku bands, respectively.

TABLE 2. Characteristics of SSC Starlink Communication Channels

Type of communication channel and direction of reception and transmission	Frequency ranges, GHz	Available MHz in one
Service: downlink (SC – UT)	10.7-12.7	2000
Service: downlink (SC – GS)	17.8-18.6 18.8-19.3	800 500
Service: uplink (UT – SC)	14.0-14.5	500
Service: uplink (GS – SC)	27.5-29.1 29.5-30.0	1600 500
Telemetry and Down Control (downlink SC - control station)	12.15-12.25 18.55–18.60	100 50
Telemetry and upstream control (uplink control station – SC)	13.85–14.00	150

All Starlink SCs operate in repeater mode, i.e. without processing information. On board, only the frequency of the received signal is changed (converted) and amplified (https://naked-science.ru/article/tech/starlink-perehvat).

In addition, the 1st generation SC does not provide for communication between satellites (ISL – Inter Satellite Link), so they can only receive and transmit information to the GS located on Earth.

4 earth stations are declared as TT&C stations (control, monitoring, telemetry reception), including the Brustner teleport, located in Washington state. The Starlink spacecraft is within the visibility range of the TT&S station for no more than five minutes, while the volume of data collected from the SC orbital constellation as of June 2020 reached 5 TB per day, i.e. at least 10 GB from one SC per day (https://en.wikipedia.org/wiki/Starlink). On board each SC Starlink there are about 70 separate processors running the Linux operating system and about 10 microcontrollers.

Being in low-Earth orbit, at an altitude of 550 km, the SC is capable of "covering" with its signal a spot on the Earth's surface with a radius of about 950 km (i.e., a diameter of about 1900 km), provided that the elevation angle for the UT is at least 25 ° [1] .

Separately, it should be noted that effective operation of antennas with a flat phased array is possible only at an elevation angle of 40 ° or more.

The initial development of SSC Starlink was focused on the use of directional antennas, the characteristics of the radiation patterns (RP) of which are given in Table 3 [1]. Table 3 correspond to the conditions according to which the diameter of the beam spot on the earth's surface is 45 km, which corresponds to the angle RP of the SC beam of 4.5 ° (when deviating from the nadir line, the angle can vary from 3 to 5 degrees, the further from the nadir line, the greater corner); EIRP – equivalent isotropic radiated power.

Theoretically, each Starlink SSC is capable of forming up to 300 access zones for UTs, taking into account left and right polarization. In addition, it can operate in two frequency bands, provided that the maximum tilt angle of the UT antenna system is not less than 25 °.

TABLE 3. Characteristics of Up and Down Lines

Channel type	Frequency	Modulation type	Maximum EIRP	Half Power RP Beam Width
Downlink (SC – UT)	10.7–12.7 GHz	from QAM-2 to QAM-64	No data	3.5 ° (boresight) 5,5 ° (at slant)
Uplink (UT – SC)	14.0–14.5 GHz	from QAM-2 to QAM-64	38.2 dBW	2.8 ° (boresight) 4,5 ° (at slant)

In Fig. 1 shows the topology of SC Starlink availability zones for UTs declared by SpaceX [1].

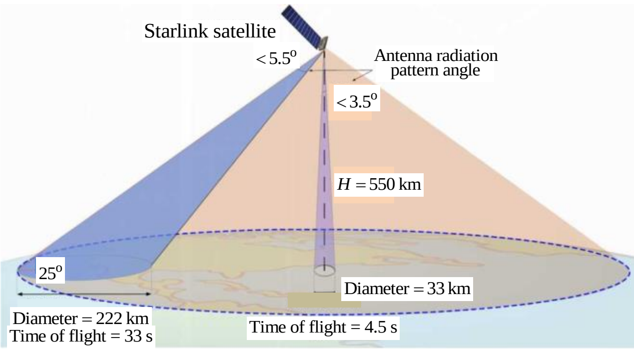

Fig. 1. Starlink SSC Availability Area Topology for UT, Formed by RP SC

The generated downlink channel from SC to UT has a maximum width of 240 MHz, while the uplink channel bandwidth is only 60 MHz (https://pikabu.ru/story/yentsiklopediya_starlink_ot_spacex_rozhdenie_struktura_i_razvitie_ch2_7762860). This configuration is optimal from the point of view of efficient use of the frequency resource, since as a result, no more than 16 beams are formed within the coverage area of one SC, which fully use the available frequency resource of the Ku-band, equal to 4000 MHz. These values are obtained taking into account the guard intervals and frequencies used for the radio command link and telemetry transmission, in the case of using both types of polarizations when transmitting information content from SC to UT, see Fig. 2 [1]. According to the configuration the Starlink SC SSC accessibility zone with an elevation angle of up to 25 ° at an orbital altitude of 550 km is a circle with a diameter of approximately 1900 km. Accordingly, the area of such a zone is exactly 2,835,294 sq. km. Then, with an orbit altitude of 550 km, the SC flight time of the UT accessibility zone is only 4.1 minutes or about 250 s [2].

An analysis of the topology of the UT availability zone shows that the greatest efficiency of the SC – UT radio link is ensured when subscribers are not at the nadir (sub-satellite point), but in the peripheral visibility zone, even taking into account the fact that there the effective antenna area is reduced, which in turn leads to to a decrease in radio link capacity. These features are due to the possibility of rotating the UT antenna towards the SC to ensure an optimal angle between the phased array plane and the direction towards the SC (ideally 90 °).

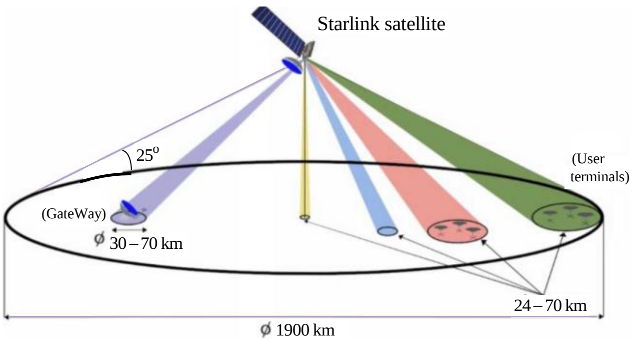

Fig. 2. SC SSC Starlink Access Configuration to UT

The overall coordination and management of the entire SSC Starlink, GS and UT network is carried out by the Network Control Center (NCC). Due to the lack of information about the NCC, it can be assumed that its basis is a set of servers interconnected by fiber optic communication lines with GS. The NCC complex also includes the ground-based complex for the Control and Collection of Telemetry of the Starlink network, consisting of 4 teleports with installed stations for the control and collection of telemetry systems in the Ku and Ka-band [1]. Geographically, they are located in Brewster (Washington State in the USA), Cordova (Argentina), Tromso (Norway), Avarua (New Zealand).

The telemetry and control channel for each SC can be active for up to 2.5 hours per day (12 minutes per revolution around the Earth) with an estimated telemetry session time of 60 minutes per day (or 10 minutes per orbit) (https://pikabu.ru/story/yentsiklopediya_starlink_ot_spacex_rozhdenie_struktura_i_razvtie_ch2_7762860).

The basis for UT access to the Internet is GS, which ensures the transmission of information through SC. In the absence of communication with the SC, for the UT to function, it is necessary that at least one GS be located in the SC access area, capable of simultaneously working with hundreds and thousands of UTs. A typical GS has 8 antennas, each of which is capable of transmitting information to its "own" SC.

Currently, SSC Starlink on GS uses 50 W transmitters and parabolic antennas with a mirror diameter of 1.5 m. These antennas, unlike phased arrays, can operate at low elevation angles (according to SpaceX – up to 5 °). At the same time, the terminal provides a channel capacity of 500 MHz (including guard intervals, up to 480 MHz). And the equivalent isotropic radiated power (EIRP) reaches 66.5 dBW (https://en.wikipedia.org/wiki/Starlink).

The operational capabilities of UT SSC Starlink are much more modest. Initially, SpaceX announced 5 types of UT, which are positioned as Model "ES, A, (B, C, D, E)". Technical characteristics of UT are presented in Table 4 (https://www.comnews.ru/content/209438/2020-10-07/2020-w41/enciklopediya-starlink).The first 2 columns refer to earth stations for satellite control and monitoring tasks, and the last five are US.

TABLE 4. Technical Characteristics of SSC Starlink Terminals

Elements	Model "Space* Telem Ku/Ka"	Model "Space* Telem X"	Model "ES A"	Model "ES – B"	Model "ES – C"	Model "ES – D"	Model "ES – E"
Antenna name and model number	CGC Technology T450	Orbital Systems 3.7 Meter	SpaceX	SpaceX	SpaceX	SpaceX	CGC Technology T450
Antenna type	Cassegrain parabolic antenna	Parabolic antenna with main focus	Phased array antenna	Phased array antenna	Type unknown	Parabolic antenna	Cassegrain parabolic antenna
Frequency range	Operation over the entire range of declared frequencies	2.0–2.1 GHz uplink 7.2–8.4 GHz descending channel	Operation over the entire range of declared frequencies	Operation over the entire range of declared frequencies	Operation over the entire range of declared frequencies	Operation over the entire range of declared frequencies	Operation over the entire range of declared frequencies
Maximum Gain / RP width at 3 dB roll-off level	Uplink (Ku): 26 dB 0.22 °. Descending line (Ku): 22 dB 0.3 °. Downward channel (Ka): 27 dB 0.2 °.	Uplink: 8.9 dB; 1.7. Downward channel: 16.8 dB; 0.8 °	3 dB at 3.5 ° full beam	7 dB at 2 ° full beam	6 dB at 2.4 ° full beam	16 dB at 0.9 ° full beam	Uplink: 26 dB; 0.22 °. Downward channel: 22 dB; 0.3 °

In Table 4 Model "Space* Telem Ku/Ka" and Model "Space* Telem X" belong to GS (used for management and monitoring of SC). UTs on the Starlink network can operate receive channels (downlink) in the frequency range 15, 30, 60, 120 and 240 MHz. This distribution allows for symbol rates of 15, 30, 60, 120 and 240 MBd/s (https://pikabu.ru/story/yentsiklopediya starlink ot spacex rozhdenie struktura i razvitie ch2 7762860). At the same time, the information speed of the incoming stream reaches 350 Mbit/s, and the outgoing one – 130 Mbit/s. Typically, UT operation is carried out in the 60 MHz band. And with an effective antenna diameter of 48 cm and an RP angle of 2.8 °, an EIRP of 38.2 dBW is provided, see Table 4. The power of the UT transmitter can vary depending on its inclination relative to the zenith line. In the case when the antenna beam is directed to the zenith, the power supplied to the antenna is 0.76 W (with a maximum deviation from the vertical of 4.06 W).

The spectral efficiency of the UT for reception with a channel width of 240 MHz and a transmission rate of 350 Mbit/s is only 1.5 bits/Hertz.

Methodology for Assessing EMA of SSC Starlink Subscribers

When assessing the Electromagnetic Availability of terminals of the Starlink Satellite Communication System, we will determine as the main indicator the probability of detecting the P_{det} signal in the receiving paths of monitoring equipment.

Next, we introduce the following assumptions:

1) the signal detection process (distribution of amplitude values of detected signals) obeys the normal distribution law:

$$\Delta F_{res} T_{av} >> 1, \ (\Delta F_{res} T_{av} \geq 10), \qquad (1)$$

where ΔF_{res} – receiver path bandwidth, Hz; T_{av} – process averaging time, s;

2) at the first stage, only the internal noise of the receiver is taken into account;

3) signal spectrum width ΔF_s, Hz, coordinated with the bandwidth of the control means receiving path ΔF_{res}, т. е. $\Delta F_s = \Delta F_{res}$.

Under the assumptions made, the value of P_{det} can be calculated using the following formula [3–5]:

$$P_{det} = \Phi\left(\frac{h^2\sqrt{\Delta F_{res} T_{av}} - \Phi^{-1}(1 - P_{fa})}{1 + h^2}\right), \qquad (2)$$

where h^2 – signal-to-noise ratio in terms of power at the receiver input, dB; P_{fa} – false detection probability; $\Phi(x) = 1/\sqrt{2\pi}\int_{-\infty}^{x}\exp(-t^2/2)dt$ – probability integral; $\Phi^{-1}(x)$ – inverse function $\Phi(x)$.

To solve the detection problem, we determine the value of P_{fa} in the range of values from 10^{-6} to 10^{-3}.

As initial data we will assume:

– signal bandwidth equal ΔF_s = 60 MHz;
– duration of signal processing no more 33 mks;
– process average value T_{av} = 40 mks;
– probability of false alarm $P_{fa} = 10^{-3}$.

Taking into account the accepted initial data and the assumptions made, expression (2) can be transformed to the following form:

$$P_{det} = \Phi\left(\frac{4{,}9\,h^2 - 3{,}2}{1 + h^2}\right), \qquad (3)$$

where $h^2 = P_s/\sigma_N^2$ – ratio of signal power P_s to power/noise spectral density σ_N^2 (SNR) at the control receiver input.

In Fig. 3 shows a graph of the probability of detecting the SSC Starlink signal in the 60 MHz band according to the Neyman-Pearson criterion at the false alarm probability value $P_{fa} = 10^{-3}$ [6].

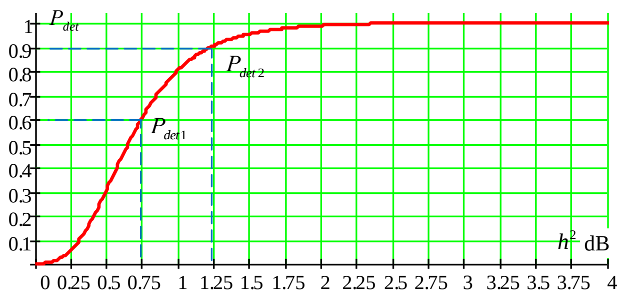

Fig. 3. Dependence of the Probability of Detecting a Starlink SSC Signal on the SNR Value in the Channel

In Fig. 3 shows two points corresponding to the probability values $P_{det\,1}$ = 0.6 and $P_{det\,2}$ = 0.9.

Note that for the conditions under consideration the probability $P_{det\,1}$ = 0.6 is ensured at an SNR value of the order h_1^2 = –1.25 dB. And the probability $P_{det\,2}$ = 0.9 provided at SNR value h_1^2 = 1 dB.

The obtained result allows us to conclude that, theoretically, SSC Starlink signals are quite easily detected, despite the wide operating frequency range.

Next, we will evaluate the conditions for radio monitoring of UT signals during operation of the uplink UT – SC. Thus, the power of the SSC Starlink signal at the receiving point can be estimated by the following expression [7, 8]:

$$P_s = \frac{P_{tr}\, G_{tr}(f_s)\, G_a(f_s)\lambda^2}{(4\pi R)^2}, W, \qquad (4)$$

or else

$$P_s = P_{tr} + G_{tr}(f_s) + G_a(f_s) + 20\lg(\lambda^2) - 20\lg(R) - 22, \text{dB}, \qquad (5)$$

where P_{tr} – SSC Starlink terminal transmitter power, dB; $G_{tr}(f_s)$, $G_a(f_s)$ – antenna gains of the SSC Starlink terminal and radio control receiver, dB; λ – signal emission wavelength, m; R – distance from the SSC Starlink terminal to the location of radio control facilities, m.

Next, let's estimate the noise level:

$$\sigma_N^2(\Delta F_{res}) = \sigma_{n.a.}^2(\Delta F_s) + \sigma_{n.res.}^2(\Delta F_s), \text{W/Hz}, \qquad (6)$$

where $\sigma^2_N(\Delta F_{res})$ – noise power dispersion; $\sigma^2_{n.a}(\Delta F_s)$ – antenna noise dispersion in band ΔF_s, W/Hz; $\sigma^2_{n.res.}(\Delta F_s) = N^2_{n.res}(f_s)\Delta F_s$ – noise dispersion in the signal reception band ΔF_s, W/Hz; $N^2_{o.n}(f_s)$ – noise power spectral density at frequency f_s, dBm (dB relatively 1 mW/Hz) in other ways dB (dB relatively 1 W/Hz); $N^2_{n.res}(f_s) = 10^{\frac{N^2_{o.n}(f_s)-30}{10}}$ – noise power spectral density at frequency f_s, W/Hz. Then:

$$\sigma^2_N(\Delta F_{res}) = \sigma^2_{n.a.}(\Delta F_s) + \sigma^2_{n.res.}(\Delta F_s). \quad (7)$$

Antenna noise power dispersion $\sigma^2_{n.a}(\Delta F_s)$ calculated as:

$$\sigma^2_{n.a}(\Delta F_s) = 10^{-12} 10^{\frac{E^*_{n.a}(f_s)}{10}} \Delta F_s h^2_a / R_a, \quad (8)$$

where $E^*_{n.a}(f_s)$ – spectral sensitivity of the antenna at frequency f_s, dB (mkV/m); $h_a = 2\sqrt{R_a G_a(f_s)\lambda^2/4\pi Z_0}$ – effective antenna height (m); R_a – antenna resistance (Ohm); Z_0 = 120π – characteristic impedance of free space (Ohm)]; $G_a(f_s)$ – enemy antenna gain (dB).

As a result, expression (8) will be presented in the following form:

$$\sigma^2_{n.a}(\Delta F_s) = 9 \times 10^{\frac{E^*_{n.a}(f_s)+40}{10}} \Delta F_s G_a(f_s)/(\pi Z_0 f^2) \quad (9)$$

and the noise power dispersion can be calculated as (10). Then the formula for h^2 let's rewrite it to form (11).

$$\sigma^2_N(\Delta F_{res}) = \left(9 \times 10^{\frac{E^*_{n.a}(f_s)+40}{10}} G_a(f_s)/(\pi Z_0 f^2) + 10^{(N^2_{o.n}(f_s)-30)/10}\right)\Delta F_s. \quad (10)$$

$$h^2 = \frac{P_{tr}\, G_{tr}(f_s)\, G_a(f_s)\lambda^2}{(4\pi R)^2 \left(9 \times 10^{\frac{E^*_{n.a}(f_s)+40}{10}} G_a(f_s)/(\pi Z_0 f^2) + 10^{(N^2_{o.n}(f_s)-30)/10}\right)\Delta F_s}. \quad (11)$$

If the parameters of the radio monitoring receiver are not determined, then the calculation can be carried out based on the EIRP value equal to 38.2 dBW (this value is determined for an effective antenna diameter of 48 sm and a beam angle of 2.8 °, see Table 4). In formula (4), the value $G_a(f_s)$ corresponds to the gain of the antennas of the SC SSC Starlink terminal.

Taking into account recommendation ITU-R P.452-16 (Prediction procedure for assessing interference between stations located on the surface of the Earth at frequencies above approximately 0.1 GHz) [9], we use the formula for signal attenuation in free space at line-of-sight ranges:

$$L = 92.5 + 20\lg f + 20\lg R + Ag, \text{dB}, \quad (12)$$

where Ag is the total absorption in atmospheric gases, which, according to Recommendation ITU-R P.676-10 (Attenuation in atmospheric gases) for the Ku-band is 0.05 dB/km [9].

Then we finally obtain for the frequency f = 14 GHz:

$$L = 92.5 + 20\lg f + 20\lg R + 0.07R, \text{dB} \quad (13)$$

and for frequency f = 14.5 ГГц:

$$L = 92.5 + 20\lg f + 20\lg R + 0.05R, \text{dB}. \quad (14)$$

In formulas (13) and (14), the values of f are in (GHz), and the values of R are in (km). In Fig. 4 shows graphs of signal attenuation in free space under conditions of no rain $L1(R)$ for a radio link at a frequency of f = 14 GHz and $L2(R)$ for a radio link at a frequency of f =14.5 GHz. The value of signal attenuation $L0$ at a distance of R = 1 km is also shown here.

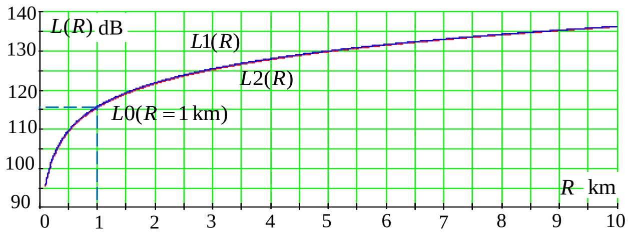

Fig. 4. Dependence of Attenuation of UT SSC Starlink Signals in Free Space

Taking into account the EIRP AT SSS Starlink, the final version of the signal attenuation value when it propagates freely is determined by the graph presented in Fig. 5.

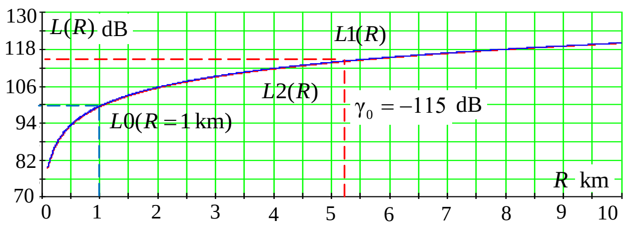

Fig. 5. Signal level of UT SSC Starlink Signals in Free Spaceas it Propagates Along the Main RP Lobe

Note that the graphs in Fig. 5 are constructed taking into account the propagation of the SSC Starlink UT signal in the direction of the main RP lobe. Analysis of the results obtained allows us to conclude that the level of signal attenuation is practically independent of frequency. And at a distance of 1 km it will reach a value of 100 dB.

At the same time, taking into account that the threshold sensitivity of the receiver γ0 is determined by the expression [10]:

$$\gamma_0 \approx 10\, P_N = 10(kT_\Sigma \Delta f), \quad (15)$$

where P_N – thermal noise power at the receiver input; T_Σ – effective noise temperature of the antenna ≈ 410 °K; k = 1,23×10^-23, J/K – Boltzmann constant; Δf = 60 MHz – noise receiver bandwidth in which noise is measured.

According to expression (15), the threshold sensitivity of the receiver will be γ0 =–115 dB.

Taking into account the obtained value, it is possible to determine the control range of ground-based UT SSC Starlink, equal to the order of Rc = 5 km (shown by the red dotted line in the graphs of Fig. 5). Note that the obtained values do not take into account the parameters of the antenna of the control complex. Thus, with a gain of even about 5 dB, the range Rc will increase to 10 km. But it should be taken into account that the calculations performed correspond to the location of the control complex along the main lobe of the RP UT SSC Starlink.

It should be noted that the calculated values were obtained for the condition that radio monitoring systems are located within the main radiation lobe, which in practice is quite difficult to ensure.

So, according to Table 4, the main lobe is a fairly limited area of space. In particular, in Fig. 6 shows the radiation pattern of the ground terminal antenna in the vertical plane.

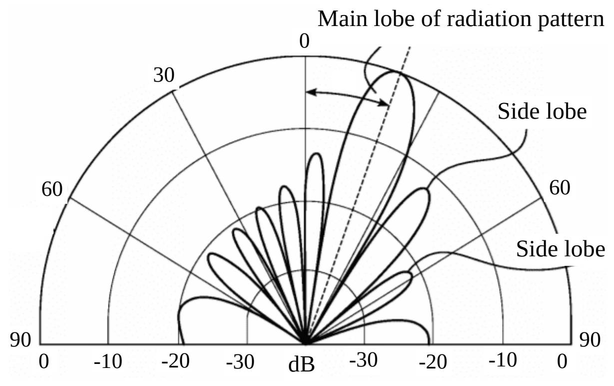

Fig. 6. Directional Pattern of the UT SSC Starlink Antenna

In the event that the guidance device does not ensure alignment of the radiation patterns within the main lobe of the antenna system of the radio monitoring receiver and the UT SSC Starlink, then, according to Fig. 6, then electromagnetic accessibility will be reduced by 12–22 dB. In such conditions, receiving signals will become almost impossible.

In addition, the article somewhat idealizes the situation of temporary contact between the satellite and the ground terminal; according to [2], the contact time may be shorter. But these conditions equally negatively affect both the radio monitoring system and the subscriber terminal. Therefore, this situation is considered from the standpoint of general restrictions.

A more complex problem that developers of radio monitoring equipment may encounter is the quasi-random nature (for an outside observer) of switching the main lobe of the radiation pattern when changing the next spacecraft leaving the accessibility zone [2].

A solution to this problem will be addressed in a subsequent study.

Conclusion

The study showed that, despite the complex operating algorithm of SSC Starlink, based on handover operations (transfer of control over the Starlink SSC UT from one SC to another without disruption or loss of communication service), control of the operation of ground-based subscribers is theoretically possible. Because with a receiver sensitivity of – 115 dB, the monitoring range is more than 5 km.

But it should be understood that in the Ku-band the level of signal attenuation along the Earth's surface is quite significant, so receiving monitoring equipment should be located on lifting platforms.

In addition, taking into account that in order to make contact between SC and UT, which is only 250 s, a constant change in the relative position of their RP is necessary, it is advisable to use widely directional antennas on control complexes. And although such a solution will reduce the efficiency of electromagnetic contact, it will significantly facilitate the practical implementation of antenna devices when they are placed on a flight-lifting platform.

Directions for further research will be related to the use of joint signal processing methods [11–13], in the interests of improving the quality of control.

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Информация об авторе:

ДВОРНИКОВ Сергей Викторович

доктор технических наук, профессор, профессор кафедры радиотехнических и оптоэлектронных комплексов (Кафедра 21) Санкт-Петербургского государственного университета аэрокосмического приборостроения, профессор кафедры радиосвязи Военной академии связи имени Маршала Советского Союза С.М. Буденного

https://orcid.org/0000-0002-4889-0001