Energetic concealment of low-frequency sattelite communication system with arbitrary recession of radiointercepting receiver

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Abstract

A method has been developed for evaluation of the energetic concealment factor of a satellite communication system that utilizes lowered carrier frequency down to 30. . . 100 MHz (such that wave propagation is followed by scattering on the ionospheric inhomogeneities), a transmitting antenna of an Artificial Earth Satellite with directional pattern width based on the zeroed radiation level within the state border of Russia and diversified signal reception with two antennas, with arbitrary recession of a radio interception receiver from a ground-based satellite communication receiver. It has been established that, in such case, the energetic concealment coefficient value of no lower that 27 dB is provided.

1 Introduction

It is known [1] that one of the main ways to increase the energetic concealment factor of the satellite communication system (SCS) is to implement transmitting antennas with a narrow directional pattern (DP). However, with a radio intelligence receiver placed closely relative to an SCS receiver, when the receivers are within the DP width of the AES transmitting antenna (service zone), this method of increasing energetic concealment becomes ineffective.

Contrariwise, a method is known [2-4] to increase energetic concealment of the SCS from radio interception (RI) of signals by the means of simultaneously reducing the carrier frequency of the signal transmitted from the AES (down to $f_0 = 30 \ldots 100$ MHz) and applying diversified signal reception with several ($n = 2 \ldots 4$) antennas on an earth-based station. This method allows to provide a significant SCS energetic concealment value ($22 \ldots 34dB$) with the RI receiver in close proximity ($R_d < 10km$) to the SCS receiver. The prerequisites of applying the method are the utilization of a single antenna ($n_d = 1$) and the inability to apply diversified reception with several ($n_d = 2 \ldots 4$) antennas (due to limitations in the mass and dimensional characteristics of the radio intelligence equipment).

However, in the frequency range of $f_0 = 30 \ldots 100$ MHz, it is difficult to implement a narrow DP of the AES transmitting antenna (for example, helical). Therefore, with a wide DP of the low-frequency SCS on-board

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transmitter, the service zone can be vast to such an extent that the RI receiver may be placed beyond the borders of Russia, where it (and the SCS receiver) is capable of using several ($n_d = 2 \ldots 4$) antennas. It presents itself as self-evident that in this case, it is possible to provide high energetic concealment for the low-frequency SCS by the means of choosing the AES transmitting antenna parameters in a way which ensures that its DP width based on the zeroed radiation level does not exceed the state border of Russia. The suggested method of providing energetic concealment for the low-frequency SCS with the arbitrarily recessed radio intercepting receiver by the means of choosing the DP width of the AES transmitting antenna based on the zeroed radiation level ($2\theta_0$) within the state border is provided in the figure 1.

The purpose of this research is to develop the method for evaluation of energetic concealment for the low-frequency satellite communication system with the choice of the AES transmitting antenna directional pattern width based on the zeroed radiation level within the borders of Russia and with arbitrary recession of the radio intercepting receiver.

2 Energetic concealment evaluation technique

Let us analyze the capabilities of the known [2-4] method of improving energetic concealment of the SCS by lowering the carrier frequency of the on-board SCS transmitter (TSM) signal (down to $f_0 = 30 \ldots 100$ MHz) and applying diversified signal reception with two (n=2) antennas (figure 1) for two cases: 1) utilizing one (n=1) antenna in the RI receiver (RCV) when it is recessed by the distance Rd within the state border (BD) ($R_d \leq R_b$); 2) recessing the RI receiver which utilizes two ($n_d = 2$) antennas by the distance Rd that exceeds the distance to the border ($R_d > R_b$). Herewith, the DP width of the AES receiving antenna based on the zeroed radiation level ($2\theta_0$) does not exceed the state border.

It is known [2-4] that the condition of providing noise immunity for the SCS is expressed in the actual signal/noise ratio h^2 exceeding the allowed value h^2_{alwd} (with which the achieved error probability value equals the value allowed in the SCS $P_{err} = P_{err\ alwd} = 10^{-5}$). This condition $h^2 > h^2_{alwd}$ can be rewritten as the expression $h^2 = h^2_{alwd} G$, where G - energetic (systemic) SCS radio link reserve.

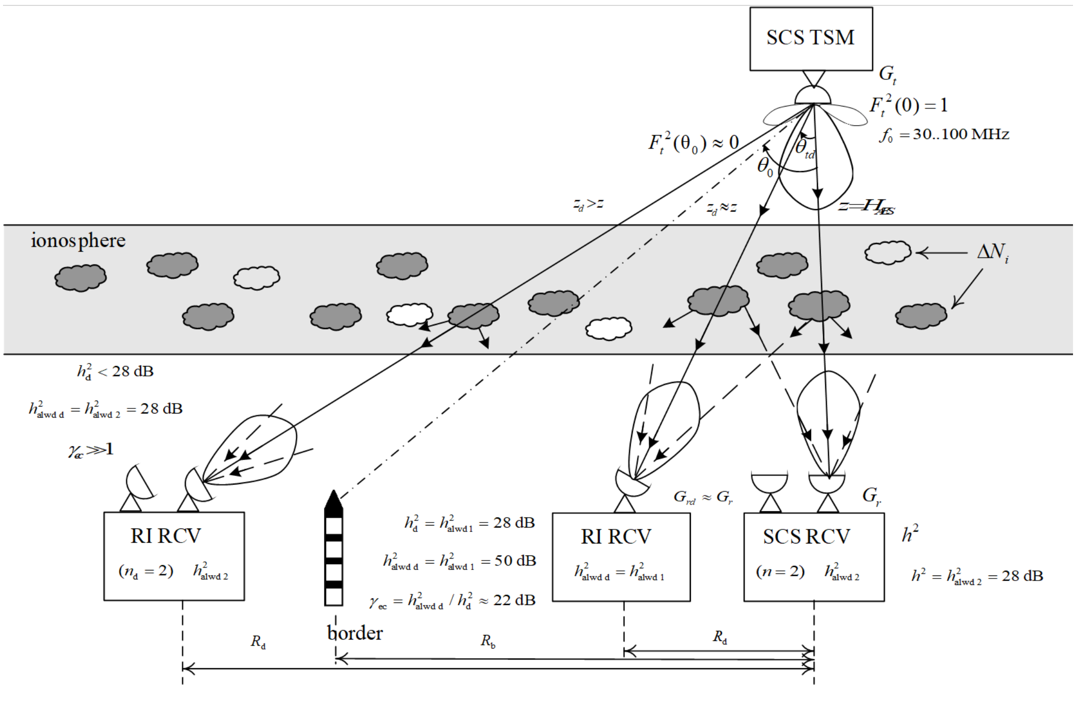

Figure 1: Method of providing energetic concealment for the low-frequency SCS with the radio intercepting receiver located within the state border of Russia $R_d \leq R_b$ and beyond it $R_d > R_b$

The condition of providing energetic concealment for the SCS is expressed as non-exceedance of the actual signal/noise ratio on the RI receiver input h_d^2 over the allowed value $h^2_{alwd\ d}$. This condition ($h_d^2 < h^2_{alwd\ d}$) can be expressed as exceedance of the energetic concealment coefficient over the value of one: $\gamma_{ec} = h^2_{alwd\ d}/h_d^2 > 1$.

According to [2, 3], the condition of providing energetic concealment for the SCS can be expressed in detail as

$$\gamma_{ec} = \frac{h^2_{alwd\ d}}{h^2_d} = \frac{1}{F^2_t(\theta_{td})} \frac{G_r}{G_{rd}} \frac{z^2_d}{z^2} \frac{L_{lr}}{L_l} \frac{T_{er}}{T_e} \frac{h^2_{alwd\ d}}{h^2_{alwd} G} > 1, \tag{1}$$

where $F^2_t(\theta_{td}) = G_t(\theta_{td})/G_t \leq 1$ - normalized DP of the AES transmitting antenna based on the power in the direction θ_{td} on the intercepting receiver (RI); G_r and G_{rd} - amplification coefficients of the SCS and RI receiver antennas; z_d and z - length of the radio links between the AES and RI/SCS receivers; L_lr and L_l - transmission losses due to wave absorption in the intelligence (radio interception) and communication radio link medium; T_{er} and T_e - equivalent noise temperatures of the receiving radio interception systems and the ground-based station.

Hereinafter, we shall suppose that in the RI receiver, the noise temperature and the amplification coefficient values are ensured to be approximately the same as in the SCS receiver (i.e. $T_{er}/T_e \approx 1$ and $G_r/G_{rd} \approx 1$). It can be shown [2] that the transmission losses due to wave absorption in the radio link intelligence and the communication medium (ionosphere) are small and are approximately equal ($L_{lr}/L_l \approx 1$). Then, the condition (1) of providing energetic concealment for the SCS comes down to an approximate form

$$\gamma_{ec} = \frac{h^2_{alwd\ d}}{h^2_d} = \frac{1}{F^2_t(\theta_{td})} \frac{z^2_d}{z^2} \frac{h^2_{alwd\ d}}{h^2_{alwd} G} > 1, \tag{2}$$

According to figure 1, with the RI receiver being in close proximity to the SCS receiver (for example, $R_d \leq$ 10 km) and with the AES orbital altitude having any value $H_{AES} = z = 700 \dots 40000$ km, the surveillance angle of the intelligence receiver from the AES is extremely small $\theta_{td} < 0.01°$. Thus, the value $F^2_t(\theta_{td}) \approx 1$, the intelligence radio link length, is almost indistinguishable from the SCS radio link length ($z^2_d/z^2 \approx 1$). Thereat, the condition of providing energetic concealment for the SCS (2) with the RI receiver RCV in close proximity ($R_d \leq 10$ km) comes down to a simplified form $\gamma_{ec} = h^2_{alwd\ d}/h^2_d \approx h^2_{alwd\ d}/h^2_{alwd} G > 1$. The known [3, 4] method for providing energetic concealment for the SCS with the RI receiver in close proximity is based (figure 1) on lowering the carrier frequency of the signal transmitted from the AES down to $f_0 = 30 \dots 100$ MHz (with which radio wave propagation is followed by dissipation in the ionospheric inhomogeneities ΔN_i, by the appearance of relative phasic shifts of the received beams $\Delta\varphi_i = \Delta N_i/f_0$ and by fading of the received signals that are close to Rayleigh) and implementing diversified signal reception with several (for example, $n = 2$) antennas. In this case, the actual signal/noise ratio on the RI receiver input (h^2_d) is almost equal (when $G = 1$) to the allowed signal/noise ratio on the SCS receiver input, which, with $P_{err\ alwd} = 10^{-5}$ and with diverse n=2 antennas, may be $h^2_{alwd\ 2} \approx 28$ dB. The allowed signal/noise ratio on the RI receiver input with single antenna ($n_d = 1$) signal reception with Rayleigh fading is $h^2_{alwd\ 2} = h^2_{alwd\ 1} = 50$ dB. In such case, a considerable SCS energetic concealment coefficient is achieved, which is conditioned by the gains in the signal/noise ratio when using diversified reception compared to unified [4]:

$$\gamma_{ec} = h^2_{alwd\ d}/h^2_d \approx h^2_{alwd\ 1}/h^2_{alwd\ 2} = 50 - 28 = 22 \text{ dB}.$$

The analysis of figure 1 shows that as the distance (Rd) between the RI receiver and the SCS receiver increases, the angle ($\theta_{td} \sim R_d$) between the AES and SCS intelligence receivers surveillance direction increases as well. This, in turn, leads to a decrease in the normalized DP of the SCS transmitting antenna in the direction of the intelligence receiver $F^2_t(\theta_{td}) < 1$ and to an increase of the intelligence range $z_d(\theta_{td})$. So, as the intelligence distance grows ($R_d \sim \theta_{td}$) , the energetic concealment coefficient grows consequently (2), which can be expressed as a function of R_d as

$$\gamma_{ec}(R_d) = \frac{1}{F^2_t(\theta_{td})} \frac{z^2_d}{z^2} \frac{h^2_{alwd\ d}}{h^2_{alwd} G} = P(R_d) \Delta h^2_{alwd\ n}(R_d)/G > 1. \tag{3}$$

Here

$$P(R_d) = \frac{1}{F^2_t(R_d)} \frac{z^2_d(R_d)}{z^2} \geq 1 \tag{4}$$

- SCS spatial concealment coefficient (which grows gradually with recession R_d of the RI receiver from the SCS receiver)

$$\Delta h^2_{alwd\ n}(R_d) = h^2_{alwd\ dn}(R_d)/h^2_{alwd\ 2} \begin{cases} \gg 1, \text{ if } n_d = 1 \text{ when } R_d \leq R_b; \\ \leq 1, \text{ if } n_d \geq 2 \text{ when } R_d > R_b. \end{cases} \tag{5}$$

– gains in energetic concealment from utilization of spatially diverse fading signal reception in the low-frequency SCS, i.e. a constituent of the SCS energetic concealment coefficient, that is conditioned by lowering the carrier frequency and applying diversified reception with n=2 antennas. According to figure 1, when placing the RI receiver within the borders ($R_d \leq R_b$) and forcefully utilizing a single ($n = 1$) antenna, the amount of gains is $\Delta h^2_{alwd\ n}(R_d) = h^2_{alwd\ 1}(R_d)/h^2_{alwd\ 2} \approx 22$ dB. When placing the RI receiver beyond the borders ($R_d > R_b$) and willingly utilizing two ($n = 2$) diversified antennas, such gains are non-existent: $\Delta h^2_{alwd\ n}(R_d) = h^2_{alwd\ 2}(R_d)/h^2_{alwd\ 2} = 1$ dB (i.e. 0 dB). Therefore, for the considered (figure 1) case, the expression (5) takes the following form

$$\Delta h^2_{alwd\ n}(R_d) = h^2_{alwd\ dn}(R_d)/h^2_{alwd\ 2} \begin{cases} 22, \text{ dB if } n_d = 1 \text{ when } R_d \leq R_b; \\ 0, \text{ dB if } n_d = 2 \text{ when } R_d > R_b. \end{cases} \tag{6}$$

The analysis of figure 1 and the relations (3-6) indicates that the ability to meet the requirements of providing energetic concealment for the SCS $\gamma_{ec}(R_d) = P(R_d)\Delta h^2_{alwd\ n}(R_d)/G > 1$ when the RI receiver is placed beyond the borders ($R_d \geq R_b$) is determined by the increase in spatial concealment $P(R_d) \gg 1$, and when it is placed in close proximity to the SCS receiver RCV ($R_d \leq R_b$) - by the increase in the second constituent of $\Delta h^2_{alwd\ n}(R_d) = h^2_{alwd\ 1}(R_d)/h^2_{alwd\ 2} \gg 1$, that is conditioned by the decrease in the SCS frequency and the application of diversified reception with two ($n = 2$) antennas when the RI receiver has only one ($n = 1$) antenna. According to (4), to determine the SCS spatial concealment coefficient $P(R_d \sim \theta_{td})$, it is required to establish the dependencies on the intelligence distance R_d , normalized intelligence range $z_d(R_d)/z = z_d(R_d)/H_{AES}$ and the normalized AES antenna DP $F^2_t(\theta_{td} \sim R_d)$.

To determine the intelligence range $z_d(R_d \sim \theta_{td})$, let us consider the simplest case (see figure 1), when the AES transmitting antenna aiming point matches the under-satellite point ($z = H_{AES}$) where the SCS receiver is located, and the RI receiver is recessed by R_d. The intelligence distance R_d corresponds to one half of the surveillance angle $0,5\alpha_{srv} = \alpha_d$ of this distance from the center of Earth with the radius of $R_E = 6370$ km:

$$\alpha^\circ_d = R_d/(2\pi R_E/360^\circ) \approx R_d[km]/111,2 \approx 9 \cdot 10^{-3} R_d[km] \tag{7}$$

To bind α_d to the intelligence direction angle θ_{td}, a consideration should be made for the known [5] dependency for the AES service zone surveillance angle (β_{srv}) of the ground area $2R_d$ on the angle size of this area from the center of Earth (α_{srv}):

$$\theta_{td} = 90^\circ - \frac{R_d[km]}{222,4} - arctg\left[\frac{H_{AES}}{(2R_E + H_{AES})tg(R_d[km]/222,4)}\right] \tag{8}$$

The dependence of the specified angles α_d and θ_{td} on the RI receiver recession (R_d) determines the maximum intelligence range, i.e. the distance between the AES and the location point of the intelligence (radio interception) receiver

$$z_d(R_d) = R_E \cdot \sin\alpha_d / \sin\theta_{td} \tag{9}$$

The analysis of the expressions (7-9) and figure 1 shows that as the distance R_d between the RI and SCS receivers increases, the angle of the intelligence receiver direction $\theta_{td}(R_d)$ and the intelligence range $z_d(\theta_{td})$ also increase. Aside from that, as the AES orbital altitude decreases (H_{AES}), the angle of the intelligence receiver direction $\theta_{td}(R_d, H_{AES})$ and the intelligence range $z_d(\theta_{td}, H_{AES})$ increase. To determine the second constituent of spatial concealment of the SCS (10) $P(R_d) \sim 1/F^2_t(R_d)$, let us apply the expression (8), which establishes the connection $\theta_{td} = \psi(R_d, H_{AES})$, and the general expression for the DP normalized by the tension of a cylinder spiral antenna with n_c coils [6]

$$F_t(\theta_{td}) \approx \frac{2}{\pi n} J_0(ka\sin\theta_{td})\cos\theta_{td}\frac{\sin\pi n\xi}{\xi^2 - 1} \tag{10}$$

Here $J_0(x)$ - Bessel function; $k = 2\pi/\lambda_0$ - wave number domain; a - spiral radius; $\xi = 1 + ka(1 - \cos\theta_{td})tg\alpha$ - wave velocity factor; α - spiral coil ascent angle. With traditional values $\alpha = 12 \ldots 14$, when $ka \approx 1$, the expression (10) comes down to a more simple form

$$F_t(\theta_{td}) \approx \frac{2}{\pi n_c} J_0(\sin\theta_{td})\cos\theta_{td}\frac{\sin\pi n_c\xi}{\xi^2 - 1} \tag{11}$$

where

$$\xi = 1 + 0.22\,(1 - \cos\theta_{td})\,tg\alpha \tag{12}$$

According to [6], when $ka \approx 1$ and $\xi \approx 1$, the value $\sin \pi n_c \xi/(\xi^2 - 1) = \pi n_c/2$. Thus, with $\theta_{td} = 0$, we shall have $J_0(\sin\theta_{td}) = J_0(0) = 1$ and $F_t(\theta_{td} = 0) = 1$. Provided on the figure 2 are the DP of the spiral antenna normalized by the tension $F_t(\theta_{td})$ and by the power $F_t^2(\theta_{td})$, which are structured according to (10, 11) with $n_c = 13$ and $\alpha_0 = 5$ m ($f_0 = 60$MHz).

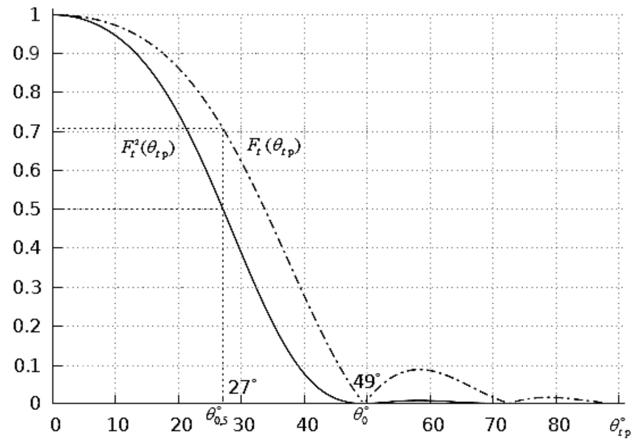

Figure 2: Normalized directional pattern of the spiral antenna

The analysis of figure 2 shows that the DP width of the given spiral antenna by halved power is $2\theta_{0,5} \approx 54°$, and by the zeroed radiation level it is $\theta_0 \approx 2 \cdot 49° = 98°$. The sought dependency $F_t^2(R_d)$ of the normalized DP of the spiral antenna on recession of the RI receiver is determined by the expressions (11) for $F_t^2(\theta_{td})$ and (8) for $\theta_{td} = \psi(R_d, H_{AES})$. The general expression (4) for the calculation of the SCS spatial concealment coefficient can be expressed in decibels as the sum of 2 summands:

$$P(R_d)_{dB} = F_t^{-2}(R_d)_{dB} + [z_d(R_d)/H_{AES}]^2_{dB} \tag{13}$$

Provided on figure 3 is the dependency of the SCS spatial concealment (13) $P(R_d)_{dB}$ and its constituents $F_t^{-2}(R_d)_{dB}$ and $(z_d(R_d)/H_{AES})^2$ on recession of the RI receiver (R_d) with low AES orbital altitude $H_{AES} = 700$ km.

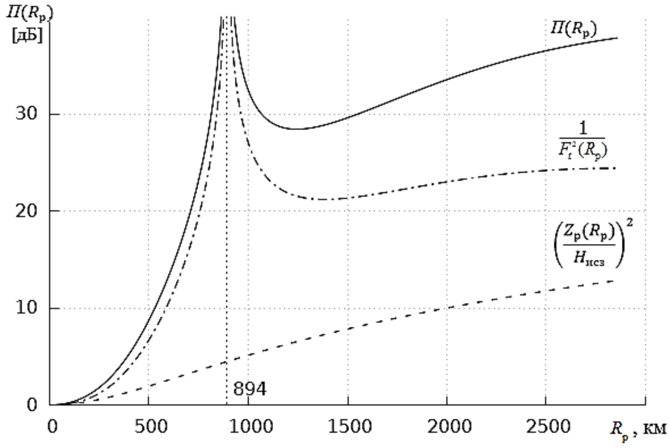

Figure 3: Dependency of the SCS spatial concealment coefficient on recession of the radio interception receiver

The analysis of figure 3 indicates that the graph $F_t^{-2}(R_d)_{dB}$ (dotted line) takes on the maximum value ($P_{dB} \to \infty$) when the angle ($\theta_{td} \sim R_d$) between the RI receiver direction and the SCS receiver is equal to one half of the DP width based on the zeroed radiation level of the AES transmitting antenna ($\theta_{td} = \theta_0 \approx 49°$) and $F_t^2(\theta_{td} = \theta_0) = 0$. Corresponding to this zeroed radiation angle is the intelligence distance that is equal to the distance to the border ($\theta_0 \sim R_d = R_b$), which, with the AES altitude of $H_{AES} = 700$ km, is $R_b = 894$ km. The contribution of the second summand is much less prominent, and with $R_b = 894$ km it is just $(z_d(R_d)/H_{AES})^2_{dB} \approx 6$ dB. With the RI receiver recessed to the distance that exceeds the boundaries $R_d > R_b$, the SCS spatial concealment shall be considerable: $P_{dB} > 28$ dB.

The general expression for the calculation of energetic concealment of the SCS can be expressed in decibels as 3 summands

$$\gamma_{ec}(R_d)_{dB} = P(R_d)_{dB} + \Delta h^2_{alwd\ n}(R_d)_{dB} - G_{dB} \tag{14}$$

According to the expression (6), when using one antenna ($n = 1$) in the RI receiver and dual reception ($n = 2$) in the SCS receiver, a gain is achieved $\Delta h^2_{alwd\ n}(\theta_{td}) = 22$ dB, which can be considered constant when recessing the RI receiver up to the borders ($R_d \leq R_b$) . Therefore, the dependency graph $\Delta h^2_{alwd\ n}(\theta_{td})$ with ($R_d \leq R_b$) will have the form of a rectangle with the sides $\Delta h^2_{alwd\ n} = 22$ dB and $R_b = 894$ km (in cohesion with the AES altitude $H_{AES} = 700$ km).

The dependency of the low-frequency SCS energetic concealment coefficient on the RI receiver recession $\gamma_{ec}(R_d)_{dB}$ with the AES altitude of $H_{AES} = 700$ km, with no radio link energetic reserve ($G_{dB} = 0$ dB), and both of its constituents: $P(R_d)$ and $\Delta h^2_{alwd\ n}(\theta_{td})$ are provided on figure 4. The dependency corresponds to the one provided on figure 3, and $\Delta h^2_{alwd\ n}(\theta_{td})$ is structured according to (6).

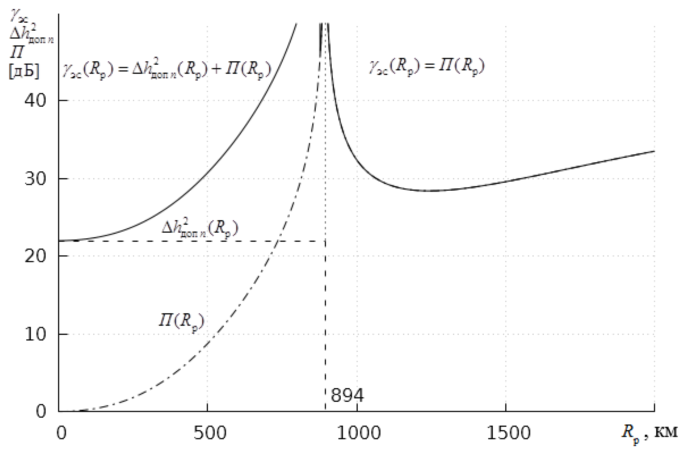

Figure 4: Dependency of the low-frequency SCS energetic concealment coefficient on the radio inter-ception receiver recession

The analysis of figures 4 and 1 shows that when deploying the single-antenna ($n_d = 1$) RI receiver in close proximity ($R_d < 10$ km) to the SCS receiver with lowered frequencies and two ($n = 2$) antennas, the energetic concealment of the SCS is determined by the gains provided by the application of spatially diversified reception of fading signals in the low-frequency SCS and roughly equals to $\gamma_{ec}(R_d)_{dB} \approx \Delta h^2_{alwd\ n}(R_d)_{dB} \approx 22$ dB. When recessing the RI receiver to the distance of $R_d \approx 430$ km, energetic concealment of the SCS increases to $\gamma_{ec}(R_d)_{dB} \approx \Delta h^2_{alwd\ n}(R_d)_{dB} + P(R_d)_{dB} \approx 28$ dB due to the growth of the spatial concealment coefficient by $P(R_d)_{dB} \approx 6$ dB. When recessing the RI receiver to the border distance $R_d = R_b = 894$ km, the low-frequency SCS energetic concealment will be determined by the spatial concealment coefficient, the value of which $\gamma_{ec}(R_d)_{dB} \approx P(R_d)_{dB} \to \infty$ is conditioned by the zeroed radiation direction of the AES transmitting antenna that corresponds to (see figure 2) $\theta_0 \approx 49°$.

This value θ_0 and the known expression for the DP width of the spiral antenna based on the zeroed radiation level [6]

$$\Delta\theta_0 = 2\theta_0 \approx 162\sqrt{\lambda_0/L_s} = 162\sqrt{\lambda_0/Sn_s} \tag{15}$$

allow to determine the length L_s and the pitch $S = L_s/n_s$ of a spiral. Hence, with $\lambda_0 = 5$ m, the required spiral antenna will have the length of $L_s = 13.7$ m, the pitch of $S = L_s/n_s \approx 1.05$ m and the coil length of $l_s = S/\sin\alpha \approx \lambda_0 = 5$ m. Such an antenna provides the antenna directivity factor of $D \approx 15(L_s/\lambda_s) \approx 41$ (i.e. 16 dB).

When deploying the RI receiver beyond the state border ($R_d > R_b = 894$ km) and utilizing two ($n = 2$) antennas, the gains from the application of spatially diversified reception with two ($n = 2$) antennas in the RI receiver are not evident ($\Delta h^2_{alwd\ n}(R_d)_{dB} = 0$ dB) and the SCS energetic concealment is totally (with $G = 0$) determined by the spatial concealment coefficient $\gamma_{ec}(R_d)_{dB} = P(R_d)_{dB}$. The least value of this coefficient $P(R_d)_{dB} = 28$ dB is observed when recessing the RI receiver RCV to the distance of $R_d \approx 1250$ km, which corresponds to the direction of maximal radiation of the first side lobe of the AES transmitting antenna DP (refer to figure 1).

It is worth noting that, according to figure 4, the low-frequency SCS energetic concealment coefficient exceeds the value $\gamma_{ec}(R_d)_{dB} > 28$ dB when recessing the RI receiver to the distance of $R_d > 430$ km both with one ($n = 1$) and two ($n = 2$) antennas. However, with the recession of $R_d = 430 \ldots 740$ km, this effect is achieved mainly by utilizing spatial diversification with two antennas $\gamma_{ec}(R_d)_{dB} \approx \Delta h^2_{alwd\ n}(R_d)_{dB} > 28$ dB, and with the recession of $R_d > 740$ rm – by the ability of the AES on-board antenna to provide spatial concealment $\gamma_{ec}(R_d)_{dB} \approx P(R_d)_{dB} > 28$ dB.

CONCLUSIONS

In the research, the method has been developed for evaluation of the suggested technique for providing energetic concealment for the low-frequency SCS when choosing the AES transmitting antenna directional pattern width based on the zeroed radiation level within the state border and with arbitrary recession of the radio interception receiver (figure 1). It is based on the representation of the low-frequency SCS energetic concealment as (3-6) a product of the spatial concealment coefficient (conditioned by the AES transmitting antenna DP) and the gain from the application of spatially diversified reception and lowered frequency.

In contrast to the known methods, applicable only in near or far location of the radio interception receiver, the method allows to evaluate the energy stealth low-frequency SCS at an arbitrary location of the radio receiver.

The method consists of three main stages: 1) determining the dependency $P(R_d)$ of the SCS spatial concealment coefficient on the RI receiver recession, according to the expressions (7-9) and (11-13); 2) determining the gain $\Delta h^2_{alwd\ n}$ from the application of spatially diversified reception and lowered frequency according to the expressions (5-6); 3) determining the dependency $\gamma_{ec}(R_d)$ of the low-frequency SCS energetic concealment coefficient on the RI receiver recession, according to the expression (14).

The obtained (figure 4) dependency $\gamma_{ec}(R_d)$ points to the ability of providing an exceptionally high energetic concealment coefficient for the low-frequency SCS ($\gamma_{ec}(R_d) > 28$ dB) with arbitrary recession of the radio interception receiver. Besides, with the RI receiver in close proximity, high values of energetic concealment for the low-frequency SCS are provided by the means of spatially diversified fading signal reception, and with the recession distance of $R_d > 740$ km – by the means of spatial concealment of the AES transmitting antenna radiation.

Provided on figure 4 is the dependency of the energetic concealment for the low-frequency SCS, in which a dual reception is used at a carrier frequency of $f_0 = 60$ MHz at an orbit altitude of $H_{AES} = 700$ km.

The algorithm for applying the developed methodology for an arbitrary case consists of the following steps:

1. Obtaining characteristics of SCS, such as orbit height, distance from receiver to boundary, carrier frequency;

2. The choice of an antenna that satisfies the requirement of the direction of the the zeroed radiation level within the state border ($F_t(R_b) = 0$);

3. determining the dependency $P(R_d)$ of the SCS spatial concealment coefficient on the RI receiver recession, according to the expressions (7-9) and (11-13);

4. Determining the gain $\Delta h^2_{alwd\ n}$ from the application of spatially diversified reception and lowered frequency according to the expressions (5);

5. Determining the dependency $\gamma_{ec}(R_d)$ of the low-frequency SCS energetic concealment coefficient on the RI receiver recession, according to the expression (14).

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