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Procedure for Calculating the Dependence of the Energy Concealment Factor on Carrier Frequency Selection for Low-Frequency Satellite Communications System[1]

A. F. Chipiga[a, *], V. P. Pashintsev[a, **], V. A. Tsymbal[b], and S. N. Shimanov[b]

[a] *North Caucasus Federal University, Stavropol, 355009 Russia*

[b] *Engineering Physics Institute, Serpukhov, 142210 Russia*

**e-mail: chipiga.alexander@gmail.com*

***e-mail: pashintsevp@mail.ru*

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Abstract—The paper analyzes high energy concealment factor techniques for satellite communications systems by lowering the carrier frequency (to $f_0 = 100...30$ MHz) is carried out. According to research experiments, fading in communication channels with diversity reception is also determined by the influence of small-scale variations of the ionospheric total electron content. A procedure is developed for calculating the dependence of the energy concealment factor on carrier frequency selection for satellite communications system using space-diversity signal reception by two antennas. The calculation procedure is based on the standard deviation of small-scale variations of the ionospheric total electron content.

Keywords: satellite communications system, energy concealment, carrier frequency

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1. INTRODUCTION

The technique that ensures a very high energy concealment factor (γ_{ec}) of a satellite communications system (SCS) for a closely spaced (less than 10 km) intercept receiver near the SCS's ground-based receiver by lowering the carrier frequency (to $f_0 = 100-30$ MHz) and using space-diversity signal reception with several ($n \geq 4$) antennas is well known [1, 2]. The value of an SCS's energy concealment factor (γ_{ec} = 36 dB), which is given in [2], is obtained graphically for the case of quad-signal reception ($n = 4$) by assuming a Rayleigh distribution of fading of the received signal (fluctuation amplitude) on a frequency f_0= 60–80 MHz. However, according to experimental data [3], the fading of an SCS's received signal has a Rician distribution and depends on selection of the carrier frequency (f_0), as well as on variations of the ionospheric total electron content (TEC) caused by small-scale inhomogeneities of the electron density (ΔN_T). Therefore, an analytic dependence, $\gamma_{ec} = \Psi(\Delta N_T, f_0)$, of the energy concealment factor for low-frequency SCSs on both small-scale TEC variations and carrier frequency selection is needed. In addition, the dependence is efficient for diversity signal reception with two antennas ($n = 2$), which is the most usable in practice.

The paper gives a new procedure for calculating the dependence of the energy concealment factor on both small-scale TEC variations and carrier frequency selection $\gamma_{ec} = \Psi(\Delta N_T, f_0)$ using dual ($n = 2$) space-diversity signal reception for low-frequency SCS with a closely spaced intercept receiver.

The goal of the work is to develop a procedure for obtaining the dependence of the energy concealment factor on small-scale variations of the total ionospheric electronic content and the selection of the lower carrier frequency $\gamma_{ec} = \Psi(\Delta N_T, f_0)$ for a low-frequency SCS for placement of the radio interceptor receiver closely and the use of doubled (n = 2) spatial-diversity signal reception.

[1] The article was translated by the authors.

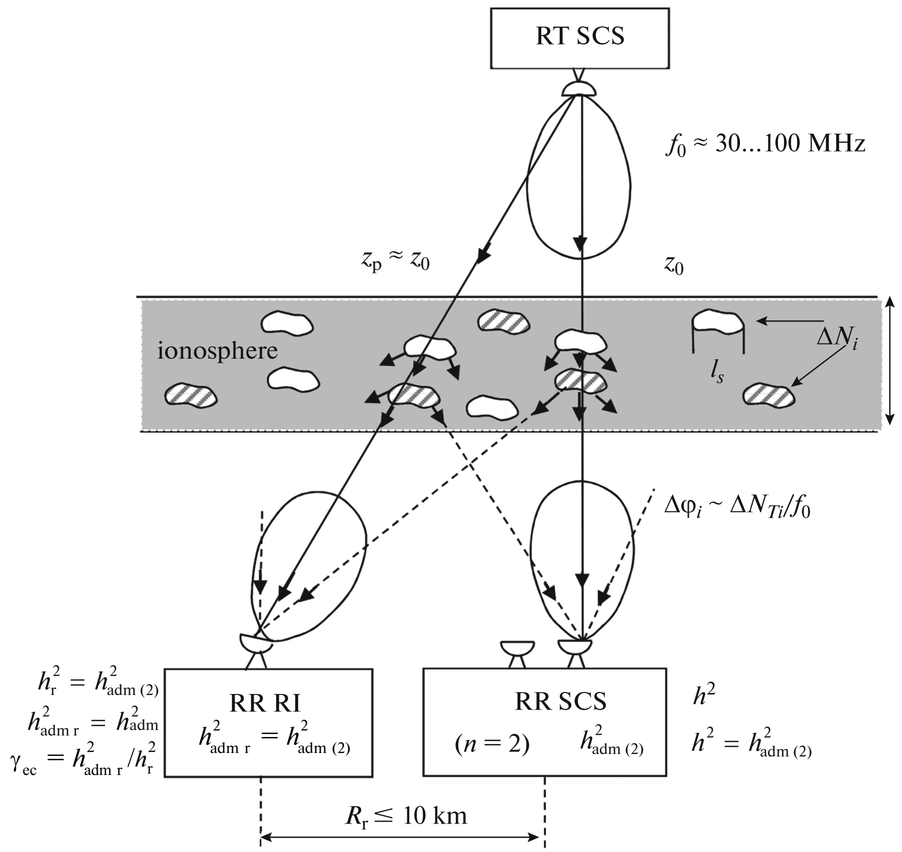

Fig. 1. Transionosferic radio wave propagation at low SCS carrier frequency (f_0 = 30–100 MHz).

2. PROCEDURE FOR ANALYZING RADIO WAVE PROPAGATION IN THE CASE OF FADING AND DIVERSITY RECEPTION AT LOW CARRIER FREQUENCIES

Figure 1 shows the features of transionosferic radio wave propagation at a low carrier frequency (to $f_0 = 30-100$ MHz) from a radio transmitter (RT) to radio receiver (RR) of SCS that uses two space-diversity antennas ($n = 2$) at closely spaced ($R_r < 10$ km) intercept receiver (IR). Small-scale inhomogeneities (100–1000 m) of ionospheric electron density (ΔN_i) lead to radio scattering at frequencies $f_0 = 30$–100 MHz multipath propagation to SCS receivers, and intercept receivers with relative offsets $\Delta\varphi_i = \Delta N_{Ti}/f_0$. The relative offsets increase in proportion both to small-scale variations of ionospheric TEC $\Delta N_{Ti} \sim \Delta N_i\, z_e$, which have an equivalent thickness z_e, and to a decrease in carrier frequency f_0. If $\Delta\varphi_i$ increases, the fade depth of received SCS signals increases and the Rician distribution parameter decreases.

In the case of Rician distribution of fading and the use of two space-diversity antennas ($n = 2$) and out-of-phase quadratic signal adding circuit, the probability of erroneous signal reception is

$$P_{err} \approx \frac{3(1+\gamma^2)^2}{(1-R^2)(h^2)^2} \exp\left(-\frac{2\gamma^2}{1+R}\right), \qquad (1)$$

where $h^2 = E_r/N_0$ is the ratio of the signal energy at the input of the SCS receiver to the noise power spectral density; $\gamma^2 = \alpha_r^2/\alpha_{fl}^2$ is the Rician distribution parameter, which is the ratio of the regular composition of the fading power to the fluctuation composition of the fading power (it ranges from $\gamma^2 = \infty$ if there is no fading to $\gamma^2 = 0$ if there is a Rayleigh fading); R is the fading spatial correlation coefficient ($0 \leq R \leq 1$)

of antennas. It is important to note that Eq. (1) is correct under two conditions: $h^2 \gg 1 + \gamma^2$; $h^2 \gg (1 - R^2)^{-1}$.

According to [5], in the case of uncorrelated ($R = 0$) Rayleigh fading and arbitrary multiplicity of diversity of the receiving antennas (n), the error probability for a quadratic adding circuit is approximated by

$$P_{\text{err}} \approx C_{2n-1}^{n}(1+\gamma^2)^n \exp(-n\gamma^2)\big/(h^2)^n, \tag{2}$$

where $C_{2n-1}^{n} = (2n-1)!\big/n!(n-1)!$.

Therefore, if a single out-of-phase orthogonal signal processing circuit is used in IR, the probability of erroneous signal reception can be approximated by (2), where $n = 1$:

$$P_{\text{err r}} \approx (1+\gamma^2)\,\exp(-\gamma^2)\big/h_r^2, \tag{3}$$

where $h_r^2 = E_{rr}\big/N_{0\text{r}}$ is the ratio of the signal energy at the input of the IR to the noise power spectral density.

According to (1) and if the admissible value of the SCS's error probability is $P_{\text{err}} = P_{\text{err adm}} = 10^{-5}$, the admissible value of the signal-to-noise ratio at the input of the SCS receiver using two ($n = 2$) space-diversity antennas is

$$h^2_{\text{adm(2)}} = \left[\frac{3(1+\gamma^2)^2}{1-R^2}\exp\left(-\frac{2\gamma^2}{1+R}\right)\frac{1}{P_{\text{err adm}}}\right]^{0.5}. \tag{4}$$

According to (3) and if the admissible value of IR's error probability is the same as SCS's error probability ($P_{\text{err adm r}} = P_{\text{err adm}} = 10^{-5}$), the admissible value of signal-to-noise ratio at the input of IR is:

$$h^2_{\text{adm r}} = (1+\gamma^2)\,\exp(-\gamma^2)\big/P_{\text{err adm}}. \tag{5}$$

Obviously (see Fig. 1), the actual value of signal-to-noise ratio at the input of IR closely spaced ($R_r \le 10$ km) near the SCS receiver is almost the same as the actual signal-to-noise ratio at the input of the SCS receiver: $h_r^2 \approx h^2$. Therefore, if the latter is equal to the admissible value ($h^2 = h^2_{\text{adm (2)}}$), the actual signal-to-noise ratio at the input of IR is equal to the admissible signal-to-noise ratio at the input of the IR using two ($n = 2$) space-diversity antennas: $h_{\text{r}}^2 = h^2_{\text{adm (2)}}$.

Then, according to (4) and (5), the energy concealment factor of the SCS, which is determined by the ratio of the admissible signal-to-noise ratio ($h^2_{\text{adm r}}$) to the actual signal-to-noise ratio (h_{r}^2) at the input of the IR is

$$\gamma_{\text{ec}} = \frac{h^2_{\text{adm r}}}{h^2_{\text{r}}} = \frac{h^2_{\text{adm r}}}{h^2_{\text{adm(2)}}} = \left(\frac{1-R^2}{3P_{\text{err adm}}}\right)^{0,5}\exp\left(-\frac{\gamma^2 R}{1+R}\right). \tag{6}$$

Figure 2 shows a diagram of the Rician dependence of the SCS energy concealment factor $\gamma_{\text{ec}} = \Psi(\gamma^2)$, which is constructed according to (6) and based on various fading spatial correlation coefficients ($R = 0.5–0.995$) of the antennas.

Figure 2 shows that SCS's energy concealment factor for a closely spaced IR increases if both the fade depth of received signals (γ^2 factor reduction) and fade decorrelation for space-diversity antennas (R factor reduction) increase. Using values of $\gamma^2 = 1-3$ and $R = 0.5-0.8$ makes it possible to achieve high energy concealment factor values $\gamma_{\text{ec}} \approx 20-16$ dB.

3. IMPACT ANALYSIS OF ELECTRON DENSITY FLUCTUATIONS OF SMALL-SCALE IONOSPHERIC IRREGULARITIES ON THE ENERGY CONCEALMENT FACTOR

The relationship between the fade depth (γ^2) and carrier frequency selection (f_0) is determined by the value of the standard deviation (SD) of phase shifts ($\Delta\varphi_i \sim \Delta N_{\text{T}\,i}/f_0$) at receiving point $\sigma_\varphi = \left\langle \Delta\varphi_i^2 \right\rangle^{0.5}$ of transionosferic radio wave propagation [1]:

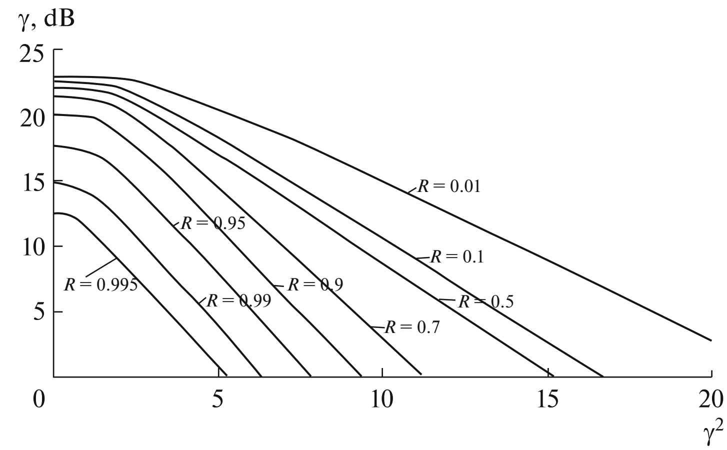

Fig. 2. Dependence of SCS energy concealment factor on both fade depth and fading spatial correlation coefficient of antennas.

$$\gamma^2 = a_{\mathrm{r}}^2 / a_{\mathrm{fl}}^2 = [\exp(\sigma_\varphi^2) - 1]^{-1}. \quad (7)$$

The value of $\sigma_\varphi = \langle \Delta\varphi_i^2 \rangle^{0.5}$ is equal to the standard deviation value of phase wavefront fluctuations with frequency f_0 at the output of the inhomogeneous ionosphere [4]:

$$\sigma_\varphi \approx 80.8\pi\sigma_{\Delta N_{\mathrm{T}}} / cf_0 \quad (\mathrm{rad}), \quad (8)$$

where 80.8 is a coefficient with dimension $[\mathrm{m}^3/\mathrm{s}^2]$; $c = 3 \times 10^8$ m/s is the velocity of light; f_0 has the dimension [Hz]; $\sigma_{\Delta N_{\mathrm{T}}} = \langle \Delta N_{\mathrm{T}i}^2 \rangle^{0.5}$ is the SD of small-scale variations of the ionospheric TEC with dimension $[\mathrm{el/m}^2]$.

The value of $\sigma_{\Delta N_{\mathrm{T}}}$ is determined by the parameters of small-scale ionospheric irregularities [4]:

$$\sigma_{\Delta N_{\mathrm{T}}} \approx \sigma_{\Delta N} \left[(\pi)^{0.5} l_s z_{\mathrm{e}} \sec\alpha \right]^{0.5} \quad (\mathrm{el/m}^2),$$

where $\sigma_{\Delta N} = \langle \Delta N_i^2 \rangle^{0.5}$ is the SD of electron density fluctuations (ΔN_i) of small-scale ionospheric irregularities $[\mathrm{el/m}^3]$ at the maximum ionization height; l_s is the average size of ionospheric irregularities [m]; z_{e} is the equivalent thickness of the ionosphere [m]; α is the radio wave angle.

Experimentally [6], the parameters of small-scale ionospheric irregularities ($\sigma_{\Delta N}$, l_s, z_{e}) can vary over a wide range (by one order of magnitude or more) and their measurement by traditional vertical ionospheric sounding is difficult. Recently, new methods [3] have appeared for real-time monitoring of small-scale SD variations of the ionospheric TEC ($\sigma_{\Delta N_{\mathrm{T}}}$) using a dual-frequency GPS receiver (e.g., NovAtel GPS-6). Methods are based on Rician parameter (γ^2) prediction of transionospheric radio channels at a known carrier frequency (f_0). The monitoring results of small-scale SD variations of the ionospheric TEC (the TEC measurement unit is $1\ TECU = 10^{16}\ \mathrm{el/m}^2$) at the latitude of Rostov-on-Don were obtained on December 18, 2015, at North Caucasus Federal University using a dual-frequency GPS-6 receiver (Fig. 3). Figure 3 shows that the *TECU* value varies over a wide range: $\sigma_{\Delta N_{\mathrm{T}}} = 2 \times 10^{-3} - 8 \times 10^{-3}\ (TECU)$.

Note that according to (7) and (8), if the value is $\sigma_\varphi \ll 1$, we have $\gamma^2 = 1/\sigma_\varphi^2 \sim f_0^2/\sigma_{\Delta N_{\mathrm{T}}}^2$; i.e., the Rician parameter depends on both the selection of the SCS's low carrier frequency and the SD value of small-scale variations of the ionospheric TEC.

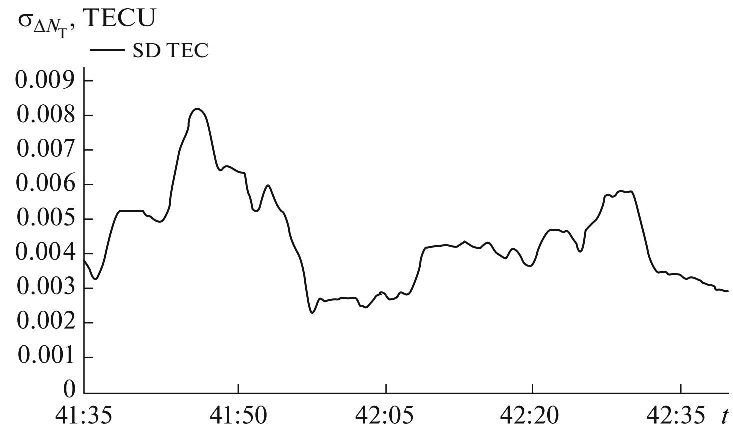

Fig. 3. Monitoring results of small-scale SD variations of mid-latitude ionospheric TEC.

According to (6), the spatial correlation coefficient of fading (R) of transionospheric radio channels depends on the SD of arriving waves phase shifts $\sigma_\varphi = \Psi(f_0)$ as well as γ^2:

$$R = \exp\left[-(\Delta\rho_a/\Delta\rho_k)^2\right] = \exp\left[-(\Delta\rho_a\sigma_\varphi/l_s)^2\right], \tag{9}$$

where $\Delta\rho_k = l_s/\sigma_\varphi$ is the interval of fading spatial correlation; σ_φ depends on both $\sigma_{\Delta N_T}$ and selection of carrier frequency f_0 using (8).

The table shows the values of $\sigma_\varphi = \Psi(f_0)$ and $\gamma^2 = \Psi(\sigma_\varphi)$, calculated by (7) and (8) with the average SD value (see Fig. 3) of small-scale variations of the ionospheric TEC $\sigma_{\Delta N_T} = 5\times10^{-3}$ $(TECU)$ = 5×10^{13} (el/m^2) for different carrier frequencies in the range f_0 = 30 MHz–1 GHz. Calculation by (9) yields intervals ($\Delta\rho_\kappa$) and fading spatial correlation coefficients (R) (the average size of irregularities is $l_s = 390$ m and the spatial diversity of antennas is $\Delta\rho_a = 300$ m).

According to (7)–(9), Rician fading parameter γ^2, and fading spatial correlation coefficient R (in the case of space-diversity antennas at a distance of $\Delta\rho_a = 300$ m), the dependences on selection of carrier frequency f_0, and the data in the table, Fig. 4 shows the diagram of the desired dependence of the SCS energy concealment factor $\gamma_{ec} = \Psi(\sigma_{\Delta N_T})$ on the selection of the carrier frequency for a value of $\sigma_{\Delta N_T}$= 5×10^{-3} $(TECU) = 5\times10^{13}$ (el/m^2) for different carrier frequencies in the range f_0 = 30 MHz–1 GHz

Figure 4 and the table show that SCS space-diversity signals reception with two antennas (n = 2) with standard parameters of small-scale variations of the mid-latitude ionospheric TEC ($\sigma_{\Delta N_T} \approx 5\times10^{13}$ (el/m^2))

Dependence of SCS fading parameters on frequency selection

f_0, Hz	10^9	5×10^8	2×10^8	1.5×10^8	1.3×10^8	10^8	8×10^7	7×10^7	6×10^7	5×10^7	4×10^7	3×10^7
σ_φ	0.04	0.08	0.21	0.28	0.32	0.42	0.53	0.6	0.70	0.85	1.06	1.41
γ^2	558	139	21.8	12.08	8.95	5.10	3.10	2.3	1.55	0.96	0.49	0.16
$\Delta\rho_k$, m	9218	4609	1844	1383	1198	922	737	645	553	461	369	276.6
R	0.999	0.996	0.974	0.95	0.94	0.9	0.85	0.8	0.74	0.65	0.52	0.31

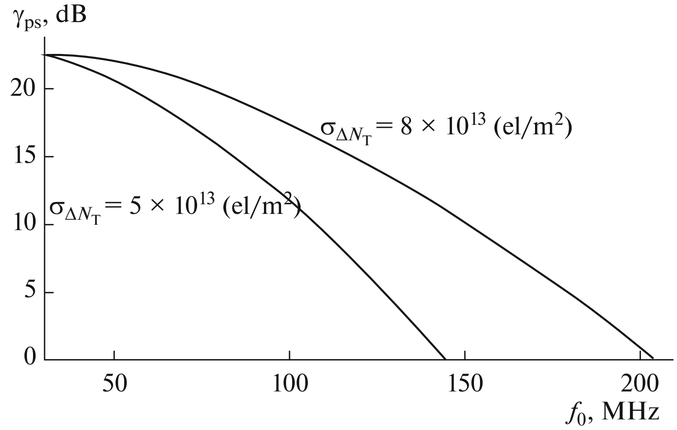

Fig. 4. Dependence of SCS energy concealment factor on selection of carrier frequency using dual signal reception.

does not yield energy concealment (γ_{ec} = 0 dB) for traditional values of the SCS carrier frequency $f_0 \geq 150$ MHz.

If the carrier frequency is reduced to f_0 = 30 MHz, the SCS energy concealment factor increases to $\gamma_{ec} \approx 22$ dB. For the recommended low-frequency range f_0 = 60…80 MHz, the SCS energy concealment factor is $\gamma_{ec} \approx$ 19–16 dB because according to the table, this frequency range has a small Rician parameter ($\gamma^2 \approx 1.5-3$) and low fading correlation coefficient (R = 0.74…0.84) in the case of space-diversity antennas at a distance of $\Delta\rho_a$ = 300 m.

For comparison, Fig. 4 shows the dependence of the SCS energy concealment factor $\gamma_{ec} = \Psi(f_0)$ on the carrier frequency selection according to (6)–(9) in case of high value (see Fig. 3) of small-scale SD variations of the mid-latitude ionospheric $\sigma_{\Delta N_T} = 8\times10^{-3}$ ($TECU$). Here, the energy concealment factor of a low-frequency SCS is higher than $\gamma_{ec} \approx$ 22–20 dB, because according to (7)–(9), if ionospheric TEC fluctuations $\sigma_{\Delta N_T}$ are large in the same frequency range f_0 = 60–80 MHz, the phase shifts of arriving waves $\sigma_\varphi \sim \sigma_{\Delta N_T}/f_0$ increase and both the Rician parameter $\gamma^2 = 1/\sigma_\varphi^2 \sim f_0^2/\sigma_{\Delta N_T}^2$ and the fading correlation coefficient of space-diversity antennas $R \sim 1-(\Delta\rho_a\,\sigma_\varphi/l_s)^2$ derease.

4. CONCLUSIONS

Analysis of Fig. 4 shows that selection of a low-carrier frequency for low-frequency SCSs strongly depends on ionospheric conditions. To ensure SCS energy concealment (e.g., $\gamma_{ec} \approx 18$ dB), the carrier frequency should be selected as $f_0 \approx 70$ MHz with standard parameters of small-scale variations of the mid-latitude ionospheric TEC $\sigma_{\Delta N_T} = 5\times10^{13}$ (el/m^2). In the case of intensified small-scale variations of the TEC $\sigma_{\Delta N_T} = 8\times10^{13}$ (el/m^2), the carrier frequency should be increased to $f_0 \approx 100$ MHz. Thus, we have developed a procedure for calculating the dependence of the energy concealment factor on selection of the carrier frequency for an SCS $\gamma_{ec} = \Psi(f_0, \sigma_{\Delta N_T})$ with space-diversity signal reception by two antennas (n = 2) based on the sounding of small-scale variations of ionospheric TEC.

An advantage of this procedure compared to similar one is that well-known publications [1, 2] were limited to rationalizing the possibility of increasing the energy concealment factor of a low-frequency SCS by lowering the carrier frequency (down to f_0 = 60–80 MHz with typical ionospheric inhomogeneity parameters) and spatial-diversity signal reception. However, this procedure makes it possible to calculate the increment of the energy concealment factor of a low-frequency SCS when using doubled signal reception as the carrier frequency decreases by utilizing the results of the ionospheric TEC from GPS sounding.

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