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Questions on Optimization of Measurement of Total Electron Content in Ionosphere with GPS

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Abstract

The analysis of existing method for calculation of total content of electrons (TEC) in ionosphere using GPS occultation method does show that due to different values of signal/noise ration in GPS signals L_1 and L_2, the new method of optimum measurements of relevant frequency components of TEC measured by phase and code methods should be developed. The optimum quantity of measurements of the above-mentioned frequency components is determined taking into account the limitation imposed on general number of necessary measurements.

Keywords

GPS Receiver, Ionosphere, Optimization, Total Electron Content, Measurements

1. Introduction

It is well-known that the measurements of total electron content (TEC) and scintillation parameters of ionosphere can be carried out with GPS which is important for study of this layer of atmosphere.

The measurement of said parameters of ionosphere was carried out during last 20 years, but accuracy of such measurements was not so high. Increase of accuracy of said measurements is important from the view point of modification of monitoring of ionosphere and is vital for study of non-stability and turbulence of ionospheric plasma.

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As it is noted in the work [1], the distortions of results of GPS measurements caused by ionosphere factors are one of the most significant components of total error of positioning using GPS. Delay of GPS signals due to effect of ionospheric electrons can be featured and taken account by carrying out double frequency measurements, signed as GPS L_1 and L_2.

2. Critical Review of Existing Methods

According to [1], if the frequency of the GPS signal too exceeds the frequency of ionospheric plasma, the group delay Δr measured by meters, should be defined as:

$$\Delta r = \frac{40.3}{f^2} \cdot TEC, \tag{1}$$

where *TEC*—total electronic content (electrons per square meter); f —frequency of GPS signal.

It should be noted, that one unit of *TEC*, equal to 10^{16} electron·m^{-2} causes delay of L_1 equal to 0.163 m, and L_2 −0.267 m.

According to [1], the following interrelation of major parameters used in double frequency measurements of TEC does exist,

$$TEC_\rho = \frac{\rho_{L_1} - \rho_{L_2}}{0.104 mTECU^{-1}}, \tag{2}$$

where $TECU = 10^{16}$ electron·m^{-2}; ρ_{L_1} and ρ_{L_2} —measured pseudo ranges.

It should be noted, that the Formula (2) is true for carrying out of GPS code measurements.

As it is noted in [1], the total electron content in ionosphere also can be determined by carrying out the measurements of phase of carrier signal of L_1 and L_2. If that, the following formula is true,

$$TEC_\varphi = \frac{-\varphi_{L_1} + \varphi_{L_2}}{0.104 mTECU^{-1}}, \tag{3}$$

where φ_{L_1} and φ_{L_2} —phases of signals L_1 and L_2, transformed to ranges.

In order to calculate the resulting values of TEC_f the following algorithm is suggested in [1]:

The averaged value of difference $TEC(t)_\rho - TEC(t)_\varphi$ as a function of time should be calculated using least squares method,

$$TEC_\delta = l.s.m.\left[TEC(t)_\rho - TEC(t)_\varphi\right]. \tag{4}$$

The final value of difference TEC_f should be determined as:

$$TEC_f = TEC_\varphi - TEC_\delta. \tag{5}$$

According to [1], the above described method allows to calculate the smoothed and absolute amount of TEC_δ in link with each satellite during whole time of its functioning.

At the same time, such method of calculation of TEC in ionosphere is non-effective due to following reasons. As it is noted in the work [2], the disperse nature of ionosphere causes the temporal delay inversely proportional to square of frequency of radio signal. This, in principle, allows removing the ionospheric error during geodetic GPS measurements carrying out combinational double frequency method of positioning. In this case, the above said dispersive property is strictly observed in the Formula (1). According to this formula the group delay should be more at the frequency L_2 (we remind, that $L_1 = 1.575$ GHs; $L_2 = 1.227$ GHs).

In line with works [3]-[5], the signal/noise ratios for frequencies L_1 and L_2 are sharply different. Upon use of radio occultation method the signal/noise ratios of received GPS signals are not constant temporally due to defocusing and/or attenuation of radio signal. The difference between signal/noise ratios for L_1 and L_2 frequencies is not less than 15% - 20% and can reach 100% and more.

Taking into account such a significant difference between signal/noise ratios for L_1 and L_2, the method described in [1], based on of Formulas (2)-(5), can be considered as non-rational, because this method provides for carrying out of joint statistical processing of signal featured by different level noisiness.

Authors of the work [6] suggest taking into account the different level of noises in L_1 and L_2 signals in

GPS occultation measurements by calculating the linear combination of these signals. It is noted, that custom linear combination of L_1 and L_2 is functioning well only if noises are miserable. But, in reality the quality of signal L_1 is more higher, than that of L_2, which commonly is not taken into account in such linear combinations.

Authors of [6] suggest to develop such a combination of signals, which would take into account the different levels of their noisiness. In this case L_1 and L_2 should be processed independently each other. The weight coefficients of these components accord to their estimated dynamic accuracy. It is noted, that such a method allows increasing the total effectiveness of radio occultation method.

3. Optimization of Measuring of TEC in Ionosphere Using GPS

The purpose of the present article is further development of idea, suggested in [6] concerning independent processing of L_1 and L_2 signals by way of optimization of the measurement process using the limitation condition imposed on general resources of measuring operations.

As it was noted above, in line with the method, suggested in [1], the average value of $TEC(t)_p$ and $TEC(t)_\varphi$ should be calculated using formula [4]. In its turn, to calculate the average value of $TEC(t)_p$, in line with Formula (2), the average values of ρ_{L_1} and ρ_{L_2} should be calculated.

But it is well-known that upon calculation of averaged values of noisy measuring signals the random error of measurement decreases by $\sqrt{n}$ times, where n –number of measurements.

The task of optimal organization of measurement upon realization of above described method can be formulated as follows. Assume, that the limitation condition is imposed on total number amount of carried out measurement operations by purpose to calculate the average values of ρ_{L_1} and ρ_{L_2}, *i.e.* the number of measurement operations is limited and equal to n_0.

Let us signify the random error of measurement of ρ_{L_1} as σ_{L_1} and ρ_{L_2} as σ_{L_2}.

The total random error of measuring of $TEC(t)_p$ can be determined as:

$$\sigma^2_{TEC} = \sigma^2_{L_1} + \sigma^2_{L_2}. \tag{6}$$

If we assume, that L_1 should be measured by n_1 times, then L_2 may be measured by $n_0 - n_1$ times. Therefore, the total random error can be determined as:

$$\sigma^2_{TEC_0} = \frac{\sigma^2_{L_1}}{n_1} + \frac{\sigma^2_{L_2}}{n_0 - n_1}. \tag{7}$$

Now we are searching for minimum of function (7) on n_1.

The first derivative of function (7) on n_1 gives us:

$$\left(\sigma^2_{TEC_0}\right)'_n = -\frac{\sigma^2_{L_1}}{n_1} + \frac{\sigma^2_{L_2}}{\left(n_0 - n_1\right)^2}. \tag{8}$$

Taking into account

$$\left(\sigma^2_{TEC_0}\right)'_n = 0$$

we get:

$$\frac{n_1^2}{\sigma^2_{L_1}} = \frac{\left(n_0 - n_1\right)^2}{\sigma^2_{L_2}}. \tag{9}$$

From the Formula (9) it is easy to get following square order linear equation:

$$n_1^2 + 2bn_1 - bn_0 = 0. \tag{10}$$

where

$$b = \frac{n_0}{\sigma_{L_2}^2 \left(\frac{1}{\sigma_{L_1}^2} - \frac{1}{\sigma_{L_2}^2} \right)}. \tag{11}$$

Solution of Equation (10) is following:

$$n_1 = \sqrt{b^2 + bn_0} - b. \tag{12}$$

Using method of second derivative we can show, that upon solution (12) the total random error reaches its minimum value. The second derivative of Equation (7) is as follows:

$$\left(\sigma_{TEC_0}^2 \right)''_n = \frac{2\sigma_{L_1}^2}{n_1^3} + \frac{2\sigma_{L_2}^2}{\left(n_0 - n_1 \right)^3}. \tag{13}$$

As it can be seen from Formula (13) the second derivative is always positive, which confirm the solution (12).

Therefore, it is shown, that if the limitation is imposed on total number of possible measurements of TEC_ρ we should take into account, that the minimum value of total random error of this parameter can be reached upon different numbers of measurements of ρ_{L_1} and ρ_{L_2}.

Due to simmetricity of Formulas (2) and (3) the similar conclusion is true for case of measuring TEC_φ.

4. Conclusions

Consequently, it is shown that upon imposed limitation on total number of carried out measurements, due to different values of signal/noise ratios of L_1 and L_2, the minimum value of random errors TEC_φ and TEC_ρ can be obtained upon non-equal numbers of measurements of parameters ρ_{L_1} and ρ_{L_2}, and φ_{L_1} and φ_{L_2}. It is obvious that minimization of total random of TEC_ρ and TEC_φ could lead to an increase of accuracy of resulting value of TEC_f, which is the main output parameter of the known method [1], designated for calculation of total electron content in ionosphere.

In conclusion we can formulate following results of research carried out:

The analysis of existing method for calculation of total electron content in ionosphere using the GPS occultation measurements does show that due to different values of signal/noise ratios for GPS signals L_1 and L_2 the special method of optimal measurements of frequency components of TEC measured by phase and code measurements methods should be developed.

The optimal number of measurements of above said frequency components is determined taking into account the limitation condition imposed on total number of measurements carried out.

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