DOI 10.1007/s11182-018-1430-6

Russian Physics Journal, Vol. 61, No. 3, July, 2018 (Russian Original No. 3, March, 2018)

INFLUENCE OF THE ATMOSPHERIC PHENOMENA ON THE TROPOSPHERIC DELAY OF SATELLITE NAVIGATION SIGNALS

F. N. Zakharov, S. A. Mikhailenko, and D. V. Timoshin UDC 537.877

An error in calculating the tropospheric delay of satellite navigation signals is estimated for different atmospheric phenomena. As atmospheric phenomena, different precipitation types (hydrometeors) and electrical phenomena (thunderstorms and summer lightning) are considered. The tropospheric delay is calculated for the Saastamoinen and Hopfield models with the vertical profiles of the atmospheric meteorological parameters obtained by aerological sounding. The error of the given methods is determined by a comparison of the calculated and true values of the zenith tropospheric delays. The influence of the atmospheric phenomena on the error value is analyzed.

Keywords: tropospheric delay, atmospheric phenomena, Saastamoinen model, Hopfield model, aerological sounding, global navigation satellite systems.

INTRODUCTION

At present, global navigation satellite systems (GLONASS, GPS, etc.) are widely used. The object coordinates in such systems are determined by measuring pseudo-ranges from the object to the navigation satellite [1–3]. The accuracy in determining the pseudo-range is influenced by different factors. One of the factors is the delay of the navigation signal in the troposphere due to the difference between the velocity of radio wave propagation in the troposphere and the velocity of light.

When the navigation receiver operates in the differential regime, the tropospheric signal delay and some other errors in measuring pseudo-ranges are compensated by differential corrections provided by the base station. If the navigation receiver operates in the independent regime and performs high-precision measurements, the troposphere will influence significantly the accuracy of measuring pseudo-ranges [4, 5]. It should be noted that in navigation, the tropospheric delay is taken to mean the signal delay in the lower 50-kilometer layer of the neutral atmosphere, since about 85% of the delay is observed in the troposphere at altitudes below 12–15 km [1].

The existing methods of delay calculations are based on deterministic vertical profiles of the tropospheric parameters as functions of the altitude and local measurements of meteorological parameters near the Earth surface. In calculations, the tropospheric delay is tentatively subdivided into two components: dry (hydrostatic) and wet ones. The dry component is determined mainly by dry gases of the troposphere and can be determined with high accuracy [3].

The wet component of the delay is determined by the moisture content in the troposphere. Masses of water and water vapor are irregularly distributed in the troposphere, which complicates the description of vertical humidity profile by deterministic models. This leads to the fact that in high-precision navigation or geodetic measurements, the wet component is the main source of error when correcting for the tropospheric delay in spite of the fact that its contribution to the total delay makes only 15% [6].

Tomsk State University of Control Systems and Radioelectronics, Tomsk, Russia, e-mail: ZakharovFN@main.tusur.ru; mikhailenko.94@main.tusur.ru; d.v.timoshin@main.tusur.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 3, pp. 116–123, March, 2018. Original article submitted September 5, 2017; revision submitted February 5, 2018.

Thus, the accuracy of calculation of the tropospheric delay is influenced by different atmospheric phenomena (AP), leading to deviations of the true vertical humidity profiles from model ones. Works in which the dependence of the tropospheric delay on the atmospheric phenomena is investigated are few in number (for example, see [7, 8]). The AP in the present work are taken to mean different precipitations (hydrometeors) and electrical phenomena (thunderstorms and summer lightning). In this connection, the work analyzes the influence of different AP on the error in calculating the tropospheric navigation signal delay.

METHODS OF CALCULATING THE TROPOSPHERIC DELAY

To calculate precisely the tropospheric delay τ, it is necessary to know the refractive index N along the path S of navigation signal propagation:

$$\tau = \int_S 10^{-6} N(s) ds \text{ [m]}. \quad (1)$$

The presence of AP leads to significant fluctuations of the vertical profiles of the refractive index. In particular, in [9] the structures of inhomogeneities of the refractive index corresponding to different meteorological formations are considered, and examples of experimental profiles of the refractive index measured with a radio refractometer are given obtained by vertical sounding of lower layers of the troposphere. In [4] these profiles are analyzed and errors in calculating the tropospheric delay (in a 4-kilometer layer of the troposphere) are calculated from formula (1) for different models of the measured vertical profiles of the refractive index.

In actual practice, it is extremely difficult to obtain values of the refractive index along the propagation path. In practice, the methods of calculations based on knowledge of the meteorological parameters (pressure, temperature, and humidity) in the place of arrangement of the navigation signal receiver are used. The given parameters are either directly used in calculation formulas [1–3], or are recalculated to the near-ground refractive index which is then used to calculate the delay [1, 4, 5]. The most widespread are models suggested by J. Saastamoinen and H. Hopfield [1–3].

The Saastamoinen model does not use information on the structure of the troposphere and is based on the following assumptions:

1) the water vapor behaves as an ideal gas,
2) all water vapor in the atmosphere is concentrated in the troposphere,
3) the temperature decreases linearly with increasing altitude,
4) the gravitation is constant along the radio signal propagation path.

Using these assumptions, Saastamoinen derived the following expressions for dry (τ_d^z) and wet (τ_w^z) components of the tropospheric delay in the zenith direction:

$$\tau_d^z = 0.002277 P_s \left(1 - 0.0026 \cos 2\varphi + 2.8 \cdot 10^{-7} h_s\right) \text{ [m]}, \quad (2)$$

$$\tau_w^z = 0.002277 \left(0.5 + \frac{1255}{T_s}\right) e_s \text{ [m]}. \quad (3)$$

Here P_s is the atmospheric pressure in the vicinity of the place of arrangement of the navigation receiver, in mbar; T_s is the temperature, in degrees of Kelvin; e_s is the humidity, in mbar; φ is the latitude of the observation point, in radians; h_s is the altitude of arrangement of the navigation receiver above the sea level, in meters.

The Hopfield model describes the vertical profiles of the dry (N_d) and wet (N_w) refractive index components by the fourth degree polynomials:

$$N_{d,w}(h) = N_{sd,sw}\left(1 - \frac{h}{H_{d,w}}\right)^4, \tag{4}$$

where N_{sd} and N_{sw} are the dry and wet components of the near-ground refractive index calculated for the measured meteorological parameters [3], and H_d and H_w are altitudes at which it is possible to consider the dry and wet refractive indices equal to zero. Integrating Eq. (4) over altitude yields the value of the zenith tropospheric delay.

To determine the zenith tropospheric delay, results of aerological sounding of the atmosphere can be used. Aerological sounding allows the vertical profiles of the meteorological parameters to be obtained that are recalculated to the refractive index profile using the Smith–Weintraub formula [10]

$$N = \frac{77.6}{T}\left[P + \frac{4810e}{T}\right]. \tag{5}$$

In the present work, the intermediate values of the meteorological parameters were obtained by linear interpolation of the temperature and humidity and exponential interpolation of the pressure.

INPUT DATA

To determine the error in calculating the tropospheric delay for different AP, the true delays were compared with its calculated values. The true zenith tropospheric delays are accessible on the site of the Branch of the Joint Stock Company "Research and Production Corporation "Precision Instrument-Making Systems" (http://glonass-svoevp.ru) in the form of files with extension "tro." The declared accuracy of such data is 4 mm. Observations from January 1, 2015 till September 30, 2016 at the Navigation Station located in Novosibirsk (the code number "NOVS") were analyzed. Values of the true tropospheric delays were registered at the Station round the clock every 2 h.

To calculate the delay for the Saastamoinen and Hopfield models, the meteorological parameters recorded at the Meteorological Station Ogurtsovo (Novosibirsk) were used. Measurements of the meteorological parameters and registration of AP were performed at the Meteorological Station every 3 h. Values of the meteorological parameters, AP, their intensities, and amounts of precipitations are accessible for free from special databases [11, 12] of the All-Russia Scientific Research Institute of Hydrometeorological Information.

To calculate the delay from the aerological profiles, the profiles obtained at the Novosibirsk Station of Aerological Sounding were used. Aerological sounding was carried out at 0 and 12 h, Greenwich time. The profiles of aerological sounding are accessible for free on the site of Wyoming University of the USA (http://www.uwyo.edu). To compare the true tropospheric delays with meteorological measurements and AP, the delays were recalculated to the standard meteorological terms using linear interpolation of intermediate values.

RESULTS OF CALCULATIONS

Influence of the AP on the error

The error of delay calculation was determined by subtraction of the true values from the calculated ones. Then the difference files were statistically processed. Statistical processing consisted in calculations of the average error, standard deviation (SD), and mean square error (MSE). The MSE was defined as the square root of the sum of squares of the average error and SD.

Table 1 lists the examined AP, their code numbers according to the Manual to Hydrometeorological Stations and Posts, and the number of measurements of the meteorological parameters and aerological sounding events for the corresponding AP. In addition, the number of measurements without the examined AP and measurements during the indicated period, including cases without AP, are given.

TABLE 1. Examined AP Types and Number of Measurements from January 1, 2015 till September 30, 2016

AP Code	AP name	Number of meteorological measurements	Number of aerological measurements
10	Dew	791	165
21	Haze	448	94
23	Translucent fog	53	13
24	Ground fog	24	6
28	Surrounding fog	6	3
62	Drizzle	6	0
63	Rain	8	0
64	Shower	571	131
65	Hailstone	6	2
70	Snow	212	32
71	Shower snow	485	54
73	Wet shower snow	148	27
80	Thunderstorm	116	30
81	Summer lightning	16	0
Without AP		2444	507
Total number of measurements		4992	961

TABLE 2. Error in Calculating the Zenith Tropospheric Delay, cm

AP code	Saastamoinen model			Hopfield model			Aerological measurements		
	SD	Average	MSE	SD	Average	MSE	SD	Average	MSE
10	2.5	1.1	**2.7**	2.4	–2.2	**3.3**	2.1	0.8	**2.2**
21	2.4	0.1	**2.4**	2.5	–3.2	**4.1**	2.2	0.9	**2.3**
23, 24, 28	2.7	0.2	**2.7**	2.7	–3.2	**4.2**	2.2	0.2	**2.2**
62, 63	1.3	–0.4	**1.4**	1.3	–3.5	**3.7**	-	-	**-**
64	2.4	–0.8	**2.5**	2.4	–4.1	**4.7**	2.2	0.8	**2.4**
65	1.6	–0.8	**1.8**	1.8	–4.0	**4.4**	0.2	–1.0	**1.0**
70, 71, 73	1.5	–0.3	**1.6**	1.6	–3.5	**3.8**	1.4	0.8	**1.6**
80, 81	2.2	–1.1	**2.5**	2.2	–4.6	**5.1**	1.8	0.2	**1.8**
Without AP	2.3	0	**2.3**	2.3	–3.3	**4.0**	2.1	0.8	**2.2**
Total	2.2	–0.1	**2.2**	2.2	–3.4	**4.1**	2.1	0.8	**2.2**

Table 2 presents results of statistical processing of the tropospheric delay difference files by the three methods. For convenience of analysis and presentation, some AP were combined into groups based on similarity of external AP manifestations.

Figure 1 shows histograms of errors in calculating the zenith tropospheric delay for the Saastamoinen model relative to the true delay for the indicated AP types. The solid curve in Fig. 1 shows the plot of the normal distribution with the parameters from Table 2. Testing of histograms on the compliance with the normal distribution law using the χ-square criterion on a significance level of 0.95 yielded positive result only for dew and electrical AP.

Table 2 presents the errors calculated for the satellite located in zenith. However, this situation is rare. Therefore, the situation when the satellite is at a certain angle to the horizon is of interest. In this case, the error in calculating the inclined tropospheric delay will be larger due to lengthening of the signal propagation path in the troposphere and the presence of horizontal inhomogeneities of the refractive index in the troposphere [13].

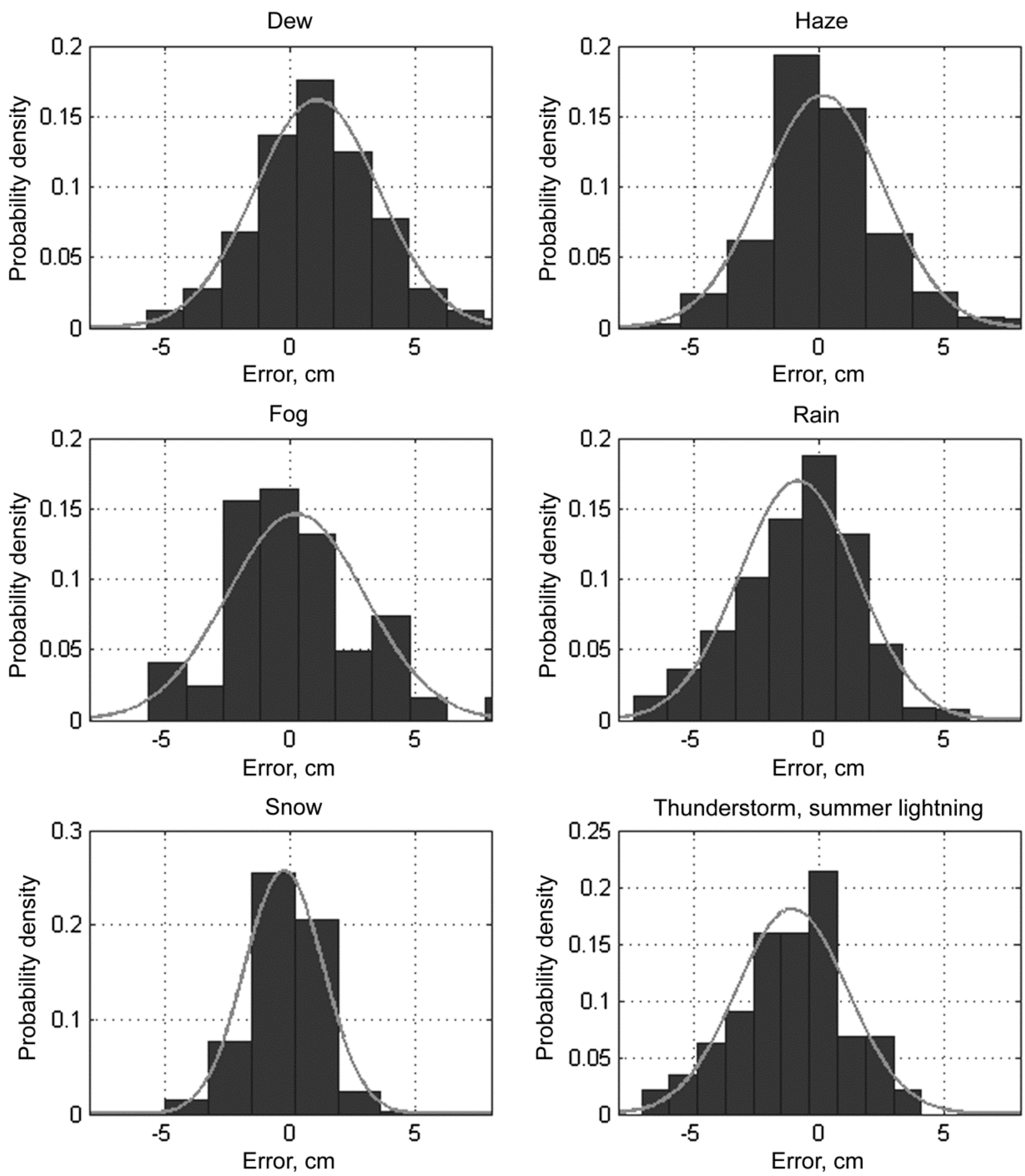

Fig. 1. Histograms of errors in calculating the zenith tropospheric delay for the Saastamoinen model and indicated AP types.

Table 3 shows the MSE for the methods of registration of satellite signals at angles of 3 and 15° to the horizon. The zenith delay τ^z was recalculated to the inclined one $\tau(\alpha)$ using the mapping function [1]

$$\tau(\alpha) = \tau^z m(\alpha), \tag{6}$$

$$m(\alpha) = \frac{1}{\sqrt{1 - \left(\frac{\cos\alpha}{1.001}\right)^2}}, \tag{7}$$

TABLE 3. MSE in Calculating the Inclined Tropospheric Delay, cm

AP code	Elevation angle 15°			Elevation angle 3°		
	Saastamoinen model	Hopfield model	Aerological measurements	Saastamoinen model	Hopfield model	Aerological measurements
10	10.3	12.6	8.5	39.1	48.0	32.5
21	9.3	15.5	8.9	35.3	59.2	33.8
23, 24, 28	10.5	15.9	8.5	39.9	60.6	32.3
62, 63	5.3	14.2	-	20.3	54.0	-
64	9.6	18.0	9.1	36.5	68.5	34.5
65	6.9	16.6	3.7	26.2	63.4	14.1
70, 71, 73	6.0	14.7	6.1	22.9	55.9	23.3
80, 81	9.4	19.4	7.0	35.7	74.0	26.6
Without AP	8.6	15.1	8.4	32.9	57.7	32.1
Total	8.3	15.5	8.5	31.8	59.0	32.2

where $m(\alpha)$ is the mapping function and α is the angle of satellite location.

Influence of the AP intensity and amount of precipitations on the error

We further consider the influence of the AP intensity and amount of precipitations on the error value in calculating the tropospheric delay. The AP intensity was subdivided into three types: weak, moderate, and strong [11]. The following AP were considered: shower and three types of snow precipitations (snow, shower snow, and wet shower snow).

Table 4 presents results of statistical processing of the error for the Saastamoinen and Hopfield models and the indicated AP intensity, and Table 5 presents the dependence of the error on the amount of precipitations. The amount of precipitations is given for the interval between observations [11] (that is, for 2 h). The dependences of the errors calculated from the aerological profiles on the intensity and amount of precipitations are not presented because they were obtained for small samples and could be unreliable. The errors for strong AP intensity were also obtained for small samples and can be used only for rough estimation.

An increase in the error with the amount of precipitations was observed for all three types of snow precipitations; therefore, in Table 5 they were combined into one AP type.

DISCUSSION OF RESULTS

Based on the results presented here, the following conclusions can be drawn. The Saastamoinen model allows the zenith tropospheric delay to be calculated with small average error not exceeding 1.1 cm (for dew, thunderstorm, and summer lightning). In this case, the SD does not exceed 2.7 cm. The maximum MSE is observed for dew and fog, and the minimum MSE is observed for drizzle (drizzle and rain), hailstone, and snow. In this case, the MSE is even less than the MSE calculated for the entire set of measurements, including cases without AP.

For dew and fog, the large error can be explained by high relative humidity in the lower layer of the troposphere, whereas the structure of the upper layers of the troposphere is close to the standard atmosphere, which is not considered by the model. Without AP, the Saastamoinen model yields zero average error, because it was developed for the standard atmosphere described by ideal gas laws.

The Hopfield model allows the tropospheric delay to be calculated with the same SD as the Saastamoinen model. However, in this case the average error is much greater. The Hopfield model is based on processing of a large number of measurements in different regions of the Earth and is the average model of the atmosphere. The total error in calculating the delay in the zenith direction for the given model exceeds 3.3 cm; it reaches 12–19 cm for satellite

TABLE 4. Dependence of the Error on the Precipitation Intensity, cm

AP	Intensity								
	Weak			Moderate			Strong		
	SD	Average	MSE	SD	Average	MSE	SD	Average	MSE
Saastamoinen model									
Shower (code 64)	2.3	–0.8	2.4	2.7	–0.9	2,8	3.2	–1.4	3.5
	452*			113*			6*		
Snow (code 70)	1.3	–0.5	1.4	0.7	–0.3	0,8	-	-	-
	188*			24*			0*		
Shower snow (code 71)	1.6	–0.1	1.6	1.6	–0.3	1,6	1.2	0.5	1.3
	352*			127*			6*		
Wet shower show (code 73)	1.4	0	1.4	2.0	–1.0	2,3	0.4	0.1	0.4
	93*			49*			3*		
Hopfield model									
Shower (code 64)	2.3	–4.0	4.6	2.7	–4.1	5.0	3.2	–4.8	5.8
	452*			113*			6*		
Snow (code 70)	1.4	–4.0	4.2	0.8	–3.6	3.8	-	-	-
	188*			24*			0*		
Shower snow (code 71)	1.6	–3.3	3.7	1.8	–3.5	3.8	1.2	–2.6	2.9
	352*			127*			6*		
Wet shower snow (code 73)	1.4	–3.1	3.4	2.0	–4.0	4.5	0.4	–3.0	3.0
	93*			49*			3*		

Note. Here * indicates the number of measurements.

TABLE 5. Dependence of the Error on the Amount of Precipitations, cm

Amount of precipitations between observations, mm	Saastamoinen model			Hopfield model			Number of measurements
	SD	Average	MSE	SD	Average	MSE	
Rain (codes 63, 64)							
<3	2.1	–0.4	**2.1**	2.1	–3.6	**4.2**	73
From 3 to 6	2.2	–0.6	**2.3**	2.2	–3.8	**4.4**	28
>6	2.4	–2.0	**3.2**	2.4	–5.3	**5.8**	19
Snow (codes 70, 71, 73)							
<3	1.4	–0.1	**1.4**	1.5	–3.4	**3.7**	120
From 3 to 6	1.6	–1.1	**1.9**	1.6	–4.2	**4.5**	12
>6	2.3	–1.5	**2.8**	2.3	–4.6	**5.2**	3

observation at an angle of 15°, and for observation at an angle of 3°, it is 50–70 cm. For a comparison, the error in calculations from the aerologic profiles for an elevation angle of 15° does not exceed 9.1 cm, and for satellite observation angle of 3°, it is equal to 34.5 cm.

The average error of calculations from the aerological profiles is approximately constant (except for fog and electrical AP). Such value of the average error is most likely due to small-scale tropospheric inhomogeneities disregarded in aerological sounding [5].

The calculation from the aerological profiles yields the MSE being minimal of the three methods. In this case, the error value depends on the AP only slightly (small MSE for hailstone is statistically unreliable). This is due to the fact that the Saastamoinen and Hopfield models are based on the results of near-ground meteorological measurements and cannot consider the influence of the layered tropospheric inhomogeneities. Aerological sounding allows both the state of the lower part of the troposphere and the large-scale tropospheric inhomogeneities to be taken into account [5].

From Table 4 it follows that with increasing intensity of “dry” precipitations (snow and shower snow), the error decreases, whereas with increasing intensity of “wet” precipitations (rain and wet shower snow), the increase of the error in calculating the tropospheric delay based on the models is observed. These conclusions are valid for weak and moderate intensities. The number of observations of intensive AP is insufficient for reliable conclusions.

From Table 5 it follows that with increasing amount of precipitations, the error in calculating the delay increases. In this case, both the modulus of the average error and its SD increase. Such dependence is observed for “dry” and “wet” precipitations.

CONCLUSIONS

The influence of the examined AP on the error in calculating the delay is mainly reduced to the influence of the layers with enhanced or reduced humidity that are not taken into account in calculations with the models. The maximum accuracy of calculations of the tropospheric delay has the method based on the application of the aerological sounding of the atmosphere. However, this method does not allow data on the atmospheric state to be obtained in real time at any arbitrary point. As an alternative, the ATOVS satellite data [14] on the vertical profiles of the tropospheric parameters can be used, and in this case, the accuracy of calculation of the zenith tropospheric delay [15] is comparable to the accuracy of aerological sounding. Nevertheless, the most widespread and applied method is based on the Saastamoinen model with ground-based meteorological measurements. This model, in comparison with the Hopfield model, has a smaller error both with and without AP. The Hopfield model is inapplicable for the conditions of Novosibirsk, because it calculates the tropospheric delay with a large average deviation.

The results obtained can be used for estimating the budget of errors in measuring pseudo-range and forecasting errors in measuring the coordinates in the presence of different atmospheric phenomena.

The part of this work on processing of aerological measurements was carried out within the framework of Assignment No 8.7348.2017/8.9 of the Ministry of Education and Science of the Russian Federation from January 1, 2017. The work on processing of meteorological measurements was carried out within the framework of Assignment No. 5.3279.2017/4.6 of the Ministry of Education and Science of the Russian Federation from May 31, 2017.

REFERENCES

1. K. M. Antonovich, Application of Satellite Navigating Systems in Geodesy, Vol. 1 [in Russian], Federal State Unitary Enterprise “Kartgeotsentr,” Moscow (2005).
2. A. I. Perov and V. N. Kharisov, GLONASS. Construction and Operation Principles [in Russian], Radiotekhnika, Moscow (2010).
3. B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins, Global Positioning System: Theory and Practice, Springer Science & Business Media (2012).
4. F. N. Zakharov and M. V. Krutikov, Doklady TUSUR, No. 2 (32), 7–12 (2014).
5. F. N. Zakharov, S. G. Gosenchenko, and M. V. Krutikov, Doklady TUSUR, No. 1 (35), 9–17 (2015).
6. D. Yu. Pershin, Vestnik NSU. Series Information Technology, **7**, No. 1, 84–91 (2009).
7. V. I. Lutsenko *et al*., in: Proc. 24th Int. Crimean Conf. “Microwave & Telecommunication Technology” (CriMiCo’ 2014), Sevastopol (2014), pp. 1125–1126.
8. S. P. Shchekin *et al*., Radiofiz. Elektron., **7** (21), No. 3, 40–47 (2016).
9. L. V. Pavlova, in: Proc. XX All-Russian Sci. Conf. “Propagation of Radio Waves, N. Novgorod (2002), pp. 352–353.
10. B. R. Bin and E. J. Datton, Radio Meteorology [Russian translation], Gidrometeoizdat, Leningrad (1971).

11. O. N. Bulygina, V. M. Veselov, V. N. Razuvaev, and T. M. Aleksandrova, Description of the file of urgent data on the main meteorological parameters at the Russian stations, Certificate of State Registration of Database No. 2014620549.
12. O. N. Bulygin, V. M. Veselov, T. M. Aleksandrova, and N. N. Korshunova, Description of the file of data on atmospheric phenomena at the Russian meteorological stations, Certificate of State Registration of Database No. 015620081.
13. F. N. Zakharov, S. G. Gosenchenko, and M. V. Krutikov, Usp. Sovrem. Radioelektr., No, 11, 14–17 (2016).
14. V. B. Kashkin and E. B. Petrov, Izv. Vyssh. Ucheb. Zaved. Fiz., **53**, No. 9/2, 27–29 (2010).
15. V. B. Kashkin, V. M. Vladimirov, and A. O. Klykov, Opt. Atm. Okeana, **27**, No. 7, 615–621 (2014).