A model for converging tropospheric delay corrections

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Abstract. In response to the current problem that tropo-spheric delay correction is constrained by the measured meteorological parameters, resulting in low efficiency and limited application, this paper proposes a GE-Sa fusion model combining GPT2w and EGNOS models. The algorithm provides high-precision meteorological data through GPT2w and EGNOS models, and uses the Saastamoinen model to achieve the zenith tropospheric delay (ZTD) correction, the ZTD series of 2017 from 20 stations acquired by the Global Geodetic Observing System (GGOS) Atmosphere product data were used as the standard approximation to calculate the bias and RMS values of the model respectively, and the experimental results showed that the accuracy of the GE-Sa model was higher than that of the EGNOS model, GPT2w+Saastamoinen model, and 68.12% and 16.33%, respectively. The model improves the accuracy of calculating ZTD and expands the scope of application while getting rid of the limitation of measured meteorological parameters.

Keywords: tropospheric delay correction model, Saastamoinen model, EGNOS model, GPT2w model.

1. Introduction

The tropospheric delay is a key factor affecting the Global Navigation and Positioning System, and for the correction of tropospheric delay, the model correction method is currently used in the mainstream. Model correction methods can be divided into models with meteorological input parameters and models with non-meteorological parameters [1,2,3,4]. Among the models relying on measured meteorological parameters, the international classical models include the Saastamoinen model[5,6,7], the Hopfield model[8], the Black model[8], etc. The correction accuracy of these models can reach the centi-metre level if the exact measured meteorological para-meters are available, but in practice, not every station is equipped for high altitude weather detection due to the high cost of professional weather sensor equipment. In order to meet the demand for real-time tropospheric delays, non-meteorological models constructed using atmospheric reana-lysis data include the GPT series of models, UNB models and EGNOS models [9,10,11], which are easy to use, but their applicability needs further research. On the one hand, in order to get rid of the limitation of the measured meteorological parameters and expand the application scope of the models, and on the other hand, in order to improve the accuracy of calculating tropospheric delay, this paper proposes a GE-Sa fusion tropospheric model combining GTP2w and EGNOS models.

2. Model Introduction

2.1 Saastamoinen Model

Saastamoinen in 1972 proposed the formula for calculat-ing the dry delay component in the zenith direction as

$$D_{\mathrm{Zdry}} = \frac{0.0022768 \times P}{f(\varphi, h)} \tag{1}$$

$$f(\varphi, h) = 1 - 0.00266 \times \cos(2\varphi) - 0.00028 \times h \tag{2}$$

Where: h is the elevation of the station; φ is the latitude of the station; P is the barometric pressure of the station; $f(\varphi,h)$ is a model of the correlation between elevation and dimensionality, reflecting the variation of gravitational acceleration with geographical location and altitude. The wet delay is mainly caused by the lower tropospheric atmosphere and the wet delay component is given by

$$D_{\text{Zwet}} = \frac{0.0022768 \times e \cdot (0.05 + \frac{1255}{T})}{f(\varphi,h)} \tag{3}$$

Where: T is the absolute temperature of the station. e is water vapor pressure of the station. The total zenith delay (zenith tropospheric delay, ZTD) is

$$ZTD = D_{\text{Zdry}} + D_{\text{Zwet}} \tag{4}$$

The Saastamoinen model requires predicted meteorolo-gical parameters for navigation and positioning. The model requires the use of parameters such as air temperature, air pressure, water vapour pressure, station altitude and latitude to calculate the zenith tropospheric delay, so the accuracy of the model is closely related to the accuracy of the three meteorological measurements obtained for air temperature, air pressure and water vapour pressure, and therefore the constraints of the measured parameters also limit the use of the model for real-time navigation and positioning The use of the model in real-time navigation is therefore limited by the measured parameters.

2.2 EGNOS Model

The EGNOS model [12] is the tropospheric delay model used by the EU's satellite-based wide-area augmentation system. The model does not require measured meteorological parameters for the calculation of the ZTD, but only requires the input of the annual cumulative day and the location of the station to provide the five meteorological parameters needed to calculate the tropospheric zenith delay, which are: temper-ature, pressure, temperature gradient, water vapour pressure and water-air gradient. The model first finds the five meteorological parameters for mean sea level from the observation time and latitude, calculates the zenith delay at mean sea level, and then solves for the tropospheric zenith delay at the receiver from the elevation. The mathematical formulation of the model is

$$D_{\text{dry}} = d_{\text{dry}} \left[1 - \frac{\beta \times h}{T_0} \right]^{\frac{g}{R_d \times \beta}} \tag{5}$$

$$D_{\text{wet}} = d_{\text{wet}} \left[1 - \frac{\beta \times h}{T_0} \right]^{\frac{(\lambda+1) \cdot g}{R_d \times \beta}} \tag{6}$$

Where: D_{dry} is the dry delay component; D_{wet} is the wet delay component; T_0 is the mean sea level temperature; $g = 9.806\,6\ \text{m/s}^2$; $R_d = 287.054\ \text{s}^2/\text{K}$; $\beta = 0.006\,5\ \text{K/m}$. d_{dry} is the mean sea level zenith dry delay, which is given by

$$d_{\text{dry}} = \frac{10^{-6} k_1 \times R_d \times P_0}{g_m} \tag{7}$$

Where: P_0 is the mean sea level pressure; and others in the formula, $g_m = 9.784\ \text{m/s}^2$; $k_1 = 77.604\ \text{K/mbar}$; d_{wet} is the mean sea level zenith wet delay, which is given by

$$d_{\text{wet}} = \frac{10^{-6} \mathrm{k}_2 \times \mathrm{R}_\mathrm{d} \times e_0}{\left[\mathrm{g}_\mathrm{m} \times (\lambda + 1) - \beta \times \mathrm{R}_\mathrm{d}\right] \cdot T_0} \tag{8}$$

Where: e_0 is the mean sea level water vapour pressure; β is the temperature gradient; λ is the water vapour gradient; $\mathrm{k}_2 = 377\,600\ \mathrm{K}^2 / \mathrm{mbar}$.

2.3 GPT2w Model

Using 10 years of ERA-Interim reanalysis data provided by ECMWF from 2001-2010, Bohm has further improved the GPT2 model to obtain a GPT2w model with a high horizontal resolution of $1^\circ \times 1^\circ$. This model improves the horizontal resolution of GPT2 and also provides information on atmospheric weighted average temperature. The GPT2w model [4,14,15] provides tropospheric parameters such as surface temperature T_s, surface pressure P_s, water vapour pressure e_s,water vapour pressure decrement factor λ and atmos-pheric weighted average temperature T_m.The model express-ions are

$$\begin{aligned} X(t) = A_0 + A_1 \cos\left(2\pi \times \frac{\mathrm{doy}}{365.25}\right) + A_2 \sin\left(2\pi \times \frac{\mathrm{doy}}{365.25}\right) \\ + A_3 \cos\left(4\pi \times \frac{\mathrm{doy}}{365.25}\right) + A_4 \sin\left(4\pi \times \frac{\mathrm{doy}}{365.25}\right) \end{aligned} \tag{9}$$

where $X(t)$ is the meteorological parameters T_s, P_s, e_s and T_m at the grid point; doy is the annual cumulative day; A_0 is the mean value; A_1 and A_2 are the annual periodicity coefficients of the meteorological parameters; and A_3 and A_4 are the semi-annual periodicity coefficients of the meteorological parameters.

3. GE-Sa GE-Sa Fusion Tropospheric Model Algorithm

In the case that not all stations are equipped with professional meteorological sensor equipment, the use of meteorological forecast information becomes an effective means of calculating ZTD [16]. The GPT2w model can provide meteorological parameters that can provide air pressure and water vapour pressure parameters on a global scale, the EGNOS model can provide higher accuracy mean sea level air temperature, and after the elevation correction can obtain the air temperature at the station, and then the obtained The three tropospheric meteorological parameters are combined with the Saastamoinen model to obtain high accuracy zenith tropospheric delay information.

The station position and annual cumulonimbus date are read from the tropospheric product, the position information and annual cumulonimbus date are converted into latitude, longitude, altitude and simplified Julian date respectively, the GPT2w model with a horizontal resolution of $1^\circ \times 1^\circ$ is downloaded from the website (https://vmf.geo.tuwien.ac.at/), and the simplified Julian date and the latitude, longitude and altitude of the station are entered into the GPT2w model. The air pressure and water vapour pressure at the station are obtained. Temperature is one of the key parameters in the calculation of tropospheric delay, according to equation (10), the station latitude altitude and annual cumulative days are input into the EGNOS model to obtain the mean sea level temperature, and after the elevation correction, the station temperature is obtained, and the elevation correction equation is

$$T = T_\mathrm{s} - 0.0068h \tag{10}$$

The computational flow of the GE-Sa fusion tropospheric model is shown in Figure 1.

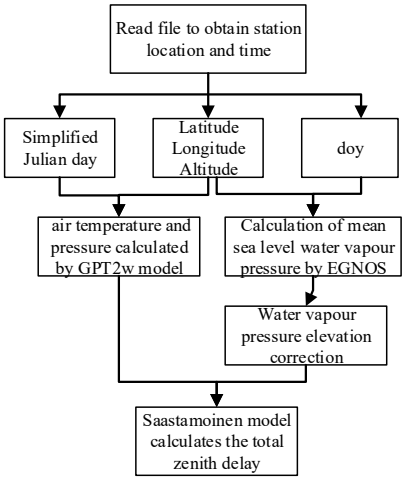


Figure 1. Flow chart of the GE-Sa convective layer model algorithm

4. Data Sources and Accuracy Assessment Methods

4.1 Data Sources

In this paper, a total of 365 d of ZTD sequences from 20 IGS stations provided by GGOS in 2017 were used as the baseline approximation, including 8 stations in the Chinese region and 12 stations distributed globally, the sampling interval for this experiment was 6 h and the total sample was 29200.

4.2 Accuracy Assessment Methods

In order to compare and analyse the models and object-tively assess the accuracy of the GE-Sa model, this paper uses the location and time information of these 20 stations to calculate the actual ZTD sequences of the GE-Sa model while setting up a control group to calculate the ZTD values obtained from the EGNOS model, as well as the real ZTD sequences of the GPT2w+ Saastamoinen model constructed from the GPT2w model as introduced in the previous section. The real ZTD sequences of the combined Saastamoinen model were compared with the baseline ZTD sequences provided by GGOS, respectively, and the bias and RMS of each group were calculated and averaged to achieve an analysis of the model accuracy.

5. AnalYsis of Experimental Results

In order to verify the accuracy of the GE-Sa fusion tropospheric model in calculating ZTD, this paper sets up 2 groups of tropospheric model control groups to compare the ZTD sequences provided by GGOS. The bias and RMS values of the 3 models for 20 IGS stations in the period of annual accumulation days of 001-365 in 2017 are shown in Table 5, the experimental results show that the absolute average bias value and average RMS value of the GE-Sa model for the 20 stations The absolute mean bias and RMS values of the GE-Sa model were 20.22 mm and 47.35 mm for the 20 stations; the absolute mean bias and RMS values of the EGNOS model were 136.26 mm and 148.56 mm, respectively; the absolute mean bias and RMS values of the GPT2w+Saastamoinen model were 32.43 mm and 56.60 mm, respectively; and the absolute mean bias and RMS values of the GE-Sa model were 32.43 mm and 56.60 mm, respectively. The accuracy of the GE-Sa model was 68.12% and 16.33% higher than that of the EGNOS and GPT2w+Saastamoinen models, respectively. Among the above models, the accuracy of the EGNOS model is lower and significantly lower in the Chinese region than in the Nordic region, because the EGNOS model was built by relying on the European numerical forecasting centre information. The accuracy of the EGNOS model and the GPT2w+Saastamoinen model increases gradually with increasing latitude, as can be seen from Table 1.

Table 1. Statistical results of errors for each model (mm)

Station	GE-Sa		EGNOS		GPT2w+Saastamoinen	
	bias	***RMS***	***bias***	***RMS***	***bias***	***RMS***
ANMG	35.31	44.01	278.00	281.27	73.71	77.99
WUH2	38.37	71.78	142.20	161.68	53.57	82.32
WUHN	38.34	71.75	142.15	161.61	53.53	82.27
NAUR	27.83	52.68	95.38	112.65	30.57	56.02
DAV1	-8.36	22.55	-104.30	109.25	-8.44	22.67
PIMO	24.69	56.43	269.08	272.64	61.71	77.23
GOPE	-1.26	29.53	71.71	77.95	5.49	30.12
SHAO	12.98	65.39	135.35	158.09	28.01	71.33
PRDS	-3.57	20.34	43.661	50.74	4.41	24.00
WIND	11.54	32.66	112.66	117.33	12.10	34.70
FTNA	15.73	60.29	248.91	253.12	51.69	73.92
HKSL	28.73	57.03	205.00	212.16	53.64	72.99
JFNG	37.65	71.15	141.43	160.60	52.70	81.50
BAKO	30.98	44.68	254.55	257.20	46.62	60.26
BILL	6.20	36.74	47.10	66.66	7.28	43.09
BJFS	16.76	46.37	54.56	81.25	19.25	49.75
BJNM	7.57	44.54	52.28	78.90	8.94	45.95
HKWS	37.26	56.60	205.64	212.89	52.58	72.46
CAGS	17.35	37.22	37.20	55.34	19.13	44.13
GRAZ	4.00	25.37	84.03	89.87	5.13	29.29
Absolute average	20.22	47.38	136.26	148.56	32.43	56.60

In the longitudinal comparison of the GE-Sa model, bias and RMS do not vary significantly in the longitude and altitude directions, but generally tend to decrease with increasing latitude, a characteristic that becomes more evident when the number of stations is increased, a phenomenon that exists because the model combines GPT2w and Saastamoinen and has the qualities of both models.

6. Summaryg

In this paper, we introduce the Saastamoinen model, EGNOS model and GTP2w model in detail, compare the accuracy of Saastamoinen model and EGNOS model, and on this basis, we propose a GE-Sa fusion tropospheric model algorithm, using the one-year ZTD sequence of 20 stations provided by GGOS, comparing the EGNOS model and the existing accuracy The experimental results show that the accuracy of the GE-Sa fusion model is 68.12% and 16.33% higher than that of the EGNOS model and GPT2w+Saasta-moinen model, respectively. The simple algorithm of the model improves the accuracy of the traditional tropospheric model and extends the application range of the model while freeing it from the dependence on measured meteorological parameters. More data and further research are needed on how the model can be applied and how its accuracy can be further improved.

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