The GEMTEC Model: Assessment of Quality of Ionospheric Correction in Satellite Radio Navigation Systems

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***Abstract*- A global empirical model of the total electron content of ionosphere (GEMTEC) is presented. It is based on experimental TEC values expanded in the natural orthogonal functions. The GEMTEC model considerably compensates ionospheric delay of GNSS radio signals and increases position accuracy of single-frequency equipment. We give an assessment of the GEMTEC model efficiency as compared to the Klobuchar model recommended by the GPS Interface Control Document [1] and other techniques. The efficiency was assessed by solving a navigation problem with real data from a number of IGS stations over a long observation period. The navigation problem was solved by comparing four variants: no ionospheric error correction, applying Klobuchar model error correction, applying the GEMTEC model for ionospheric error correction, and using double-frequency observations of ionospheric error correction. The data used were supplied by seven IGS stations situated in different regions for the years 2002-1010. It is shown that the ionospheric delay correction by the GEMTEC model considerably decreases an average position error, and the model can be recommended for use instead of the standard Klobuchar model.**

Keywords*- *Satellite Radio Navigation; Navigation Error; Ionosphere; Total Electron Content; Ionospheric Correction

I. INTRODUCTION

The delay of radio signals during their propagation through the ionosphere greatly reduces position accuracy in global navigation satellite systems (GNSS). The single-frequency GNSS equipment can correct the error only by applying models of total electron content (TEC) of ionosphere. The GPS Interface Control Document of GPS system recommends applying the Klobuchar model [2]. The model enables to calculate the TEC over the specified point of the earth's surface for the given time. The input parameters of the model are eight coefficients transmitted in GPS navigation messages with the periodicity from several days to several weeks. According to the model specification, it compensates approximately 50 ÷ 60% of ionospheric delay of navigation signals. That can't be considered as quite sufficient, therefore efficiency of compensation of the ionospheric delay must be improved.

The Klobuchar model is a simplified calculating scheme applied in navigation receivers with limited calculating resources. Nowadays economy of calculating resources is no longer a necessity and more sophisticated and accurate models can be used. There are works which contain a forecast of vertical TEC on the base of more accurate physical models. So the work [3] suggests creating a regional TEC model (Japan) proceeding from the models of critical frequencies of the F region of the ionosphere. In the article [4] the short-term forecast of TEC is performed with applying of the maps of the GIM global ionospheric model. The use of TEC global maps seems to be more prospective. But their direct use in the software of navigation devices is hardly possible. To implement the ionospheric correction technique, it is absolutely necessary to compress input data (GIM maps) and to smooth random fluctuations of the input data. These are the operations that are performed in the model developed by the authors.

The experience of empirical modeling of ionospheric parameters enabled the authors to create a model of total electron content described in detail in the work [5]. The authors called it GEMTEC—the Global Empirical Model of Total Electron Content. The GEMTEC model is based on data of TEC values expanded in the natural orthogonal functions (NOF). The data are supplied as IONEX files from a number of specialized centers. Due to the natural orthogonal functions expansion method applied, the primary information was considerably compressed, and random fluctuations were smoothed. The only input parameter for the GEMTEC model is a solar activity index, which is easily accessible in the geo-physical data centers.

II. A SHORT DESCRIPTION OF THE GEMTEC MODEL

It is known that any function of several variables in the form of a multidimensional array of discrete numbers can be presented as expanded in the natural orthogonal functions. The complete NOF system provides the accurate presentation. On clipping NOF rows with high-order numbers the presentation gets approximate so that smoothed become higher "harmonics" which should be considered as noise or random fluctuations. Meanwhile, the set of the expanded numerical data is very effectively compressed as required for model implementation.

The initial table of numerical data for the model is a set of GIM maps formed from RINEX-files for the last cycle of solar activity. The maps having been processed, the table is a multidimensional array which has the following levels:

1. month-averaged time variation of TEC with a discretisation step of 2 hours;
2. seasonal variation of TEC with a discretisation step of one month;
3. latitudinal variation from 70^0 N to 70^0 S with a gradation step of 10^0;
4. 7 gradations by the level of solar activity (index $F_{10.7}$) from 70 to 179.8 units with a discretisation step of 18.3 units;
5. longitudinal variation from 0^0 to 360^0 with a gradation step of 30^0.

On the first stage of NOF calculation, the expansion in hours a day is performed. The expansion coefficients are considered to be dependent on the month of a year and are expanded in second-stage NOF. Then the transition to another stage occurs. On the last stage, the NOF and corresponding coefficients depending upon longitude are formed.

These values of vertical TEC in multidimensional network nodes can be expanded:

$$f(t,s,F,\phi,\lambda)=\sum_{i}^{l_1}\sum_{j}^{l_2}\sum_{k}^{l_3}\sum_{m}^{l_4} X_i(t)Y_{ij}(s)\Phi_{ijk}(\phi)Z_{ijkm}(F)L_{ijkm}(\lambda)$$

where $X_i(t)$ are the NOF of local time t, $Y_{ij}(s)$ are NOF of month s, $\Phi_{ijk}(\phi)$ are NOF of latitude ϕ, $Z_{ijkm}(F)$ are NOF of solar activity level F, and $L_{ijkm}(\lambda)$ are expansion coefficients depending only upon longitude λ. l values specify lengths of summation rows for corresponding NOF. For intermediate values of arguments the linear interpolation is used. The linear extrapolation is used if the values of the index of solar activity are more than 180 or less than 70.

Clipping the NOF summation rows leads to non-identical reproduction of the initial data by the model. This is not a disadvantage of the GEMTEC model. On the contrary, it promotes smoothing random fluctuations in the initial data arrays. The statistical assessment of accuracy of initial relations reproduction by the GEMTEC model is also performed in the work [5].

With given parameters of row clipping the average relative error of reproduction has a value of approximately 20%. The authors find such efficiency of the GEMTEC model quite sufficient. Meanwhile, the unit of the numerical data making up the model has a value of several tens of kilobytes and this ensures the implementation of the model in the modern navigation equipment.

III. STATISTICS OF POSITION ERRORS

Nowadays the GEMTEC model is ready for practical use. A comparative testing of the GEMTEC model was necessary to assess its ionospheric error compensation efficiency. The authors performed quantitative research of position accuracy obtained by the GEMTEC model, the Klobuchar model and the method based on ionospheric delay correction in double-frequency code measurements.

The research was performed with the help of the GPS Toolkit [6, 7] (Tolman, Harris 2004, Harris, Mach 2007), which includes the RINEXPVT software (program). This software is designed to solve a navigation problem in the post processing mode with input data as navigation and observation RINEX files. To correct the ionospheric error, the program applies the Klobuchar model and the mode of code measurements of pseudoranges. The ionospheric delay correction can be excluded. Calculations in the RINEXPVT program were performed on the base of standard observation and navigation files obtained at http://sopac.ucsd.edu/cgi-bin/dbDataBySite.cgi.

The RINEXPVT program has an open source in the C++ programming language. This allows integrating into program the subprogram-function's own code, which implements the GEMTEC model. We also modified the Klobuchar model algorithm to use the model input parameters from GPS almanac archives.

After RINEXPVT modification, we performed statistical research of efficiency of ionospheric error compensation by the GEMTEC model. To do that we obtained averaged values of position errors in the following modes:

- no ionospheric error correction;
- applying the Klobuchar model error correction;
- applying the GEMTEC model for ionospheric error correction;
- using the double-frequency code (P1 and P2) observations of ionospheric error correction.

Statistical data were chosen for the specified IGS stations. Position errors were determined according to the coordinates represented in information files of the stations. Six IGS stations were chosen:

- three stations of the Northern Hemisphere (Kely, Nrc1 and Usno);
- three stations of the Southern Hemisphere (Chat, Ohi3 and Tidb);

Calculations were performed for the years 2002-1010. The coordinates averaged over the days were determined for the 22nd of each month from 2002 to 2010. With 30-second interval between epochs in RINEX-files the total sampling for each station had a value of approximately 300000, invalid data being excluded.

Fig. 1 represents the time variation of position errors D (meter) over 9-year interval with daily averaging for the specified days for Chat station. A position error is the Euclidean distance from the precise location of the station receiving antenna to the location calculated on solving a navigation problem. The month numbers N within the 9-year interval are shown along the horizontal axis. The zero month is January, 2002, the last one (107th) is December, 2010. The error (in meters) is shown along the ordinate. The error according to the double-frequency positioning data is represented by the black line. The red line represents the position error by applying the GEMTEC model. The blue line is the error by applying the Klobuchar model. The lilaccolored line is the error for solving a navigation problem without any ionospheric correction. Fig. 2 shows the time variation of indexes of solar activity $F_{10.7}$ for the days corresponding to Fig. 1.

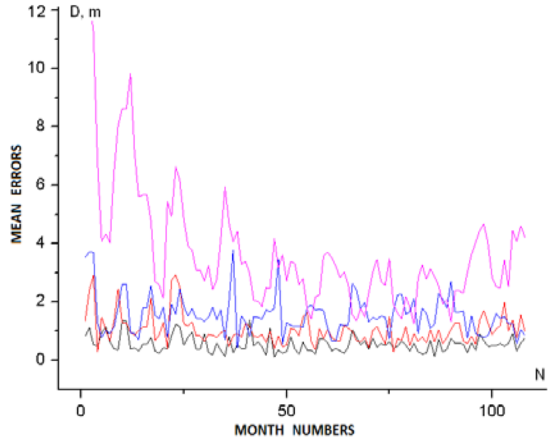

Fig. 1 Time variation of position errors over 9-year period with daily averaging for Chat station

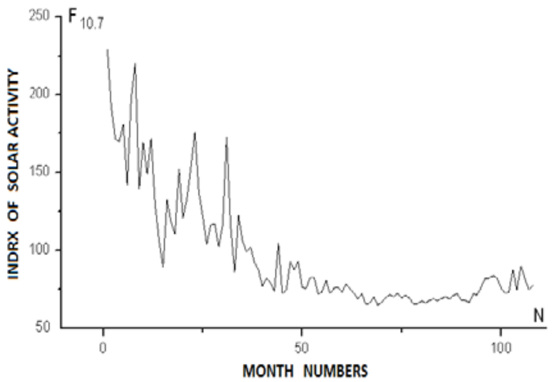

Fig. 2 Time variation of indexes of solar activity over 9-year period

The figures show that there is a close correlation between variations of position error without ionospheric correction and variations of the index of solar activity: larger error values correspond to higher solar activity, that is, to larger TEC values. The known phenomenon of winter anomaly in ionospheric morphology is also evident. This indicates that the ionosphere greatly affects the position error.

It's well seen that the three represented methods of ionospheric correction considerably improve position accuracy so that the mentioned correlations with the solar activity are almost unnoticeable. The GEMTEC model can also be considered as more efficient in comparison with the Klobuchar model. Further the appropriate quantitative estimate is given.

The total averaging of position errors over all years was performed for each station. Its results are represented in Table I. The first column contains the names of the stations, the second indicates their coordinates. The third, fourth, fifth and sixth columns contain average position errors without ionospheric correction, with correction calculated by the Klobuchar model, by the GEMTEC model, and correction in double-frequency code mode, respectively. Errors are represented in meters. The last line of the table contains errors averaged over all stations.

TABLE I AVERAGE ERRORS OF POSITIONING FOR VARIOUS STATIONS

Station	**Coordinates of Station**	**Error without Correction (m)**	**Error on Klobuchar Model (m)**	**Error on GEMTEC Model (m)**	**Error on Two-Frequency Method (m)**
Chat	43.6^0S, 176.2^0E	3.67	1.09	0.52	0.13
Kely	66.6^0N, 50.6^0W	3.17	1.06	0.46	0.61
Nrc1	45.2^0 N, 75.4^0W	3.18	1.22	0.26	0.12
Ohi3	63.2^0 S, 57.5^0W	2.17	2.26	0.72	0.20
Tidb	35.2^0 S, 148.6^0E	3.22	1.53	0.44	0.57
Usno	39.8^0 N, 77.0^0W	3.51	1.00	0.37	0.13
Average		3.15	1.36	0.46	0.29

The represented data indicate that using the GEMTEC model in solving a navigation problem greatly improves position accuracy in comparison with the Klobuchar model. Averaging over all stations shows that correction by the Klobuchar model eliminates approximately 57% of the error as compared to the error without correction, while correction by the GEMTEC model eliminates approximately 85% of its value. The close result is given by double-frequency code correction, which eliminates 91% of the error.

Position error distribution on vertical and planar coordinates is of great interest. The appropriate averaged values for Chat station are given in Table II. For ease, the errors along longitude and latitude are given in meters, as well as the errors for altitude.

TABLE II DISTRIBUTION OF POSITION ERRORS ON VERTICAL AND HORIZONTAL COORDINATES

	Latitude	**Longitude**	**Altitude**
Error without Correction (m)	-0.74	0.48	3.62
Error on Klobuchar Model (m)	-0.43	0.46	-0.77
Error on GEMTEC Model (m)	-0.21	0.39	0.29
Error on Two-Frequency Method (m)	0.12	0.08	0.01

The position errors have rather big dispersion. For the submitted data the standard deviation is approximately 2 meters at the average both horizontally and vertically. Different filtering and smoothing methods applied in users' equipment can considerably reduce the dispersion, however, the constant bias caused by the ionospheric delay in a single-frequency mode can be reduced only by modeling TEC.

Data analysis shows that most of the error relates to altitude determination. Analysis of these and similar data of the other stations allow stating that Klobuchar's model, on average, generates overstated values of the total electron content and gives the altitude value approximately 1 meter lower that the true one.

Several variants of the GEMTEC model are implemented. The variants use different sets of input data (IONEX files) from different suppliers COD, ESE, JPL, UPS and combined data from IGS. Data of COD (a

European centre) gave the best results in position error minimization. Data of IGS и ESA gave very close but a little worse results.

IV. CONCLUSIONS

Nowadays, the GEMTEC model is ready for practical use. In the nearest future, it will be optimized for high solar activity conditions. Required data will be received from coming maximum of solar activity for the current 11-year cycle.

Implementation of the GEMTEC model is a compact code with a numerical data unit of approximately 50 kilobytes. This model can be easily implemented in modern navigation receivers. The model input parameter (index of solar activity) is desirable to be implemented as a transmission in a navigation message. A prognostic model of this index can also be used, but it can partly decrease correction accuracy.

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