Accuracy analysis of the Klobuchar ionosphere model transmitted by the GPS system

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Abstract

The ionospheric delay has a distinctive impact on the GNSS observations. Single frequency GPS receivers use the Klobuchar model to correct the ionospheric delay of the L1 signals. The Klobuchar model is a single-layer model and represents the zenith delay as a constant value at nighttime and a half-cosine function in daytime. The GPS satellites broadcast eight model coefficients in their navigation message. It is expected that the model can reduce the RMS error due to uncompensated ionospheric delay by about 50%. Therefore its accuracy is often unsatisfactory even for the absolute positioning, this may be especially true in case of the increased solar activity.

In this study, the accuracy of the Klobuchar model for various geographical latitudes and ionospheric activity is analyzed. The accuracy of the model was estimated by comparing to Global Ionosphere Maps (GIM) provided by the International GNSS Service (IGS). In order to produce IGS GIMs representing the ionospheric total electron content (TEC), data from ~200 permanently tracking GNSS stations are used. This global model offers 2.5 by 5.0 degrees spatial, and 2-hour temporal resolutions.

The comparison results show that the differences between the Klobuchar model and the IGS GIMs may reach as much as 5 m of L1 delay. In general, the Klobuchar model underestimates the ionospheric delay for low latitude regions and overestimates the delay for high latitudes.

Keywords: Global Positioning System; Klobuchar model; Global Ionosphere Maps; ionospheric delay.

1. Introduction

The ionosphere is a part of higher atmosphere with altitude from 60 km to over 1000 km above the Earth’s surface. This layer is characterized by the free, negatively-charged electrons and positive ions. Although the ionosphere is less than 0.1% of total mass of atmosphere, it has a great influence on the global electric circuit, Earth’s magnetic field and propagation of the electromagnetic waves, which go through the ionosphere [1]. The ionospheric delay is one of the most significant errors in GNSS (Global Navigation Satellite System) measurements. The propagation delay in the ionosphere depends on total electron content (TEC) along the signal path between the GNSS satellite and the receiver. The ionospheric refraction also varies with signal frequency, geographic location and time [2], [3]. In order to compute and eliminate the ionospheric delay, GPS (Global Positioning System) system uses an empirical model whose parameter values are broadcast by the satellites [4].

This model was developed by Klobuchar [5] for single frequency GPS receivers. It is assumed that the Klobuchar model is a single-layer model and free electrons are concentrated on an imaginary layer of which thickness is zero at the 350 km altitude. In the model, the ionospheric delay of the L1 signal is estimated by calculation the TEC between the GPS satellite and the receiver. The zenith ionosphere delay is defined as a constant in the night which is equal to 5 ns, and a half-cosine function in daytime. The zenith ionosphere delay at local time \( t \) is given by [6]:

\[
T_{\text{ion}}^z = A_1 + A_2 \cos \left( \frac{2\pi(t - A_3)}{A_4} \right)
\]

where \( A_1 \): nighttime value of the zenith delay (5*10 – 9 s = 5 ns),
A2: amplitude of the cosine function for daytime values,
A3: phase corresponding to the peak of the cosine function (14 h local time),
A4: period of the cosine function (72,000 s).

The value for A1 and A3 are constant, however, the value of parameters A2 and A4 are determined in the navigation message broadcast by each GPS satellites and depend on the users position, satellite azimuth and elevation and local time. A set of eight coefficients is selected by the Master Control Station from 370 such sets. The parameters are usually updated every six days.

The model assumes an ideal smooth behavior of the ionosphere, therefore any significant fluctuations from day to day will not be modelled properly. The model can reduce the RMS position error due to uncompensated ionospheric delay by about 50% to 60% depending on the solar activity or the region. Therefore its accuracy is often unsatisfactory even for the absolute positioning, especially in case of the heightened solar activity [7].

At a global scale, four International GNSS Service (IGS) Ionosphere Associate Analysis Centers (IAACs) generate vertical total electron content (VTEC) maps in the IONEX (IONosphere map EXchange) format [8]. In order to produce the Global Ionosphere Maps (GIM), data from ~200 permanently tracking GNSS stations are used. The IGS GIM offer 2.5 by 5.0 degrees spatial and 2-hour temporal resolutions and the final products are computed with a latency of about 11 days. Details on how the IGS VTEC maps are generated and the characteristics of VTEC variation are described in [9].

The study’s objective is to carry out analysis of the accuracy of the Klobuchar ionosphere model transmitted by the GPS system in a maximum of the XXIVth cycle of the Solar activity. The accuracy of the model was estimated by comparing to GIMs provided by the IGS. The analyses were performed for various ionospheric activity and different geographical latitudes.

2. Methodology

In order to achieve the reliable results, the tests were carried out for two different time periods – the first one during November 25th, 2013 (DOY 329), when the ionosphere could be characterized as quiet and completely free from disturbed ionospheric conditions (Kp = 0), and the second one on November 9th, 2013 (DOY 313), when the ionosphere was stormy (Kp = 26+). Earth’s geomagnetic filed activity (Kp-index) on DOY 313 is presented in Figure 1.

According to data from the service of the ionosphere monitoring over Poland, which is carried out by the University of Warmia and Mazury in Olsztyn [10], [11], during the first day, which was taken into the research, the maximum TEC value was 18.7 TECU, and during the second day, the maximum TEC value was 41.3 TECU. Mean values of TEC over Poland during the analyzed days are showed in Figure 2.

In this study, the GPS navigation data and Global Ionosphere Map form the IGS were used. A Matlab-based software was developed in order to compute the ionospheric delays using the Klobuchar model coefficients. The calculations of the ionospheric delays using the Klobuchar model follows the procedure which was described in [12], [13]. The reference delays were read from GIMs provided by the IGS in IONEX format.

The analysis focused on the northern hemisphere and the Greenwich meridian. The ionospheric delays from both models were calculated every 2 degrees in latitude and every 3 hours. Then, the differences between the Klobuchar-derived ionospheric delays and the IGS GIM-derived ones were calculated. The average and maximum differences between the ionospheric delays were analyzed. Please note that the IGS GIMs were treated as error-free and used as a reference. Their actual estimated error is ~ 2–3 TECU, what corresponds to 30–40 cm of the L1 ionospheric delay.
3. Test results

The results of the study are presented in Figure 3–4, which show the ionospheric delay profiles along the meridian with longitude 0°. The solid line in Figure 3 and Figure 4 depicts the delay obtained from the Klobuchar model and the dashed line represents the delay according to the IGS maps. Please note that the presented delays are related to L1 signal. Figure 3 refers to the results obtained for the quiet day (DOY 329/2013). As shown in Figure 3, the maximum difference between the ionospheric delays obtained from the Klobuchar model and the IGS GIMs reached to 3–4 meters for the quiet
day. For low and mid-latitudes the Klobuchar model usually underestimates ionospheric delay, while for the high latitudes the ionosphere delay is overestimated. For middle latitudes in the nighttime, due to the lower electron concentration, errors of the Klobuchar model usually do not exceed 0.5 m. However, between 12 UT and 18 UT the values predicted by the Klobuchar model are higher by about 2.5 m. The biggest difference between the Klobuchar model and the GIM IGS can be seen for the latitudes in the range of 50º to 80º N and amounts to 4 m (see Table 1).

Figure 4 shows the results of the analyzes for the stormy day (DOY 313/2013). As it can be seen in Figure 4, the maximum difference between the ionospheric delays obtained from the Klobuchar model and GIM IGS reach up to 5 meters. For the middle latitudes, due to generally lower values of the ionospheric delay, errors of the Klobuchar model usually do not exceed 1.5 m. However, these errors often represent up to 100% of the predicted delay. The biggest difference between the Klobuchar model and GIM IGS can be seen for latitudes in the range of 0º – 30º N, where the values predicted by the Klobuchar model are lower by about 5 m in relation to the IGS maps. Generally, much larger differences were found for the stormy day. This may be caused by the fact that the geomagnetic storm occurred in a period of high sunspot number, which amounted to 159. As in the case of the quiet day, for low and mid-latitudes the Klobuchar model underestimates ionospheric delay, while for the high latitudes the ionosphere delay is overestimated.

Table 1. Differences between the L1 ionospheric delay obtained from the Klobuchar model and the IGS GIMs

<table>
<thead>
<tr>
<th>DOY</th>
<th>Maximum difference [m]</th>
<th>Mean difference [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>329</td>
<td>3.18 1.16 0.98 1.49 3.58 4.04 2.54 2.92 2.63</td>
<td>1.21 0.67 0.49 0.62 1.89 2.61 1.65 0.84 0.99</td>
</tr>
<tr>
<td>313</td>
<td>3.80 1.67 1.00 1.74 3.79 5.01 4.67 5.42 5.19</td>
<td>1.09 0.49 0.36 0.85 2.29 2.97 2.30 1.39 1.48</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of latitudinal ionospheric delay profiles on the disturbed day (DOY 313, 2013)
Maximum and mean differences between ionospheric delays obtained from the Klobuchar model and from the IGS GIM are presented in Table 1. On the basis of the table it can be concluded that the maximum difference occurs at 15 UT on the quiet day and its value is 4.04 m, while during the stormy day, the maximum difference is at 21 UT and its value is 5.42 m. This occurred near the equator and the error is higher than the actual ionospheric delay. This means that in some cases using the Klobuchar model may lead to worse results then neglecting the ionospheric delay at all. Mean difference are in the range of 0.49 m to 2.61 m during the quiet day, and in the range of 0.36 m to 2.97 m during the disturbed day.

Figure 5 depicts the ionospheric delay daily profiles from the Klobuchar model and from the IGS GIMs for geographical latitudes from 40º to 70º along 0º meridian what reflects European latitudes. The ionospheric delays predicted by the Klobuchar model for the quiet day is greatly overestimated during daytime and the differences reach up to 3 m. Again, in many cases the prediction error is greater than the actual delay itself. During the stormy day, the differences are smaller and usually amount to about 1–2 m. However, at high latitudes the Klobuchar model errors exceed 4 m. Note that at 16 UT the actual ionospheric delay was 1.5 m and the prediction showed almost 6 m! In such a case using Klobuchar model clearly deteriorates the satellite positioning. Table 2 shows maximum and mean differences between the Klobuchar and the IGS models over different latitudes. It can be concluded that at European latitudes the Klobuchar model the best represent the state of the ionosphere at 40º – 50º N, where the maximum and mean differences to IGS GIMs are the lowest. On the other hand, at high latitudes the maximum differences exceed 4 m and the average differences are close to 1.5 m.

![Comparison of daily ionospheric delay profiles for latitudes: 40º, 50º, 60º and 70ºN over 0º meridian, DOY 329, and DOY 313](image)

Table 2. Maximum and mean differences between the Klobuchar and the IGS models for different latitudes

<table>
<thead>
<tr>
<th>DOY</th>
<th>40º</th>
<th>50º</th>
<th>60º</th>
<th>70º</th>
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<td>329</td>
<td>2.82</td>
<td>2.64</td>
<td>2.95</td>
<td>3.22</td>
</tr>
<tr>
<td>313</td>
<td>1.96</td>
<td>2.45</td>
<td>2.72</td>
<td>4.37</td>
</tr>
</tbody>
</table>

4. Conclusions

The presented initial research showed that errors of the Klobuchar model vary from latitude, time and geomagnetic activity. The average error is on the level of 1.0 m for the quiet day and 1.5 m for the stormy day. It should be noted that the average ionospheric delay was 2.8 m on the quiet day and 4.2 m on the disturbed day. The maximum error of the Klobuchar model prediction may reach even ~5.5 m and in some cases it may be greater than the actual ionospheric delay itself. It was demonstrated that in a single case the predicted delay was 4 times greater than the actual one. This means that the application of the Klobuchar model may cause greater errors on the resulting position than neglecting the ionospheric delay. This was the case during the quiet day at mid and high latitudes. Also, since the Klobuchar model assumes a constant value of the ionospheric delay during the night (~1.5 m) regardless of the latitude, it almost always underestimates of the ionospheric delay at low latitudes during the nighttime.
On the other hand there were many cases where the accuracy of the Klobuchar coefficients was on acceptable level, e.g., at middle latitudes on the disturbed day.

In general, we do not recommend using this model for positioning and the European user may apply, e.g., predicted model available from the CODE AC.

References


