Anomalies in broadcast ionospheric coefficients recorded by GPS receivers over the past two solar cycles (1992-2013)

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Abstract The anomaly phenomenon of broadcast ionospheric model coefficients of Global Positioning System (GPS) is revealed after analyzing the navigation file data collected from all the IGS (International GNSS Service) stations worldwide over a 22-year period (1992 to 2013). GPS broadcast ionospheric coefficients, widely used to correct the ionosphere errors for numerous GPS applications by many single frequency users are usually believed to have only one set/version per day. However it is found that GPS receivers from the IGS network can report as many as 8 sets/versions of ionospheric coefficients in a day. In order to investigate the possible factors for such an anomalous phenomenon, the relationship between the number of coefficient sets and solar cycle, the receiver geographic locations, and receiver types/models are analyzed in detail. The results indicate that most of the coefficients show an annual variation. During the active solar cycle period from mid-1999 to mid-2001, all of the coefficients extracted from IGS navigation files behaved anomalously. Our analysis shows that the anomaly is also associated with GPS receiver types/models. Some types/models of GPS receivers report one set/version of ionospheric coefficients daily while others report multiple sets. Our analysis also suggests the ionospheric coefficient anomaly is not necessarily related to ionospheric scintillations. No correlation between the anomaly and geographic location of GPS receivers has been found in the analysis. Using the ionospheric coefficient data collected from 1998 to 2013, the impact of ionospheric coefficient anomaly on vertical Total Electron Content (VTEC) calculation using the Klobuchar model has been evaluated with respect to the Global Ionospheric Maps (GIM) generated by the Center for Orbit Determination in Europe (CODE). With different sets of coefficients recorded on the same day, the resulting VTEC values are dramatically different. For instance on 1 June 2000, the largest VTEC at one of our test stations can be as large as 153.3 TECu (Total Electron Content unit) using one set of coefficients, which is 16.36 times larger than the smallest VTEC of 9.37 TECu computed from using another set of coefficients.

Keywords Global Positioning System (GPS); Broadcast ionospheric coefficients; Anomaly and impact analysis; Klobuchar model; Vertical total electron content (VTEC)

Introduction

Ionospheric effects are a dominant factor that limits the precision and reliability of many Global Positioning Systems (GPS) applications. In ionosphere disturbance periods, the ionospheric range delay can be as large as 100 meters. In order to obtain reliable solutions of GPS positioning and navigation, ionospheric mitigation in GPS has been intensively studied over many years. Ionospheric range delays can normally be corrected in several ways. For dual- or multi- frequency GPS users, more than 99.9% of the ionospheric delay can be removed directly by a combination of dual-frequency measurements, taking advantage of the dispersive property of the ionosphere (Klobuchar and Kunches 2001). For single frequency GPS receivers, usually ionospheric models have to be used to mitigate the ionospheric errors. An examples of such a model is the Wide Area Augmentation System (WAAS) ionospheric model (Arbesser-Rastburg 2002). However this requires the receivers to have the capability to receive WAAS signals. As a matter of fact, for single frequency receivers the most widely used method is to employ the GPS broadcast ionospheric model (including eight coefficients α_n and β_n, $n = 0, 1, 2, 3$) embedded in the GPS navigation data. The GPS broadcast ionospheric model is also known as the Klobuchar model (Klobuchar 1987). Though the Klobuchar model provides a correction efficiency of only about 50% (Feess and Stephens 1987; Klobuchar 1987), it has been widely used for ionospheric corrections in single frequency GPS applications.

In the past, most of the studies on the Klobuchar model concentrated on the evaluation of model performance in correcting ionospheric range errors in GPS signals (Feess and Stephens 1987; Orús et al. 2002; Radicella et al. 2008; Luo et al. 2013; Swamy et al. 2013). No literature is available on the anomaly phenomenon of Klobuchar model coefficients as recorded by various types/models of GPS receivers over a two-decade period. By examining the Klobuchar model coefficients collected during the past two solar cycles (1992-2013), we find that Klobuchar coefficients decoded by different GPS receivers for the same observation epoch are dramatically different. GPS is generally considered to broadcast only one single set of Klobuchar coefficients (eight coefficients α_n and β_n, $n = 0, 1, 2, 3$) to global GPS users for each day. However, several sets of Klobuchar coefficients with different values have been observed over a single day period. The ionospheric range delays computed using those different sets of coefficients have different implications for single frequency receivers. For instance, we used two sets of Klobuchar coefficients recorded on 1 June 2000 to compute two vertical total electron contents (VTEC) values for a mid-latitude station for the epoch 14:00 local time of that day. The larger VTEC value computed using one set of coefficients is 153.3 TECu (1 TECu=10^{16} el/m^2), which is 16.36 times larger than the smaller one of 9.37 TECu obtained from another set of coefficients. It clearly shows that the Klobuchar coefficient anomaly issue has a large impact on GPS applications.

At present, both Galileo and Beidou systems are still under development. Their broadcast ionospheric models are not available globally at present. For instance, the current Chinese Beidou system covers only Asia-Pacific region with 14 satellites and its global coverage will not be completed until 2020 (Yang et al. 2014). Thus, for single frequency Global Navigation Satellite System (GNSS) users who are in regions not covered by Beidou service, they can only rely on the GPS broadcast ionospheric model to correct ionospheric range errors.

In addition to analyzing the Klobuchar model coefficients extracted for each GPS station in the IGS (International GNSS Service) network, we also examine the Klobuchar model coefficients that are extracted from the so-called IGS combined navigation file (brdcddd0.yyn). This combined file should contain the navigation data of all the GPS satellites for the day of year denoted by "ddd". This file contains full information of all satellites and it is more widely used by IGS users than the navigation files generated at individual GPS stations. The Klobuchar coefficients included in the combined files have been adopted to calculate VTEC in many studies (Angrisano et al. 2011; Oladipo and Schüler 2012; Rose et al. 2014). Thus it is necessary to examine whether there are anomalies in the Klobuchar model coefficients in the combined navigation files archived daily at IGS. Similar to the coefficients extracted from navigation files of all individual IGS stations, the coefficients extracted from the combined navigation files also show many anomalies over the two solar cycles (1992-2013). This suggests that a quality control of the Klobuchar coefficients when generating IGS combined navigation files is necessary. We will investigate the anomaly of these coefficients and analyze its impact on ionospheric delay calculation.

In the next section, an introduction of the Klobuchar model, i.e. GPS broadcast ionospheric model, is given first, followed by the methodology of this study. Then the Klobuchar model coefficient anomalies are analyzed. The relationship between Klobuchar model coefficient anomaly with solar cycles, GPS receiver geographic locations, and GPS receiver types/models are studied in details, which is followed by a section dedicated to the evaluation of the impacts of Klobuchar model coefficient anomaly. A conclusion is given at the end.

Klobuchar model

Klobuchar model was designed in the mid-1970s to provide an ionospheric time delay correction algorithm for single frequency GPS users (Klobuchar 1975). Assuming all the free electrons of the ionosphere are densely distributed in a single thin shell at a fixed altitude of 350 km, the model uses a simple positive cosine function plus a constant term called DC to model the diurnal variation of vertical ionospheric error (T_g). Its algorithm can be expressed as follows (Klobuchar 1975; Feess and Stephens 1987):

$$T_g = DC + A \cdot \cos\left(\frac{2 \cdot \pi \cdot (t - \phi)}{P}\right)$$

where DC is constant offset set as 5×10^{-9} s, A is amplitude, t is time for which the ionospheric delay is computed, ϕ is the phase fixed to 14 h (50400 s) local time, and P is period. The amplitude and period are modeled as third-order polynomials and expressed in the following equations:

$$A = \sum_{n=0}^{3} \alpha_n \varphi_m^n \quad P = \sum_{n=0}^{3} \beta_n \varphi_m^n$$

where n is the degree of the polynomial, and φ_m is the geomagnetic latitude of the Ionospheric Pierce Point (IPP, in unit of semicircles), α_n and β_n are the Klobuchar coefficients that are embedded in GPS navigation data and decoded by GPS receivers. The Klobuchar coefficients are selected by the GPS master control station and uploaded to the satellites as part of GPS navigation message. The selection of these coefficients is based on two criteria: the day of year (37 groups representing seasonal effects) and average solar flux value for the previous five days (10 groups). These coefficients are normally updated once per day by the GPS (Alizadeh et al. 2013). They are updated approximately every week (Feess and Stephens 1987; Komjathy 1997; Radicella et al. 2008). With the values of the eight time-varying coefficients (α_n and β_n), parameters, and user location (for the calculation of geomagnetic latitude φ_m of IPP), the Klobuchar model can calculate the ionospheric time delay of T_g for any time (denoted by t).

Methodology

This research mainly focuses on the anomaly phenomenon of the Klobuchar model coefficients. By analyzing the GPS navigation messages recorded by various GPS receivers over the past two solar cycles (1992-2013), we find that the GPS Klobuchar coefficients recorded on the same day by different GPS receivers are significantly different. This is contradictory to our expectation that the GPS Klobuchar coefficients are not updated more often than once per day (Alizadeh et al. 2013). We study the phenomenon of Klobuchar coefficient anomaly in several aspects. First, the correlation between the coefficients and the geographic location of GPS receivers is analyzed; second, the relationship between the coefficients and the types of GPS receivers is examined. To illustrate the impact of the anomaly on the calculation of ionospheric time delays, the TEC calculated from the Klobuchar model and GIM data from CODE for different geographic regions are also analyzed. It should be pointed out that we examine the daily combined broadcast navigation files (brdcddd0.yyn) produced by IGS (International GNSS Service) and that we find that the Klobuchar coefficients in IGS combined files also behave abnormally.

Klobuchar model coefficient anomaly analysis

Figure 1 shows the number of GPS navigation files in RINEX (Receiver Independent Exchange) format recorded by IGS receivers over the past two solar cycles (1992-2013), as well as the number of navigation files that contain GPS broadcast ionospheric coefficients. Each IGS GPS station has one daily navigation file. All the navigation files are downloaded from the IGS archival center (ftp://cddis.gsfc.nasa.gov/gnss/data/daily/). It can be easily found that not all the navigation files contain the Klobuchar coefficients in their header sections. This might be due to several reasons: (1) the GPS receivers fail to decode or record the ionospheric coefficients though they should offer such a capability; (2) the RINEX conversion program fails to extract the ionospheric coefficients from GPS manufacturer's proprietary data formats to RINEX format; (3) other reasons resulting in the absence of ionospheric coefficients in RINEX navigation file. Figure 1 also shows that the total number of GPS navigation files recorded by IGS has steadily increased during the past two decades. During the period January 1999 to March 2001, the number of GPS navigation files recording Klobuchar coefficients had a sudden increase but dropped to normal level again after March 2001. The underlying reason of this sudden increase is still unknown.

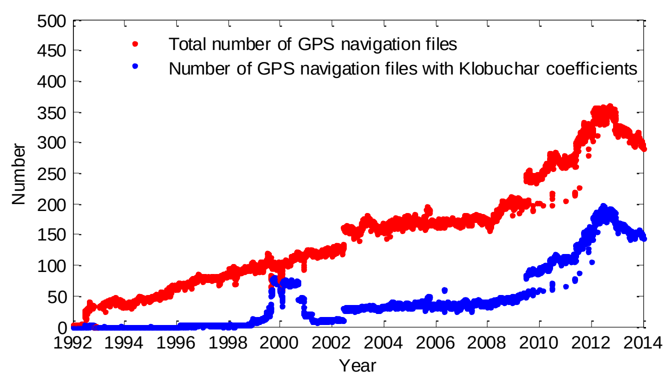

Fig. 1. The daily number of GPS navigation files and the daily number of GPS navigation files reporting Klobuchar coefficients, archived at IGS over the period from 1992 to 2013.

In order to further analyze the broadcast ionospheric coefficients, eight coefficients α_n and β_n $(n = 0, 1, 2, 3)$ are extracted from each navigation file. Theoretically, all the GPS stations worldwide should receive one and the same one set of Klobuchar coefficients in one day. However our statistical results of each day's ionospheric coefficients reveal that in most days during the past two solar cycles, multiple sets of coefficients have been recorded in each day's IGS navigation files.

Figure 2 depicts the number of sets of GPS ionosphere coefficients recorded in each day over the period 1992-2013. The number of coefficient sets of each day is depicted as one color point. As indicated in the figure, prior to mid-1996, in each day there was only one set of GPS ionosphere coefficients recorded by global IGS receivers. However from mid-1996 to 1998, the number of daily set of ionospheric coefficients was two. After 1998, the number of coefficient sets recorded even increased. For example, during the days 24-27 August 2005, as many as 8 sets of GPS broadcast ionospheric coefficients were observed in each day. The increase of the number of sets of ionospheric coefficients over the last two decades may be explained as the result of the rapid increase of the number of IGS receivers worldwide. As shown in Figure 1, the number of IGS stations grows steadily over the years. In addition, the increased diversity of using different GPS receiver models within the IGS network might also contribute to the phenomenon.

For the sudden increase period shown in Figure 1 (January 1999 to March 2001, a period of 803 days), in each day the number of ionospheric coefficient sets is always larger than one during the whole period. This interesting phenomenon is probably associated with the solar maximum during that period (1999 to 2001). After that period from 2002 to 2013, some periods were also observed to have more than one set of coefficient in each single day. However, those periods were significantly shorter compared to the 803-day period.

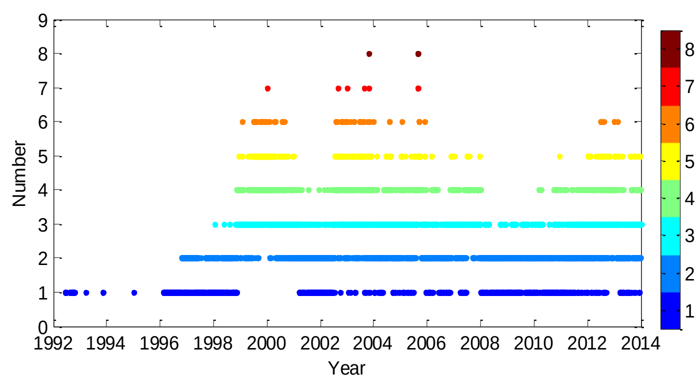

Fig. 2. Number of sets of GPS broadcast ionospheric coefficients recorded each day over the period from 1992 to 2013. Each day is represented by one color point.

Klobuchar model coefficient anomaly during solar cycles

To study the Klobuchar model coefficient anomaly, the eight coefficients for the period 1996-2013 recorded by all IGS receivers worldwide are depicted in Figure 3. This period is selected because we find that the number of sets of Klobuchar coefficients is larger than one in most days during this period as mentioned above. The units of α_n and β_n are second (s) and semi-circle (sc), respectively. The color bar to the right denotes the number of sets of coefficients obtained in a single day. As indicated in Figure 3, all the eight Klobuchar coefficients show an apparent annual variation. The only exception is coefficient α_3, whose value is almost constant at -5.961×10^{-8} s/sc^2 during most time of the period.

It should be noted that from mid-1999 to mid-2001, all of the eight Klobuchar coefficients behave dramatically different from those in other periods. The values of all the eight coefficients vary irregularly. The coefficients from different GPS receivers have different values and these values vary rapidly day by day during the whole period. At other times outside this period, the day to day variations in the Klobuchar coefficients are much smoother.

Figure 3 shows the daily Klobuchar coefficients (multiple sets of coefficients in most days) as extracted from all IGS navigation files. The Klobuchar coefficients (only one set) recorded in the IGS combined GPS broadcast navigation file (brdcddd0.yyn) is also studied are shown in Figure 4. As one cans see, the coefficients vary dramatically during mid-1999 to mid-2001. This implies that the Klobuchar coefficients from the IGS combined broadcast file also behave erratically in that period. We compare the multiple sets of coefficients shown in Figure 3 and the single set of coefficients shown in Figure 4 for the irregular period mid-1999 to mid-2001. We find that some sets of coefficients in Figure 3 show an apparent annual variation and have more regular variations than seen in Figure 4. This implies that the coefficients in Figure 3 are likely to be the correct ones and the Klobuchar coefficients in Figure 4, i.e. IGS combined broadcast navigation files brdcddd0.yyn, are possibly incorrect. This reminds us that precautions must be taken even if the IGS brdcddd0.yyn files are used.

As indicated in Figure 3 and Figure 4, the period mid-1999 to mid-2001 with anomalous coefficients largely overlaps with the sudden increase seen in Figure 1 for January 1999 to March 2001. Thus it strongly suggests that during solar maximum, not only the number of sets of GPS ionospheric coefficients increases significantly, but also the values of these coefficients vary dramatically. Outside the period mid-1999 to mid-2001, the values of the coefficients had only slight variations. In the most recent solar maximum of 2010-2012, the values of Klobuchar coefficients did not vary as much as they did the last solar maximum (1999 to 2001). This might be explained by two reasons. One is the solar activity in the most recent solar maximum was much weaker than the previous one (1999~2001) (Richardson 2013; Solomon et al. 2013). The second might be due to the enhanced GPS receiver software and hardware technologies, which enable GPS receivers in recent years to decode ionospheric coefficients and other parameters from GPS radio signals with a higher reliability and accuracy.

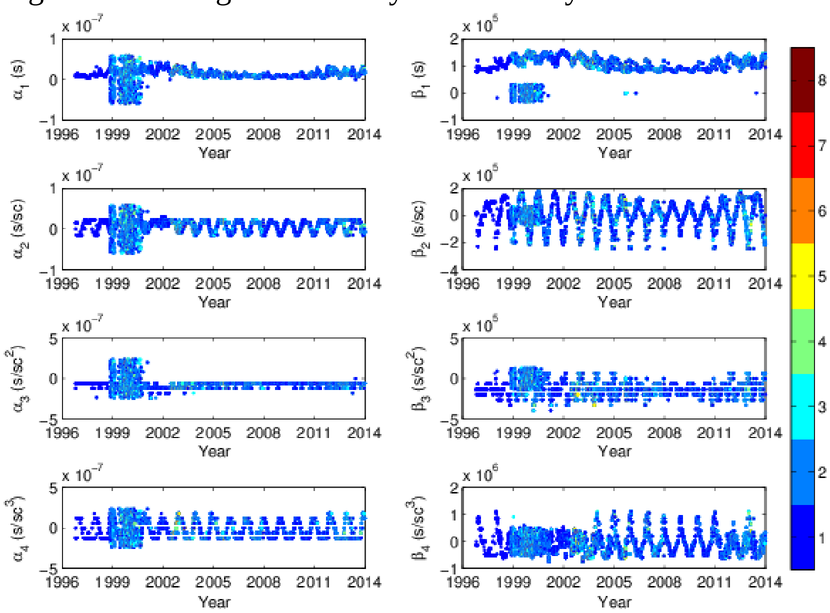

Fig. 3. Variations of Klobuchar model coefficients (α_n, β_n) recorded by global IGS receivers over the period from 1996 to 2013. The values of Klobuchar model coefficients vary

dramatically during mid-1999 to mid-2001, indicating a correlation with the solar maximum period (1999-2001).

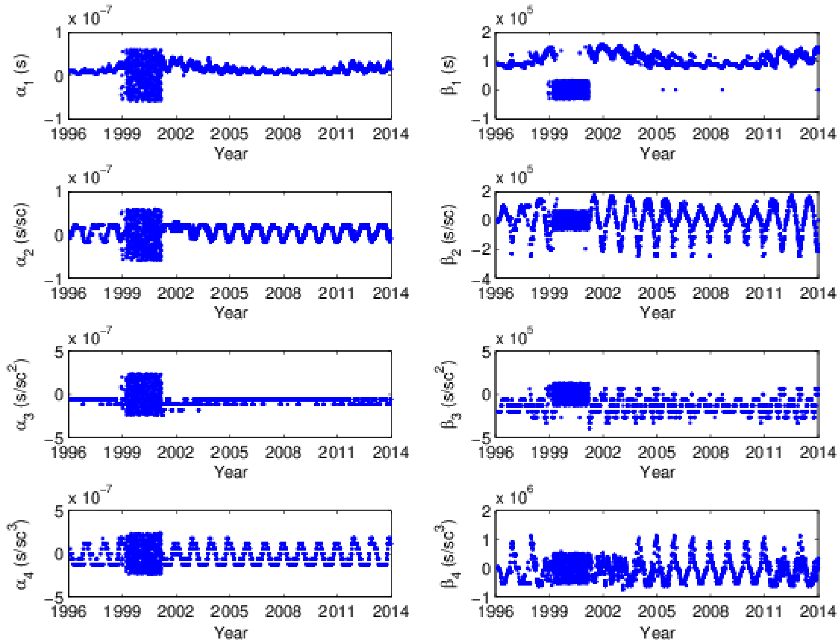

Fig. 4. Variations of Klobuchar model coefficients $(\boldsymbol{\alpha_n}, \boldsymbol{\beta_n})$ extracted from the IGS daily combined GPS broadcast navigation files over the period from 1996 to 2013.

Klobuchar model coefficient anomaly with geographic locations

Considering that the broadcast ionospheric coefficients are retrieved from GPS receivers distributed globally in the IGS network, the correlation of these coefficients with geographic locations is analyzed. As shown in Figure 5, four different days are randomly selected to study the correlation of ionospheric coefficients with geographic locations. They are: 28 April 2000, 16 September 2005, 9 August 2012, and 31 July 2013. On each day, there are 5 to 6 sets of coefficients and each set is denoted by one color, as shown in the color bar. Only GPS stations that have recorded ionospheric coefficients in their navigation files are depicted. Figure 5(a) to Figure 5(d), display 46, 47, 142 and 150 GPS stations, respectively. Each GPS station is represented by a color triangle, with color indicating the given set of ionospheric coefficients recorded at that station on that day. For instance GPS stations in red triangles indicate that these stations have recorded the 1st set of coefficients and the stations in black have recorded the 6th set of coefficients.

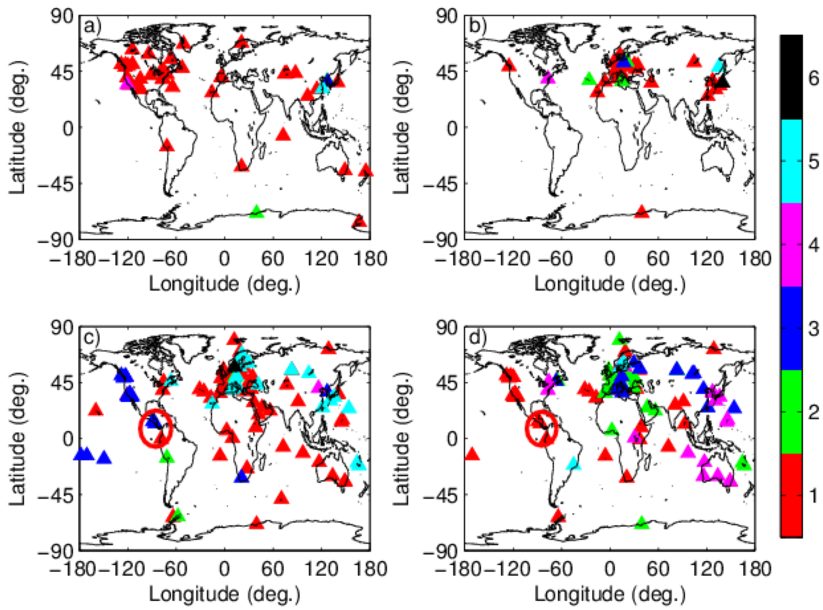

Fig. 5. Geographic distribution of different sets of GPS broadcast ionospheric coefficients. One color represents one set of coefficients and the triangle denotes the location of a GPS receiver recording such a set of coefficients. Four days are shown: a): 28 April 2000, b): 16 September 2005, c): 9 August 2012, and d): 31 July 2013.

As can be seen from Figure 5, most IGS receivers record the first set of coefficients (marked as red triangles). There are a few stations (non-red triangles) having recorded other sets of coefficients. Most importantly, GPS receivers recording the same set of coefficients (triangles in the same color) distribute in different geographic regions in a random manner. Taking the two stations marked by the red circles in Figure 5c and Figure 5d as an example, in Figure 5d both stations recorded the same set of coefficients (same red color). However in Figure 5c the southern station recorded the first set of coefficients while the northern station outputted the third set. These two stations are geographically close to each other. Figure 5 shows that GPS stations of the same color are distributed randomly worldwide without concentrating in one particular region. This suggests that the anomaly phenomenon of GPS ionospheric coefficients is not strongly correlated with the geographic location of GPS receivers.

Klobuchar model coefficient anomaly with GPS receiver types/models

Figure 5 shows that GPS ionospheric coefficients at some GPS stations indeed are different from those at other stations. However no particular pattern of geographic distribution of different sets of ionospheric coefficients has been identified. Considering that GPS stations in the IGS network are equipped with different models/types of GPS receivers and that each model/type of GPS receiver may use different receiver technologies, this section analyzes the relationship between coefficient anomaly and GPS receiver model. The days of 28 April 2000 and 9 August 2012 are analyzed in details, which correspond to the cases of Figure 5a and Figure 5c respectively. First, the values of each set of coefficients for the cases Figure 5a and Figure 5c are shown in Table 1 and Table 2, respectively.

Table 1. Five sets of GPS ionospheric coefficients recorded on 28 April 2000

Set	α_1 ($x10^{-7}$)	α_2 ($x10^{-7}$)	α_3 ($x10^{-6}$)	α_4 ($x10^{-6}$)	β_1 ($x10^{5}$)	β_2 ($x10^{5}$)	β_3 ($x10^{5}$)	β_4 ($x10^{5}$)

1	-0.4563	0.4377	-0.0857	-0.1863	-0.2790	-0.2714	-1.0440	-1.8020
2	0.3333	0.0745	-0.1788	-0.0596	1.3720	0.6554	-2.6210	2.6210
3	-0.2840	0.1025	-0.1174	-0.2198	0.3226	0.4762	0.8090	-2.5800
4	-0.5309	0.3958	0.0335	0.0577	0.0666	-0.6554	-0.9114	2.5400
5	0.2979	0.1490	-0.1788	-0.0596	1.3310	0.8192	-2.6210	1.9660

Table 2. Six sets of GPS ionospheric coefficients recorded on 9 August 2012

Set	α_1 ($x10^{-7}$)	α_2 ($x10^{-7}$)	α_3 ($x10^{-7}$)	α_4 ($x10^{-6}$)	β_1 ($x10^{6}$)	β_2 ($x10^{6}$)	β_3 ($x10^{5}$)	β_4 ($x10^{6}$)
1	0.1025	0.2235	-0.5960	-0.1192	0.1004	0.1311	-0.6554	-0.3932
2	0.1025	0.2235	-0.5960	-0.1192	0.1004	0.1311	-0.6554	-0.4588
3	0.1211	0.2235	-0.5960	-0.1192	0.1065	0.1311	-0.6554	-0.3277
4	0.1304	0.2235	-0.5960	-0.1192	0.1065	0.1311	-0.6554	-0.2621
5	0.1024	0.2235	-0.5960	-0.1192	0.1004	0.1311	-0.6554	-0.3932
6	0.1024	0.2235	-0.5960	-0.1192	0.1004	0.1311	-0.6554	-0.4588

Table 1 shows that five sets of GPS ionospheric coefficients were recorded by GPS receivers on 28 April 2000 and six sets were recorded on 9 August 2012 as shown in Table 2. The values in Table 1 vary significantly, whereas the variations in Table 2 show much smaller differences. As a matter of fact, in Table 2 only three coefficients α_1, β_1 and β_4, particularly coefficients α_1 and β_4, are different.

Table 3 summarizes the statistics of GPS receiver types reporting each set of ionospheric coefficients for this period. For each type of GPS receiver, the number of IGS stations reporting the same set of coefficients is counted and shown in the table. If examining each set of coefficients, it can be found that some sets are reported by many more GPS receivers than others. For instance on 28 April 2000, the set 1 of coefficients is recorded by a total of 41 receivers (receivers of AOA and ROGUE types). In contrast, the sets 2, 3, 4 and 5 coefficients are recorded by only 2, 1, 1 and 1 GPS receiver, respectively. This is to say that a majority of GPS receivers output the set 1 coefficients. Examining each type of GPS receivers in the table, it can be seen that some types of receiver, such as ASHTECH and LEICA, output only 1 set of coefficients on a single day, which is the expected normal outcome. Other types of receivers like AOA, JAVAD, JPS, ROGUE, SEPT (Septentrio), TPS and TRIMBLE, output at least two sets of coefficients in one single day. Some types of receivers such as JPS output as many as 6 sets of coefficients on one single day, as indicated for day 9 August 2012. Within those types of receivers reporting at least 2 sets of coefficients, some models of receivers such as AOA's BENCHMARK ACT however only report 1 set of coefficients, similarly for AOA's SNR-12 ACT, ROGUE's SNR-12 RM and others.

Table 3. GPS Receiver types outputting different sets of GPS broadcast ionospheric coefficients on 28 April 2000 and 9 August 2012

Receiver type		**28 April 2000**					**9 August 2012**					
		1	2	3	4	5	1	2	3	4	5	6
AOA	BENCHMARK ACT	4	-	-	-	-	-	-	-	-	-	-
	SNR-12 ACT	9	-	-	-	-	-	-	-	-	-	-
	SNR-8000 ACT	5	-	-	1	-	-	-	-	-	-	-

ASHTECH	Z-XII3T	-	-	-	-	-	-	-	-	-	1	-
JAVAD	TRE_G3TH DELTA	-	-	-	-	-	2	2	-	1	2	-
	TRE_G3T DELTA	-	-	-	-	-	1	-	-	-	-	-
JPS	LEGACY	-	-	-	-	-	7	-	-	-	2	-
	E_GGD	-	-	-	-	-	-	1	-	-	1	1
	EGGDT	-	-	-	-	-	5	-	1	2	2	-
LEICA	GRX1200PRO	-	-	-	-	-	1	-	-	-	-	-
	GRX1200GGPRO	-	-	-	-	-	8	-	-	-	-	-
	GRX1200+GNSS	-	-	-	-	-	1	-	-	-	-	-
ROGUE	SNR-12 RM	3	-	-	-	-	-	-	-	-	-	-
	SNR-8000	16	-	-	-	-	-	-	-	-	-	-
	SNR-8100	4	-	1	-	-	-	-	-	-	-	-
SEPT	POLARX4TR	-	-	-	-	-	1	-	-	2	-	-
	POLARX3ETR	-	-	-	-	-	1	-	-	-	-	-
TPS	LEGACY	-	-	-	-	-	-	-	-	-	1	-
	NETG3	-	-	-	-	-	-	-	-	1	2	-
	NET-G3A	-	-	-	-	-	4	5	2	-	-	-
	E_GGD	-	-	-	-	-	3	-	-	2	-	-
TRIMBLE	4000SSI	-	2	-	-	1	-	-	-	3	1	-
	NETRS	-	-	-	-	-	11	-	14	3	3	-
	NETR9	-	-	-	-	-	6	-	5	-	1	-
	NETR8	-	-	-	-	-	9	-	1	2	-	-
	NETR5	-	-	-	-	-	4	-	1	3	2	-
	4700	-	-	-	-	-	4	-	-	1	1	-
	5700	-	-	-	-	-	-	-	-	-	1	-
	4000SSE	-	-	-	-	-	1	-	-	-	-	-
Sub-total		41	2	1	1	1	69	8	24	20	20	1

In order to further analyze the anomaly of Klobuchar coefficients with respect to GPS receiver types, Figure 6 shows all the types of GPS receivers and the set number of Klobuchar coefficients they decoded over the period from 1998 to 2013. The color represents the set of Klobuchar coefficients. In case different receivers report the same set of coefficients (with same coefficient values), the receiver types are denoted in the same color. It can be seen that on a single day some types of receivers output only one set of coefficients while some other types of receivers output multiple sets of coefficients. For instance, all types of NOVATEL receivers report only one set of coefficients in each day. Other types of receivers can output either one set or multiple sets on a single day. The most typical ones are the TRIMBLE receivers. Most models of TRIMBLE receivers can output more than two sets of Klobuchar coefficients every day. To explain the relationship between anomalies of Klobuchar coefficients with receiver types better, the authors consulted the technical support engineers of a major GNSS manufacturer. The technical support explained that: each GPS satellite transmits a copy of the Klobuchar model coefficients and there is no need to require that all GPS satellites transmit the same set of coefficients; some satellites will get updated coefficients earlier than others. This explanation implies the anomaly of same model of GPS receivers reporting several sets of Klobuchar coefficients on the same single day, e.g. TRIMBLE NETR9 receivers reporting 3 sets of coefficients on 9 August 2012 as shown in Table 3, is because the receivers receiving GPS signals from different GPS satellites.

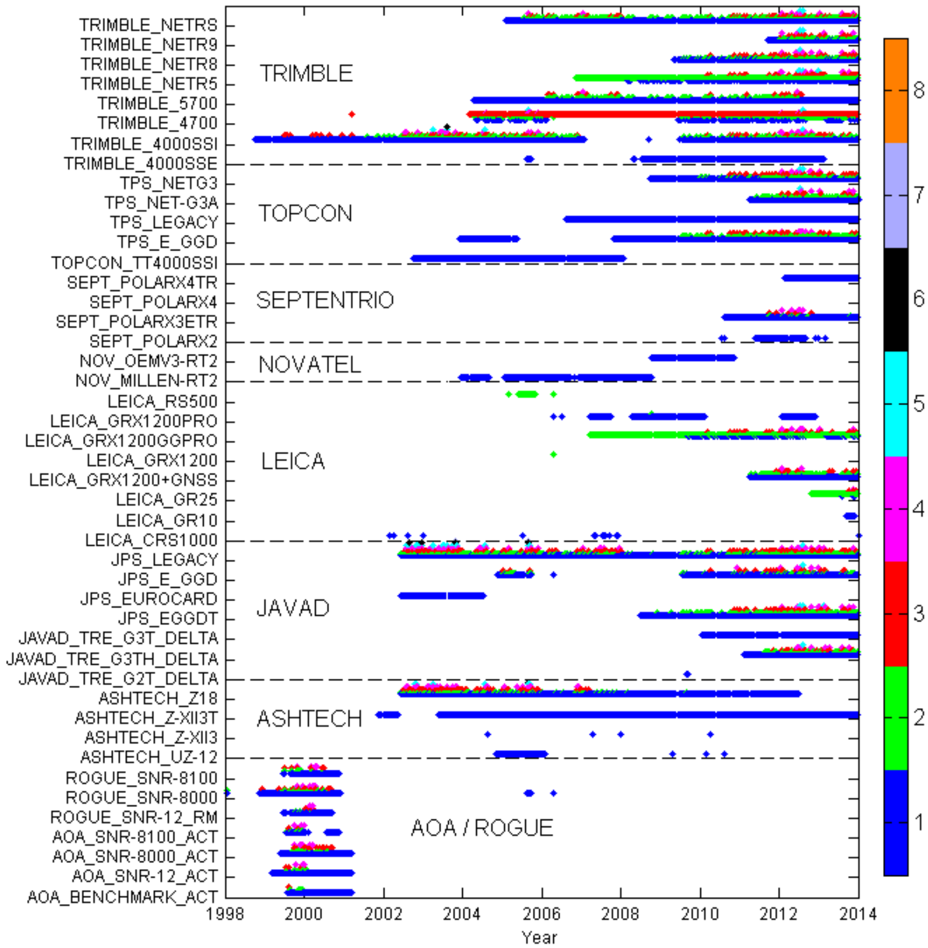

Fig. 6. GPS receiver types recording different sets of GPS broadcast ionospheric coefficients over the period from 1998 to 2013. Each color represents the set number of Klobuchar coefficients decoded by each type of receivers every day.

Following the explanation of the technical support, two GPS receivers close enough to each other should receive the same set of Klobuchar coefficients as they simultaneously receive signals from the same GPS satellites. To verify its validity, we examine the GPS receivers shown in Figure 5. There are receivers that are adequately close to each other. However they output different sets of Klobuchar coefficients. Table 4 presents respective information of four pairs of GPS stations. It should be noted that the two GPS stations in the third and fourth rows (Aug. 9, 2012 and Jul. 31, 2013) are particularly close to each other. For each pair of GPS receivers, the processing software, the processing agency, and processing date are almost identical. The only difference is that the two GPS receivers in each pair have different types. Each pair of receivers theoretically should observe the same satellite constellations and consequently report the same set GPS ionospheric model coefficients. Nevertheless, two sets of ionospheric model coefficients are reported by the two receivers in each pair. For example on 9 August 2012, two GPS navigation files were recorded at two GPS stations CHIL and CIT1. Both of them were identically processed by the USGS (U.S. Geological Survey) using the TEQC program (Translation, Editing and Quality Checking) at 5:31 UTC on 10 August 2012. However the two stations report different sets of GPS ionospheric model coefficients. Table 4 indicates that the only major difference between these two stations is the receiver type: CHIL station using TPS NET-G3A and CIT1 station using TRIMBLE NETRS. The results from all the pairs in Table 4 suggest that the explanation from manufacturer's technical support is not necessarily valid. It strongly suggests that the anomaly be associated with the GPS receiver type (hardware and/or software of the GPS receivers).

Table 4. Each pair of GPS receivers is geographically close enough to each other and is processed under almost the same conditions. However, two different sets of GPS ionospheric model coefficients are recorded by the two receivers in each pair, which suggests the coefficient anomaly is closely correlated with the GPS receiver types/models (hardware and software).

Time	**Station**	**Lat. / Lon.**	**Receiver Type**	**Program**	**Agency**	**Processing date**
28 April 2000	GOL2	35.42 243.11	ROGUE SNR-12 RM	TEQC	JPL	01-MAY-2000 20:33:36
	HARV	34.47 239.32	AOA SNR-8000 ACT	TEQC	JPL	01-MAY-2000 20:40:28
16 September 2005	BOGI	52.47 21.03	JPS E_GGD	CCRINEXN	IGIK	17-SEP-2005 00:03
	BORL	52.10 17.07	ROGUE SNR-8000	CCRINEXN	SRC PAS	17-SEP-2005 00:52
9 August 2012	CHIL	34.33 241.97	TPS NET-G3A	TEQC	USGS	10-AUG-2012 05:31:31
	CIT1	34.14 241.87	TRIMBLE NETRS	TEQC	USGS	10-AUG-2012 05:31:47
31 July 2013	HERS	50.87 0.336	SEPT POLARX3ETR	CCRINEXN	NSGF	01-AUG-2013 00:01
	HERT	50.87 0.334	LEICA GRX1200GGPRO	TEQC	NSGF	01-AUG-2013 00:01

Another potential factor contributing to the anomaly of GPS ionospheric model coefficients is the effect of strong ionospheric disturbances such as scintillations. Previous studies showed that ionospheric scintillation may result in erroneous decoding of GPS data message (Carrano et al. 2005). When the GPS receivers happened to observe scintillations, it is possible that anomalous ionospheric coefficients are decoded and recorded. However it should also be noted that not all message decoding errors should be attributed to scintillation. For instance in Figure 5c (9 August 2012), the numbers of GPS receivers recording set 1 to set 6 coefficients are 69, 8, 24, 20, 20, and 1, respectively. It can be reasonably assumed that the set 1 coefficients are the correct ones, considering that most receivers (69 stations) record this set. This implies the other sets of coefficients recorded by the remaining 73 receivers are anomalous. On the day 9 August 2012, the ionospheric activity level was very low, with the highest Kp index being 3-. Thus it was quite unlikely that on that ionospherically quiet day, so many receivers (73 receivers) were affected by scintillations. Usually low latitude and high latitude regions have more scintillations than mid-latitude regions (Xu et al. 2012; Xu et al. 2014). Examining the anomaly sets of coefficients in Figure 5c, the GPS receivers were scattered globally and not concentrated in low or high latitudes.

Impacts of Klobuchar model coefficient anomaly

In order to better understand the impact of the anomaly of GPS ionospheric model coefficients, the anomalous ionospheric coefficients are used in the Klobuchar model to estimate ionospheric total electron contents (TEC). The results are compared with reference TEC values derived from the Global Ionospheric Maps (GIM) generated by the Center for Orbit Determination in Europe (CODE). In the analysis, four locations, marked with A, B, C and D and separated widely in different continents, are chosen as anomaly impact test stations, as shown in Figure 7. Two locations, A (50°N, 90°E) and B (45°N, 110°W), are located at mid-latitudes while C (15°N, 20°E) and D (15°S, 60°W) are at low latitudes.

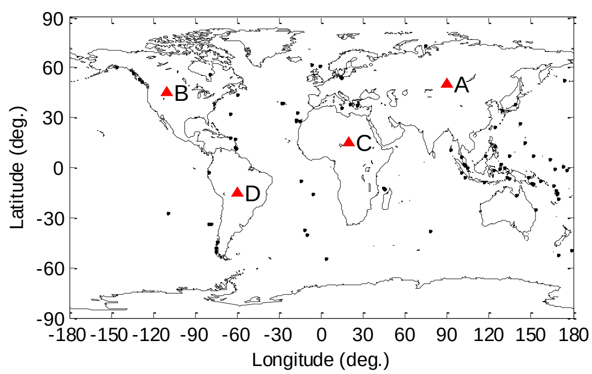

Fig. 7. Locations of four GPS test stations

When multiple sets of Klobuchar coefficients exist for a given day, multiple VTEC values are calculated accordingly for all the four test stations and the VTEC are marked with a color corresponding to a particular set of coefficients, as designated by the color bar in Figure 8. This figure indicates that both Klobuchar and GIM models can largely represent the ionospheric TEC variations at seasonal and solar cycle scales. During the 2000-2001 solar maximum period, both models clearly show significantly increased TEC levels.

However, Figure 8 also shows that when anomalous broadcast coefficients are used to compute VTEC following the Klobuchar model, the obtained VTEC values are extraordinarily large. For instance for day of 1 June 2000, the largest VTEC value computed using one set of ionospheric coefficients reaches 141.9 TECu for test station A, and for the test station B the largest VTEC is even as large as 153.3 TECu. In contrast, the VTEC computed from the GIM model is only 24.1 TECu for station A and only 35.8 TECu for station B on that day. It clearly shows that the anomalous Klobuchar model coefficients can result in a significant impact on ionospheric delay correction.

On 1 June 2000, three sets of coefficients were recorded by 60 GPS receivers in the IGS global network and other IGS stations had no record of ionospheric coefficients, as shown in Table 5. With these three sets of ionospheric coefficients the VTEC values for all the four test stations are computed and presented in Table 6. The largest VTEC using set 3 coefficients at test station B (a mid-latitude station) is 16.36 times the smallest one using the set 1 coefficients. At station C (located at low-latitude) the largest VTEC is 13.31 times the smallest one. The average

VTEC of four test stations using set 2 and set 3 coefficients is 3.93 times and 14.25 times the VTEC using set 1 coefficients, respectively. This clearly shows that the performance of the Klobuchar model is remarkably impacted when anomalous broadcast coefficients are used. The GPS users who unfortunately employ the anomalous ionospheric coefficients to correct single frequency ionospheric errors will certainly get a very poor positioning, navigation and timing solution, if the anomaly is not identified.

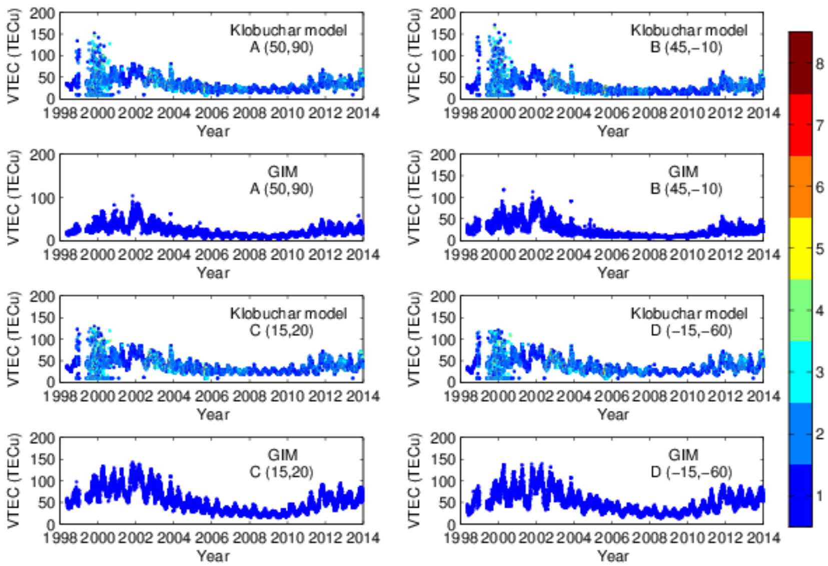

Fig. 8. Klobuchar VTEC with different sets of GPS broadcast ionospheric coefficients recorded by global IGS receivers versus GIM VTEC computed at 14:00 LT over the period from 1998 to 2013 for the four test stations.

Table 5. Three sets of GPS ionospheric coefficients on 1 June 2000 and the number of GPS receivers recording each set of coefficients

Set	α_1 (x10^{-7})	α_2 (x10^{-7})	α_3 (x10^{-6})	α_4 (x10^{-6})	β_1 (x10^{5})	β_2 (x10^{5})	β_3 (x10^{5})	β_4 (x10^{5})	Number of GPS receivers
1	-0.4331	-0.5960	-0.0987	0.0261	0.1280	-0.6451	1.1880	-4.0140	55
2	0.1676	-0.0745	-0.0596	0.1192	1.3520	-1.8020	0.6554	0.0000	2
3	0.5681	0.4936	0.0857	-0.0875	0.1280	0.0000	-0.7373	-1.3930	3

Table 6. VTEC computed for the four test stations using each set of broadcast coefficients of 1 June 2000 (Unit: TECu)

Set	VTEC of test stations				Global average (of A, B, C, D)
	A	B	C	D	
1	9.37	9.37	9.37	9.37	9.37
2	34.73	32.60	38.93	41.00	36.82
3	141.91	153.32	124.68	114.02	133.48

In order to better illustrate the differences between the Klobuchar model and GIM VTEC, the maximum and minimum absolute differences between these two models are computed at the four test stations for the epoch 14:00 LT in each day for the period from 1998 to 2013. To find the maximum and minimum absolute differences, all the sets of Klobuchar coefficients for a given day are used for VTEC computation. As shown in Figure 9, the maximum absolute differences between the two models are smaller than 30 TECu in most time. However with increased solar activities, the maximum absolute difference can reach 270.9 TECu for test station A, 335.7 TECu for station B, 149.01 TECu for the station C and 149.83 TECu for station D. These remarkable differences are due to the anomalous broadcast coefficients as shown in Figure 3.

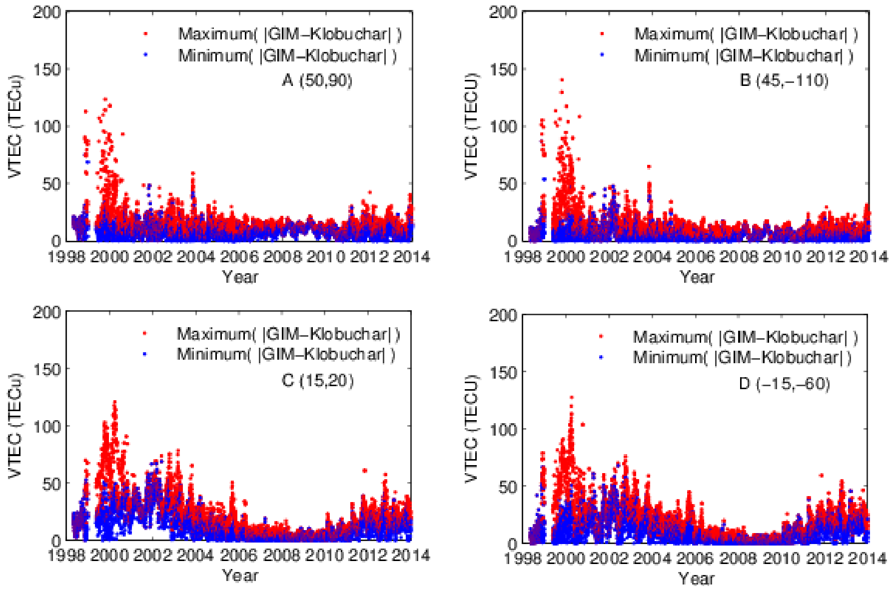

Fig. 9. Maximum and minimum absolute differences of VTEC between GIM and Klobuchar models computed for 14:00 LT each day at the four test stations over the period from 1998 to 2013. The Klobuchar model VTEC values are computed using different sets of GPS ionospheric coefficients.

As shown in Figure 4, the Klobuchar coefficients extracted from the IGS combined navigation file also displayed significant irregularities during the period from mid-1999 to mid-2001. Figure 10 shows the comparisons between the Klobuchar VTEC, calculated using the coefficients extracted from IGS combined navigation files, and GIM VTEC during the period from 1998 to 2013. Generally, the differences between Klobuchar VTEC and GIM VTEC computed at 14:00 LT are less than 30 TECu. While during the anomaly period the Klobuchar VTEC shows large differences with respect to the GIM VTEC at the four stations. The largest difference can reach 72.67 TECu for test station A that occurs on 4 November 2000, 108.22 TECu for test station B on 4 April 2000, 120.58 TECu for test station C on 26 March 2000, and 127.61 TECu for D on 8 April 2000. It clearly shows that the Klobuchar coefficients, even when extracted from the IGS combined navigation files (brdcddd0.yyn), contain also anomalies and can lead to poor ionospheric correction efficiency.

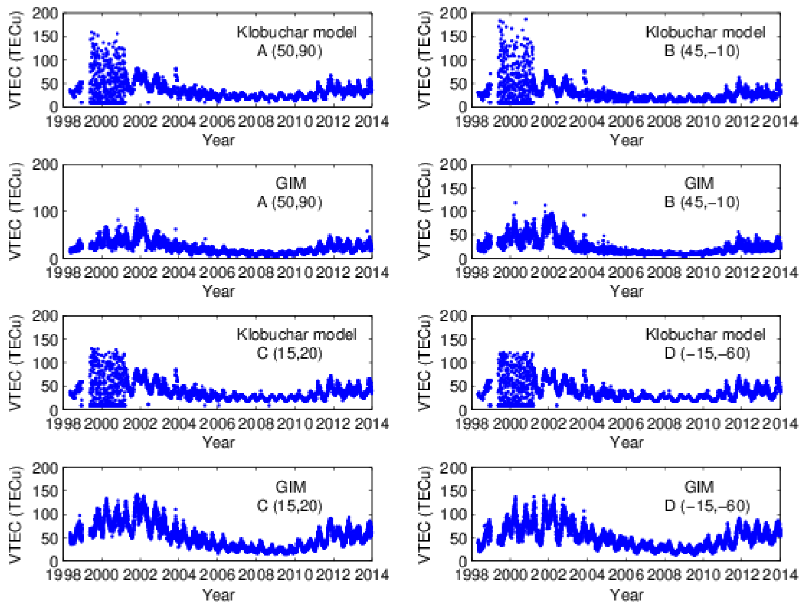

Fig. 10. A comparison of the Klobuchar VTEC using the GPS ionospheric coefficients extracted from the IGS combined navigation file (brdcddd0.yyn) and GIM VTEC computed at the four test stations at 14:00 LT each day over the period from 1998 to 2013.

In order to summarize the impact analysis of the GPS ionospheric coefficient anomaly on TEC evaluation, the root-mean-squares (RMS) of the VTEC mismodeling errors shown in Figure 9 is calculated and given in Table 7. With respect to the GIM, the RMS of the maximum VTEC mismodeling errors is ~18 TECu at mid-latitudes and ~28 TECu at low latitudes, as shown in the column 3 of the table. For the minimum mismodeling error, the RMS is less than 11 TECu at mid-latitudes and ~18 TECu at low latitudes. It shows that anomalies in Klobuchar coefficients statistically can result in a ~10 TECu error between the worst and best Klobuchar VTEC modeling accuracy for both low- and mid-latitude region GPS users.

Table 7. RMS of the maximum and minimum VTEC mismodeling errors with respect to the GIMs at different test stations (unit: TECu)

Station	**Location**	RMS_{max}	RMS_{min}	RMS_{max_r}	RMS_{min_r}	RMS_{brdc}	RMS_{brdc_r}
A	(50°, 90°)	18.49	10.14	15.19	10.10	17.56	11.44
B	(45°, -110°)	17.28	7.82	12.59	7.74	17.06	8.74
C	(15°, 20°)	28.59	18.05	21.96	16.55	27.32	17.52
D	(-15°, -60°)	26.23	15.41	21.27	14.97	24.73	16.31

If the VTEC obtained during the anomaly period mid-1999 to mid-2001 are not considered in the statistics, the maximum RMS, denoted as RMS_{max_r}, reduces by 3~5 TECu in both low and mid-latitudes while very slight change is observed for the minimum RMS (RMS_{min_r}). The difference between maximum and minimum RMS is ~5 TECu, indicating that the impact of the anomaly in Klobuchar coefficients during other periods (outside the large anomaly period mid-1999 to mid-2001) is still significant.

The RMS of VTEC mismodeling errors using coefficients from IGS combined navigation files is significantly larger than the RMS_{min} by 7-10 TECu at mid-latitude stations and by about 9 TECu at low-latitude stations. This suggests that the coefficients from the IGS combined navigation files (brdcddd0.yyn) contain large anomalies, which results in a large degradation in the VTEC modeling when compared with the best coefficient case (RMS_{min}). If the VTEC mismodeling error during the large anomaly period mid-1999 to mid-2001 is not considered in the statistics, the RMS_{brdc_r} is much smaller than the RMS_{min} but it is still about 1 TECu larger than RMS_{min_r}. The result shows that outside the large anomaly period, the Klobuchar coefficients in the IGS combined navigation files still contain anomalies, which cause about 1 TECu error when compared to the best coefficient case (RMS_{min_r}). During the large anomaly period, the Klobuchar coefficients in the IGS combined navigation files still have much larger anomalies, resulting in about 7-10 TECu at mid-latitude stations and by about 9 TECu at low-latitude stations

Conclusion

The coefficients broadcast by GPS satellites are essential input data when using the Klobuchar model to correct the ionospheric errors. We studied the anomaly phenomenon by analyzing a huge database of Klobuchar coefficients recorded daily by global IGS GPS receivers during the past two solar cycles (1992-2013). It is found that sometimes IGS receivers can report as many as 8 sets of Klobuchar coefficients, which is apparently an anomalous phenomenon. The multiple sets of coefficients recorded daily have significantly different values. We analyze the relationship between the anomaly of broadcast coefficients with solar cycle, receiver location and receiver types/models. It shows that most of the coefficients show an annual variation. We find that during an active solar cycle period (mid-1999 to mid-2001), the values of all the eight coefficients, extracted from either IGS combined navigation file brdcddd0.yyn or from other navigation files generated from GPS stations, vary irregularly in a significant manner. Our analysis also indicates the anomaly of Klobuchar coefficients is correlated with GPS receiver types/models. However we do not find that the anomaly of Klobuchar coefficients is correlated with the geographic locations of GPS receivers.

In order to better understand the impact of the anomaly of coefficients on ionospheric corrections, VTEC values for 14:00 LT at four global test stations are calculated using the Klobuchar model with different sets of the coefficients recorded over a 16.5-year period from May 1998 to December 2013. It is found that during the solar active period (mid-1999 to mid-2001), the Klobuchar model performs extremely poorly when the anomalous coefficients are used. For example, on 1 June 2000 at a mid-latitude GPS station the larger VTEC computed using one set of coefficients can be as large as 16.36 times the smaller VTEC computed using another of coefficients. This implies that when GPS users unfortunately employ the anomalous ionospheric coefficients, they would get a very poor PNT (positioning, navigation and timing) solution. The VTEC from Klobuchar model is compared with a reference VTEC data from the GIM model provided by CODE. In general the maximum absolute VTEC difference is smaller than 30 TECu but it can grow up to hundreds of TECu in an active solar cycle period (335.7 TECu in this study). With respect to the GIM, the RMS of the maximum VTEC mismodeling errors is ~18 TECu at mid-latitudes and ~28 TECu at low latitudes. The anomaly in Klobuchar coefficients statistically can result in a ~10 TECu error between the worst and best Klobuchar VTEC modeling accuracy in both low- and mid-latitude region GPS users.

This study has identified and analyzed a long unnoticed issue associated with the GPS broadcast ionospheric model that has shown to have a considerable impact on the numerous PNT applications and scientific studies conducted with millions of single-frequency GPS device.

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