Regional Ionosphere Models for Improving GNSS Navigation



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Kurzfassung

Alle Signale von Satellitennavigationssystemen erfahren durch die Atmosphäre eine Laufzeitverzögerung. Von den verschiedenen Einflüssen ist jener der Ionosphäre am stärksten. Als dispersives Medium verzögert sie die Signale frequenzabhängig. Deswegen können Empfänger mit zwei oder mehr Frequenzen durch Bildung von Linearkombinationen die Verzögerung großteils eliminieren. Allerdings besteht der überwiegende Teil der Empfänger aus solchen, die nur die GPS-Frequenz L1 nutzen, weil die Empfängerkosten wesentlich geringer sind. Im Fall von Einfrequenzempfängern kann durch die Verwendung von Ionosphärenmodellen eine Verbesserung der Positionierung erzielt werden. Die Modelle reichen von statischen globalen bis zu lokalen, die nahezu in Echtzeit berechnet werden. Durch die Übermittlung von Korrekturdaten via EGNOS kann die Genauigkeit der Empfänger von L1-Code von mehreren Metern bis zu einem Meter oder gar darunter gesteigert werden. Auf Grund der derzeit schwachen Sonnenaktivität ist der Fehlereinfluss durch die Ionosphäre eher gering. Deshalb wurden Daten von GPS-Permanentstationen während eines extremen Events des letzten Sonnenzyklus analysiert. Als Testgebiet wurde eine Region mittlerer Breite in Österreich gewählt, weil dort die Stationen eine relativ lange Zeitreihe besitzen. Es kann gezeigt werden, dass während hoher Sonnenaktivität die regionalen Modelle eine Verbesserung in der Positionierung gegenüber einem globalen Modell erzielen.

Keywords: Austria, GPS, ionosphere, OEGNOS

Abstract

GNSS signals experience significant delays when travelling through the atmosphere. The major source of the delay is due to the ionosphere which is a dispersive medium. Receivers with two or in future more frequencies can eliminate most of this influence by computing an ionosphere-free combination of frequencies. The major part of navigation receivers, however, uses only L1-signals and thus needs external corrections to improve the positions degraded by the ionosphere. This article will give an overview to which extent positions determined by means of L1-signals can be improved if different ionosphere models, ranging from global to local ones, are applied. The corrections can be transmitted in near real-time by e.g. an EGNOS server which provides those data in order to reduce the standard error of several meters to a sub-meter level for L1 code receivers. The reduction of ionospheric delay becomes especially important during the maximum of a solar cycle. For this reason, the models have been applied to data gathered from permanent stations during extreme events of the last solar maximum. The mid-latitude region of Central Austria was chosen as a regional testbed with permanent stations providing a long time series. It can be shown that with increasing solar activity, regional models improve positions slightly better compared to a global model.

Schlüsselwörter: Österreich, GPS, Ionosphäre, OEGNOS

1. Introduction

When the Global Positioning System (GPS) was designed, the introduction of the two frequencies L1 and L2 should reduce the effect of the ionosphere onto positioning, at least for military users. Additionally, ionosphere parameters of the Klobuchar model [6] are transmitted together with the broadcast ephemeris and can be used by any receiver. Thereby ionospheric time-delay, examined over one day, strongly reflects a cosine curve, which has been mathematically modelled by Klobuchar. Thus it is possible to model the daily variations which have a total electron content (TEC) maximum at early afternoon (14:00 LT) and a quite constant minimum during night. Nevertheless it has to be noted that the Klobuchar model can only correct about 50-70% of the ionospheric delay. Thus there is a need of modelling the ionosphere more accurate than the transmitted global model can do. Especially for receivers which either use range corrections from another station at distances of 1000 km and more by Differential GPS (DGPS) or want to correct their position by more adequate models like the European Geostationary Navigation Overlay Service (EGNOS [4]), the inclusion of the current ionospheric conditions is important.

The ionospheric delay of a transmitted signal with a frequency f (L1 = 1575.42 MHz) can be computed according to [5] by

$$\Delta IONO = \frac{40.3}{f^2} TEC \; .$$

Thereby the TEC is defined as the total number of electrons (N_E) per m^2 along the path s,

$$TEC = \int N_E(s)\, ds$$

and is measured in TEC Units (1 TECU = 10^{16} electrons / m^2). Implicitly each delay is also a function of time because the number of electrons is not constant in space and time. Using more than one frequency, assuming constant electron numbers within the travelling time, the TEC can either be determined or its influence on the distance measurement can be eliminated by forming linear combinations. The impact of one TECU is equivalent to a distance of about 0.16 m for the C/A code which is in the same range as the wavelength of L1 (about 0.19 m).

However, the natural variations of the ionosphere are much larger than 1 TECU and may reach some hundreds of TECUs during extreme events. On this assumption we determined global and regional ionosphere models and investigated their impact on the station coordinates. In order to validate the results, a comparison with models from the Center for Orbit Determination in Europe (CODE) has been made. The research covers time periods of high solar activity as well as the present time where less solar activity is noticeable. Finally, the regional models were computed in near real-time and the results are provided to the Austrian EGNOS data server (OEGNOS, [7]) for an improvement of the position accuracy provided by the EGNOS service.

2. Ionosphere Models

When modelling the ionosphere it is important that the parameters adapt very quickly in time and cover special regions of the ionosphere, which may deviate from predicted models. For example, rapid amplitude and phase fluctuations, known as scintillations, arise quite locally and on short term. Other interferences arise from travelling disturbances which are running from the North Pole through channels to mid-latitudes. Not to forget solar outbursts and geomagnetic storms, which have an impact on the whole northern hemisphere. Therefore, models require current measurements with good resolution in time and space. For the present study GPS measurements were used to determine the parameters of several ionosphere models. All of them were produced using the Bernese GNSS Software 5.1 [2] either in a post processing or in a near real-time mode. This software package offers the possibility to determine ionosphere models based on a Taylor series or spherical harmonics.

2.1 Global Ionosphere Model (GIM)

The models described in Sections 2.1 and 2.2 are based on the so called Single Layer Model (SLM), which assumes that all free electrons are concentrated in a thin shell of infinitesimal thickness. This assumption is necessary since it is nearly impossible to establish height dependent profiles of electron densities using ground based GPS observations [8]. However, by using data of low Earth orbiters (LEO) equipped with GPS receivers and spacecraft dedicated to measure the ionosphere parameters, like COSMIC/FORMOSAT and DEMETER, improved vertical profiles could be produced. Because those data are not easily accessible, especially not in real-time, the SLM provided by standard software will be regarded in the following.

The vertical TEC E can thus be represented as a function of geographic latitude β and sun fixed longitude s:

$$E(\beta, s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\beta)(a_{nm}\cos ms + b_{nm}\sin ms)$$

The maximum degree $n_{\max}$ of the spherical harmonics expansion is set to 15. $\tilde{P}_{nm}$ are the normalized Legendre functions and a_{nm}, b_{nm} denote the coefficients of the spherical harmonics.

For the computation of a global ionosphere model, data from approximately 220 permanent GPS stations, mainly from the IGS network [3], contributed to the solution. To determine the ionospheric delay, zero difference smoothed code observations were processed limited to an elevation mask of 10°. Beside the representation with spherical harmonics, the GIM is also provided in the Ionosphere Exchange (IONEX) format with a spatial resolution of 5.0 degrees in longitude and 2.5 degrees in latitude, and a temporal resolution of two hours. The usage of the IONEX format, especially the interpolation methods between the grid-points, is described in [8].

2.2 Regional Ionosphere Model (RIM)

The regional models are basically determined with the same procedure as the previous global model. The only difference is that the RIMs were determined with a higher temporal resolution of one hour and are spatially limited to a certain area. For the present study two different regions were evaluated.

The first selected area covers the European territory and comprises measurements of approximately 60 stations within the EUREF permanent network EPN [1]. The determination of the model is also based on spherical harmonics with $n_{\max}$ equal 15 and the co-produced TEC map is aligned with the official product from CODE, having a spatial resolution of 1° × 1°. Hereafter this model is referred to as RIM-EUR.

When calculating ionosphere models in near real-time computations, the latency is a crucial factor. The computing time increases with the number of included stations. Therefore, the second area called RIM-AUT covers a much smaller region containing measurements from 16 GPS stations in Austria and the neighbouring countries (Figure 1). The reference point is locatednear the city of Rottenmann – the testbed area of the OEGNOS project (see chapter 3 for more details).

2.3 Taylor Series

The final model describes the ionosphere based on a Taylor series of degree and order 2 ($n_{\max}$, $m_{\max}$) instead of spherical harmonics. The coefficients are also derived from GPS zero difference observations

$$E(\beta,s) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} E_{nm} (\beta - \beta_0)^m (s - s_0)^m \ .$$

E_{nm} are the TEC coefficients of the Taylor series and β_0, s_0 the origin of the series which resides near the city of Rottenmann (blue mark in Figure 1). Finally, β denotes the geographic latitude of the intersection point of the receiver-to-satellite signal path with the ionospheric layer and s the sun-fixed longitude of the ionosphere pierce point. Due to the polynomial degree and order in the (β, s) domain the model is limited to a small area. Within the testbed this model was also implemented for near real-time processing.

2.4 Validation of the Models

The Klobuchar model was developed in the late 1980s using data from a period of high solar activity during solar cycle 20. Even if the parameters are changed by the GPS providers from time to time, the adaption to real ionosphere conditions is poor. Due to the fact that the model is to map the global ionosphere and that approximations to the geometrical calculations as well as constants are used, it only corrects about 50 % of the ionospheric delay. The night-time constant, for example, is set to 5ns which is about 9 TECU. In fact, this variable is related to the sun activity and leads to deviations during solar quiet times (Figure 2, left side). Additionally there are many turbulent factors which cannot be predicted and have a major impact on the TEC behaviour (Figure 2, right side).

Within their routine analysis, CODE offers a regional ionosphere model covering Europe as well as global models with different latencies. Two predicted models are available with a validity of 24 and 48 hours. The rapid and final iono-

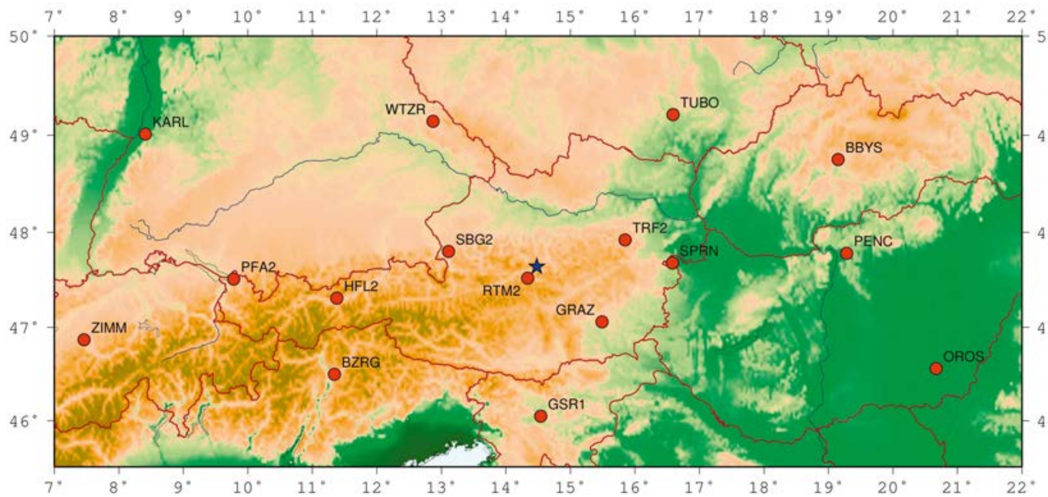

Fig. 1: Near real-time testbed RIM-AUT (Contributing stations are marked as circles and the central point near Rottenmann with a blue star)

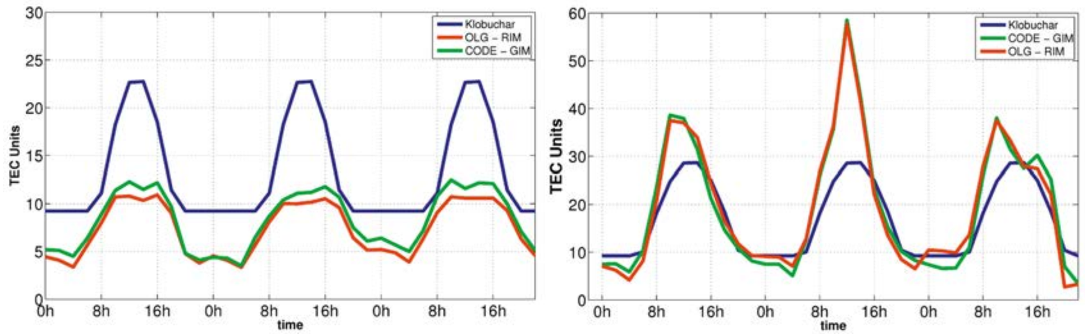

Fig. 2: Ionospheric time delay for station Rottenmann calculated using the Klobuchar model as well as the GIM and RIM during solar quiet times in 2006 (left) and the Halloween event in 2003 (right).

sphere products have a latency of one and four days, respectively. The regional European model is supplied once per month.

In order to validate our GIM and RIM-EUR solutions, a comparison with the final products from CODE was carried out. Figure 3 shows the differences between the solutions.

As expected, the main variations appear in oceanic regions and in areas where different stations were selected. Concerning the European continent the TEC differences in both models are only up to 1-2 TECU, which is the best achievable precision at present.

3. The OEGNOS Project

Comparisons between the different models, GIM, RIM and Taylor series, were carried out within the Austrian project OEGNOS [7]. Apart from the ionospheric correction, also the tropospheric delay has been computed and transmitted. This project was led by the company TeleConsult Austria GmbH. The partners were the University of Technology in Vienna (Institute for Geodesy and Geophysics), the University Center of Rottenmann (UZR) and the Austrian Academy of Sciences (AAS, Space Research Institute). A substantial part of the project was financed by the Austrian research promotion agency FFG. One goal was to refine the corrections transmitted via EGNOS within Austria as a part of Central Europe [11]. Frequently, the direct line-of-sight to the EGNOS satellite is masked in Alpine regions. Therefore a terrestrial server was developed computing regional ionosphere and troposphere corrections and adding them to the range corrections to be transmitted in the RTCM format. The AAS generated the GIM, RIM and Taylor series based models and investigated their influence on the positioning. The University of Technology Vienna provided ionospheric cor-

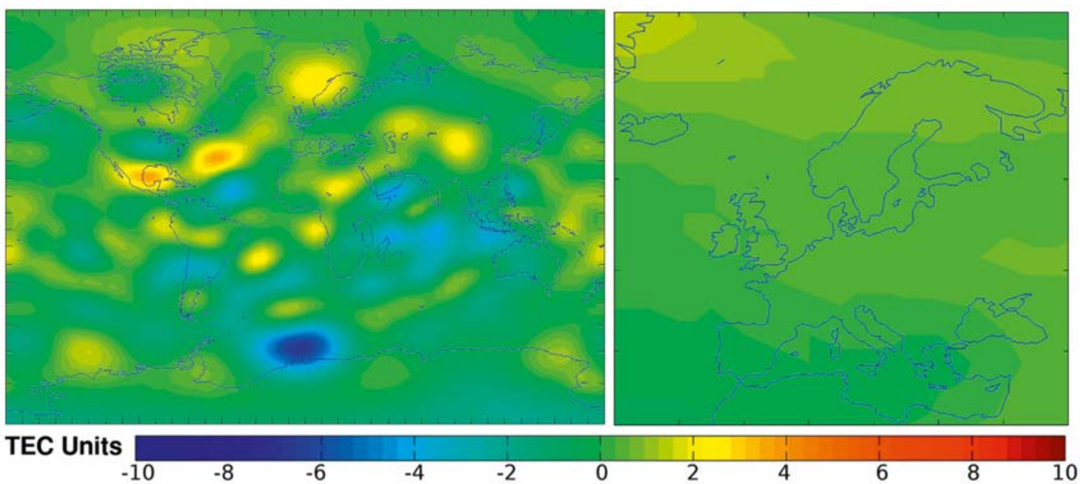

Fig. 3: Differences between TEC maps from CODE and our solutions (left GIM, right RIM-EUR), 6th June 2008 (14:00 LT)

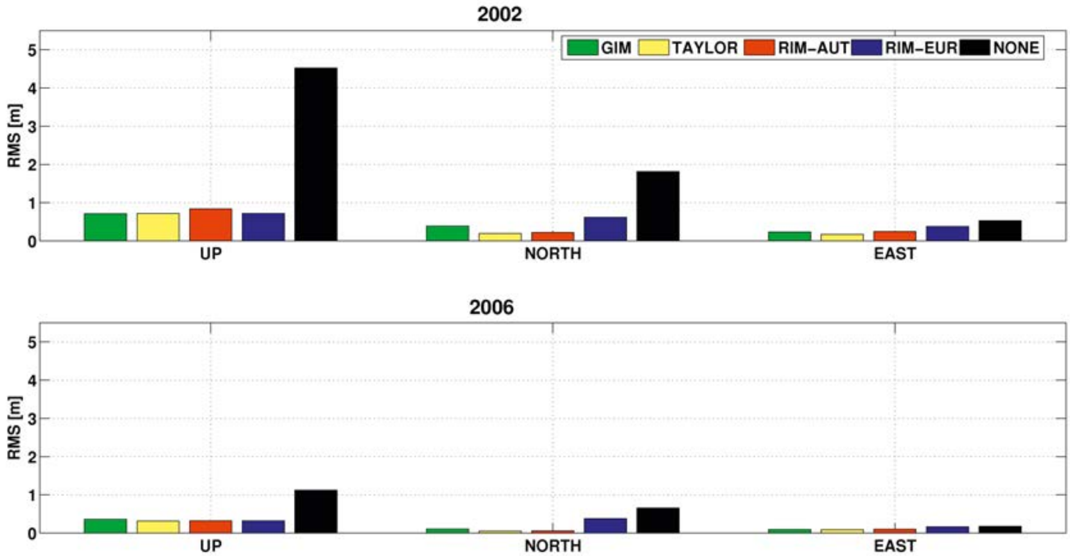

Fig. 4: RMS values of coordinate differences based on a two-week analysis for 2002 and 2006 including 16 contributing stations

rections in real-time based on decoded EGNOS messages, predicted TEC maps and modified Klobuchar coefficient models. UZR and TeleConsult designed and operated the server system and established the communication. Finally, the TeleConsult performed field tests under various conditions and used different models to check the impact in practice.

4. Comparison of Different Ionosphere Models Concerning Station Coordinates

As mentioned before, the majority of the GPS receivers can only make use of the single frequency L1. Therefore, the following results are based on a precise point positioning (PPP) using just the L1 frequency.

4.1 Post Processing Approach

In the last years the solar activity was rather low. In order to compare the models also during high solar activity, calculations for a certain time period in 2002 have been performed additionally. At that time the solar cycle 23 was nearly at the maximum. The post processing analysis based on daily GPS observations was set up for two weeks in 2002 (high solar activity) and 2006 (low solar activity).

In order to identify the effects of different ionosphere models, the obtained coordinates are compared to reference coordinates (ITRF2000 epochs 2002.0 and 2006.0 respectively, phase baseline network from post processing, EPN+AMON [10]), which have an accuracy of 1–2 centimetres.

As we can see in Figure 4, all applied models reduce the error in the coordinates by 75 % during solar quiet and 85 % in solar active times, compared to results where no ionosphere model was used. In doing so, no model shows a significant improvement compared to the others depending on the time of day. In solar quiet times a different model selection has a maximum influence of 0.15 m on the positioning. During solar maxima, however, it becomes more important to use the optimal model.

4.1.1 Impact of Extreme Solar Events on Position Solutions

Extreme solar flares can cause extraordinary ionospheric effects which in turn cause a degradation of the accuracy of positions determined by GPS. The so-called Halloween event in 2003, when two of the largest solar flares occurred (28^{th} October, 4^{th} November), was chosen to demonstrate these effects.

Observations recorded by 11 Austrian permanent GPS stations from 27^{th} October to 6^{th} November were used to calculate the stations local up, north and east coordinates. Figure 5 shows the coordinate differences in the up component using various ionospheric models and the respective values without any corrections.

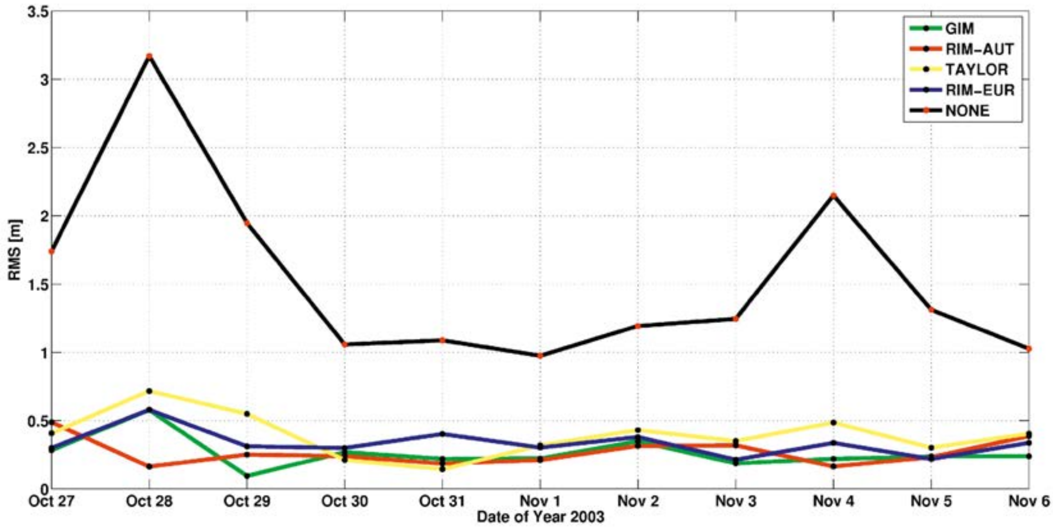

Fig. 5: Mean coordinate differences for up-direction (27th October – 6th November 2003)

The differences in north and east are considerably smaller.

The extreme solar flares are well distinguishable from the differences of the modelled and unmodeled values. The first peak indicates the solar flare at the end of October which is significantly higher than the differences induced by the second flare at beginning of November. It is clearly visible that even during extreme ionospheric conditions the application of any ionospheric model results in height differences considerably smaller than one meter.

4.2 Near Real-Time Approach

Compared to the post processing scheme, several aspects had to be considered for near real-time operation. First of all the entire determination sequence had to be automated. Secondly, we had to use ultra-rapid orbits from IGS and a change from daily to hourly GPS data was mandatory. Also the inclusion of the latest state concerning antenna, receiver and satellite information had to be ensured. As an additional feature an email notification service was implemented which automatically sends an error report to the operator in case of an incomplete computation. After collection of the hourly data from the contributing GPS stations, the complete parameter estimation process was finished within 10 minutes after every clock hour. Afterwards, the model parameters were automatically transferred via ftp to the OEGNOS server, where the delivered TEC information was transformed to vertical delays and furthermore mapped to the desired elevation of the signal by the University of Technology in Vienna. This range correction was finally forwarded to the OEGNOS server.

As previously mentioned, the global and European models from CODE are not suitable for near real-time computations due to their latency. Thus, we replaced them with the predicted ionosphere models from CODE for the final evaluation of the different models.

During the project duration in 2009 and 2010 a very low solar activity was predominate, and therefore differences between the predicted and the calculated models are in the range of 10 centimetre (Table 1). Concerning the large RMS values it must be noted that Table 1 shows the absolute differences between the PPP solutions based on hourly data and a “true” phase solution (ITRF2005, phase baseline network from post processing, EPN+AMON). During this time a predicted model may be sufficient when the near real-time calculation fails or communication line was truncated. Nevertheless, it has to be emphasized that in case of increasing solar activity or an extreme solar event, the variations are significantly higher.

Finally it should be mentioned that there are fall-back strategies in case that the processing is stopped or the communication line is blocked. Under normal conditions the choice follows the priority starting with the RIM-AUT to the model based on a Taylor series and the predicted GIM of CODE. If neither of these models is available the static Klobuchar model is used.

	UP [m]	NORTH [m]	EAST [m]
no model applied	1.41	0.88	0.93
Predicted model	1.14	0.49	0.85
Regional model	1.03	0.47	0.79
Taylor Series	1.05	0.50	0.83

Tab. 1: RMS of coordinate differences between a PPP solution for station Rottenmann over two weeks in 2009 and a 'true' phase solution

5. Conclusions

In case sub-meter accuracy by positioning with GPS and other navigation systems is required, the effect of the ionosphere must be compensated. If using single frequency receivers external support by ionosphere corrections is necessary. While predicted, global and regional models do not differ significantly in periods of low solar activity the use of a model which is created in near real-time by a regional cloud of permanent stations may improve positioning by a decimetre or more. The improvement seems to be moderate for a testbed in the mid-latitude which was presented here, but the gain will be much higher in regions where the impact of the ionosphere is larger like in polar and near-equatorial regions. The work presented in this article demonstrates that regional models of the ionosphere can be used in positioning services with an additional benefit. Sun eruptions like those occurred in October 2003 (Halloween event) demonstrated that a regional ionosphere model is more adaptive than a static global one or one which is computed days afterwards.

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