Higher-order ionosphere modeling for CODE’s next reprocessing activities

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1 Introduction

For a future reanalysis of the data from the International GNSS Service (IGS), the Center for Orbit Determination in Europe (CODE) will consider not only first-order but also higher-order ionosphere (HOI) correction terms for the analysis of space geodetic observations.
The development version of the Bernese Software (Dach et al., 2007) used at CODE was expanded by the ability to assign additional scaling parameters to each considered HOI term. By this, each correction term can be switched on and off on normal equation level and, moreover, the significance of each correction term may be verified on observation level for different ionosphere conditions.

2 Background

In order to obtain second and third order ionospheric correction terms for L1, L2, and LC (ionosphere-free) phase observations the frequency-dependent formula from Fritsche et al. (2005) were added to the parameter estimation part of the most recent development version of the Bernese Software. The algorithm is based on Bassiri et al. (1993) where the geomagnetic field is characterized by a co-centric tilted magnetic dipole.

3 Higher-order ionosphere corrections

Especially during periods of high ionosphere activity, where the mean total electron content (TEC) is significant, HOI correction terms on GPS observations may attain considerable values (see Fig. 1, left panel).

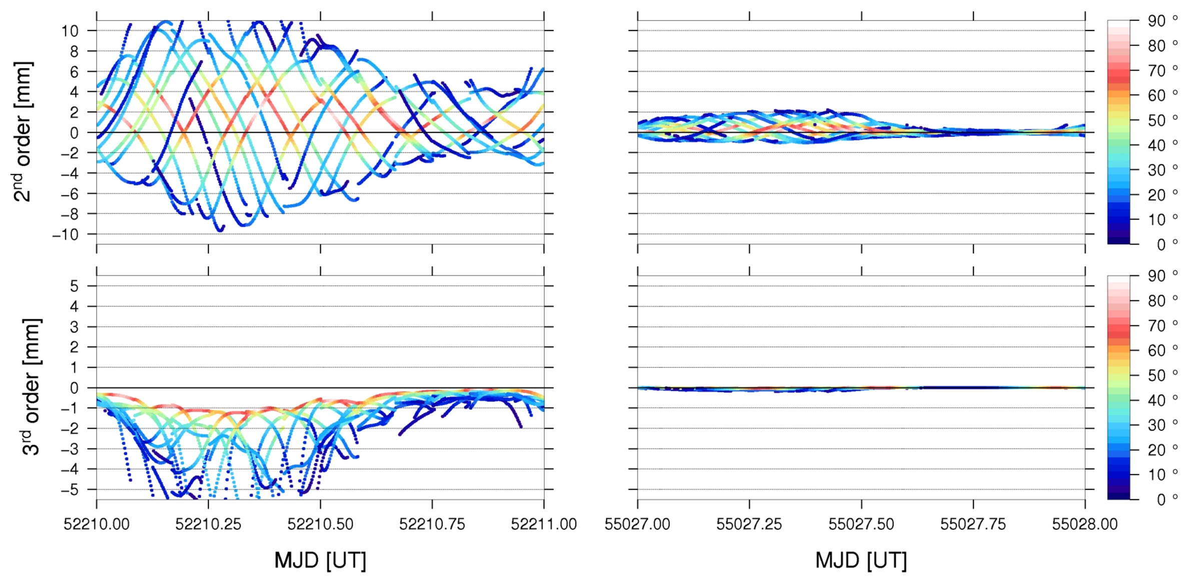

Fig. 1: HOI corrections in millimeters on LC with 30 seconds of sampling down to 3 degrees elevation at the IGS station NTUS (Singapore, 1.3° North/103.7° East/79.0 m Up, see also Fig. 4). The colors indicate the elevation angle to the observed GPS satellite.
Left panels: Day with high ionospheric activity, i. e., mean TEC of more than 50 TECU, on 28-Oct-2001 (MJD 52210); right panels: Day with minimal ionospheric activity, i. e., mean TEC of less than 10 TECU, on 15-Jul-2009 (MJD 55027); top panels: second-order correction term; bottom panels: third-order correction term (changed scale!).

Depending on station latitude, elevation angle, and time of the day, the second order correction term of one observation can reach 1 cm. The correction for the third order term is negative (i.e., a positive effect or time delay) and even for very high elevation angles may exceed 1 mm in an absolute sense.
During quiet ionospheric conditions (Fig. 1, right panel) the only noticeable influence (up to 2 mm) comes from the second-order correction term at low elevation angles.

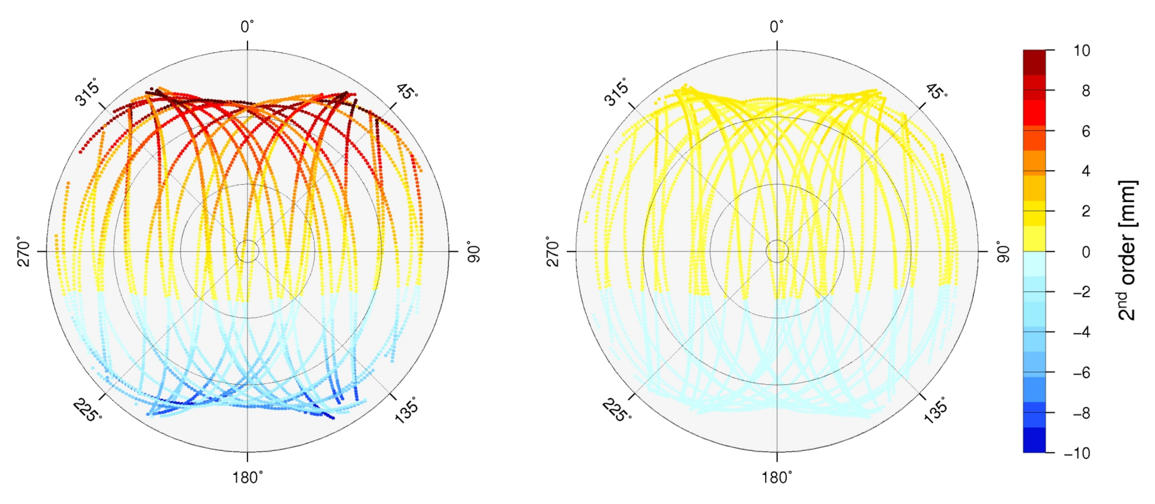

Fig. 2: HOI corrections of the second-order effect with respect to azimuth and elevation of the observation at the IGS station NTUS on 28-Oct-2001 (left panel) and on 15-Jul-2009 (right panel). Here the colors indicate the value of the correction in millimeters. The location of the geomagnetic equator can clearly be recognized at the “Zero” correction line.

4 Test periods and station network

Two times one month of data during periods of very high solar and ionospheric activity in 2001 (Fig. 3, left panel) and 2002 (Fig. 3, right panel) were analyzed in view of significancy of the higher-order ionosphere terms and the usability of the scaling factors. One week in 2009 with very low activity (global mean total electron content of less than 10 TECU) was processed to study the differences.

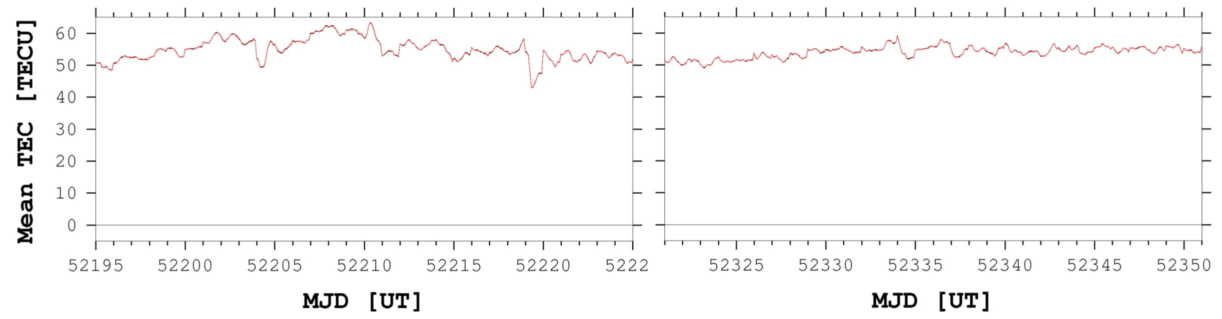

Fig. 3: Global mean total electron content in TECU extracted from the global ionosphere maps with two hours of sampling, produced by CODE, during the two time periods with remarkable ionospheric activity in 2001 (left panel) and 2002 (right panel).

The station network for this investigation (see Fig. 4) consists of the available sites of the IGS05 reference frame and some additional stations close to the equator, where the ionospheric effects are most significant, as well as some stations close to the poles to obtain a global coverage of the network.

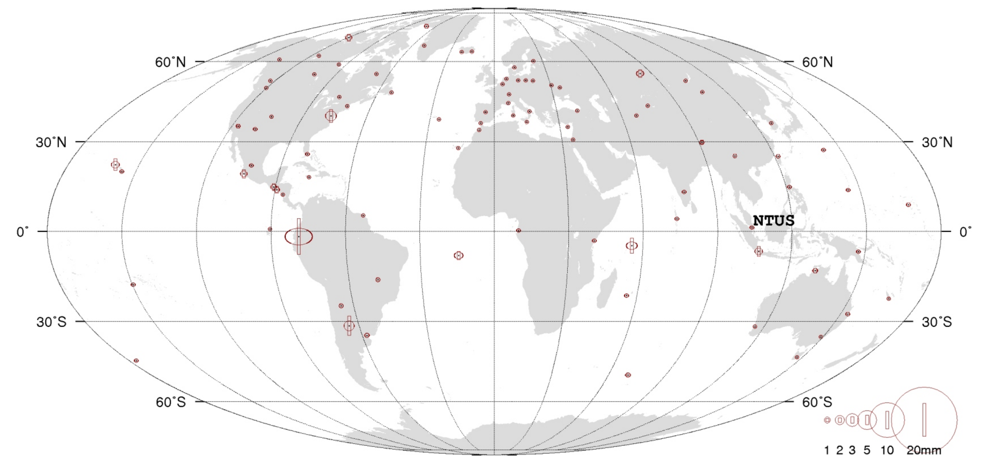

Fig. 4: Experimental station network with horizontal (ellipses) and vertical (bars) RMS-scaled symbols from the combined solution of the observation interval in 2001 and 2002 estimating also station velocities. Some bigger RMS values indicate weakly observed stations (one or two days of data only and singular velocities).
The IGS station NTUS is labeled because their ionosphere corrections are displayed in Figs. 1 and 2.

5 HOI scaling factors

The development version of the Bernese GPS Software does not only consider and apply the higher order ionosphere corrections to the observations but also assigns scaling parameters to each term. These scaling factors can be set-up globally (one for all) or station specific (one per station).

5.1 Globally stacked scaling factors

The progress of the daily and weekly globally stacked scaling factors for the second and third order ionosphere term are shown in Fig. 5.
The scaling factor of the second order term is in general better determined because its effect is more accentuated.

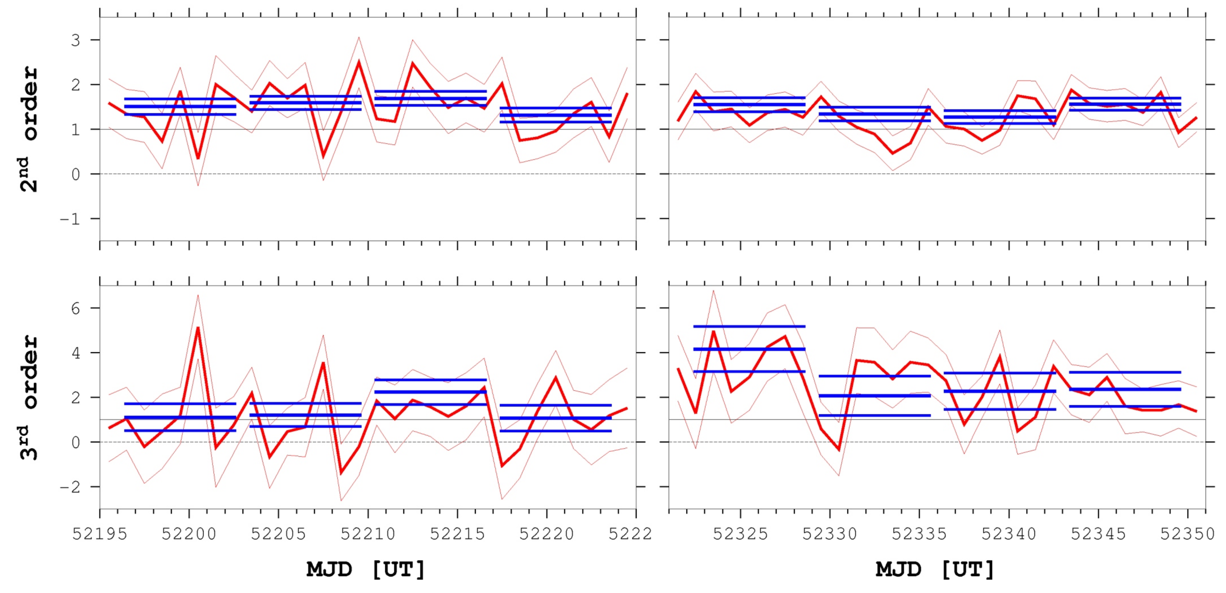

Fig. 5: Daily (red) and weekly (blue) global scaling factors within an interval of their weighted mean RMS. The left panels cover the time period in 2001 (GPS week 1136 to 1139); the right panels cover GPS week 1154 to 1157 in 2002; the top panels are the scale factors for the second-order ionosphere term; the bottom panels show the development of the third order term (changed scale!).

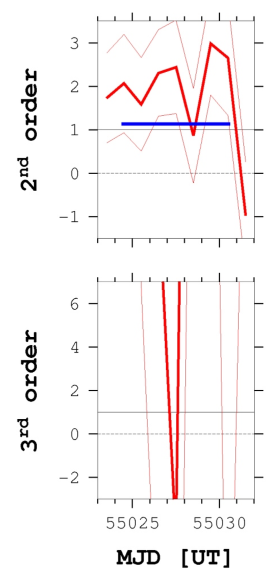

Fig. 6: The situation during a week in July 2009 (GPS week 1540) with low ionosphere activity differs remarkably. The daily scaling factors deviate much more for the second as well as for the third order term than during high ionospheric activity (Fig. 5). The weighted mean RMS of the weekly solution exceeds even the limits of the plot.

5.2 Station-wise, temporally stacked scaling factors

Setting up station-wise scaling factors for the higher-order ionosphere terms allows to analyze the behavior of single stations with respect to the ionosphere parameters.
The station-specific, temporally stacked HOI scaling factors for the combined solution of the two time periods in 2001 and 2002 are shown in Fig. 7. The scaling factors with their mean weighted RMS are plotted against the Z-coordinate.

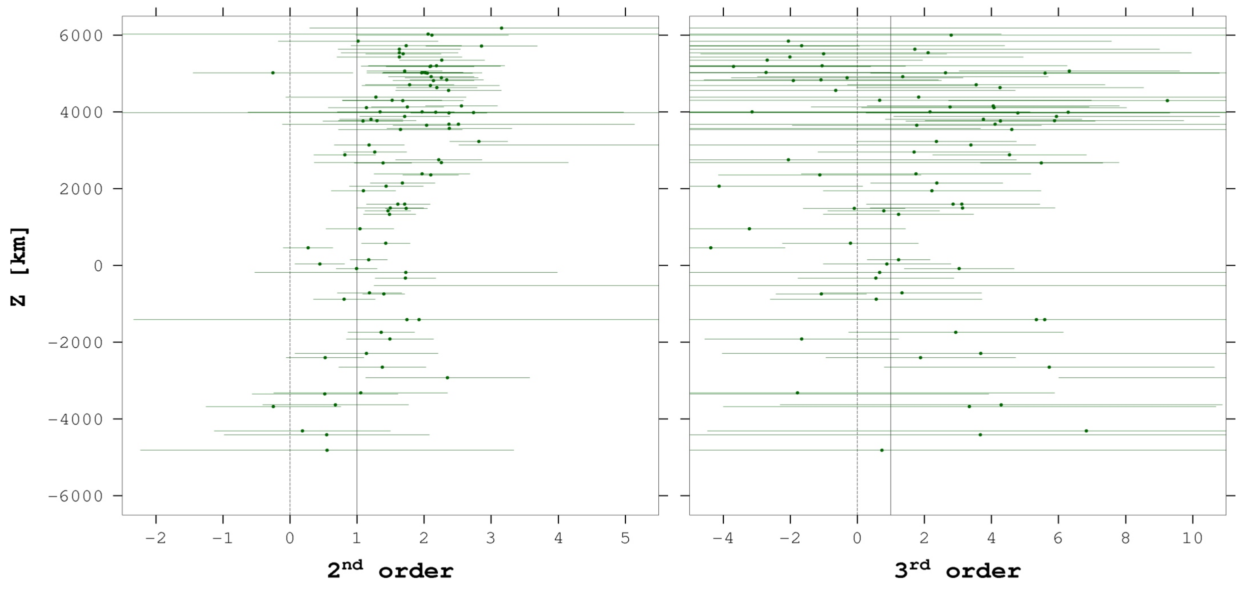

Fig. 7: Station-wise higher-order ionosphere scaling factors and their mean weighted RMS stacked over the two time intervals in 2001 and 2002 (two times four weeks). With this data sample some systematics can already be extracted: The scaling factors, and thus the higher-order ionosphere corrections, of stations close to the equator are better determined (close to one and small RMS) than mid-latitude stations if enough data is available.
For the next reprocessing efforts, the longer time series will give an even more realistic view on the station (receiver, antenna) specific ionosphere modeling.

6 Effect on coordinates (preliminary results)

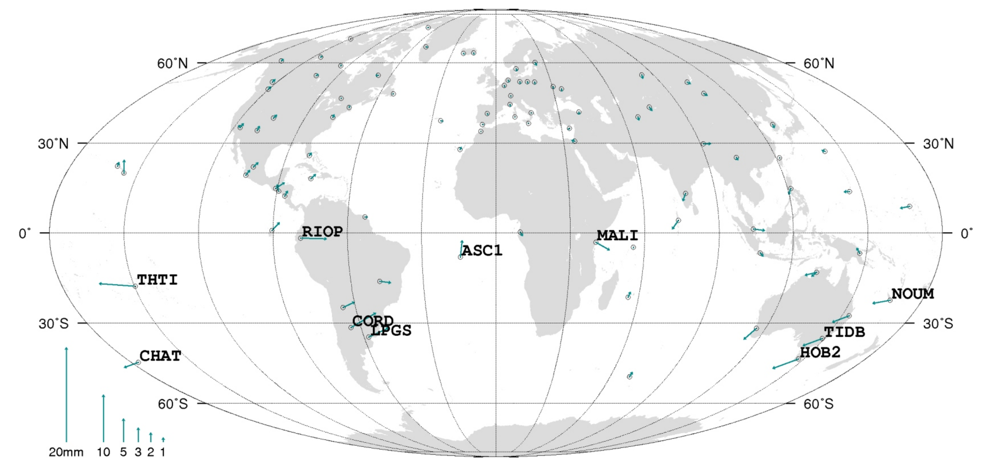

Fig. 8: The combined solution of the two month data from 2001 and 2002 (mean TEC of more than 50 TECU) applying higher-order ionosphere corrections is compared with the same solution without HOI terms by means of a 7 parameter Helmert transformation. None station on the northern hemisphere is critically affected but some stations between the equator and 45° South (including some IGS05 fiducial stations) reach differences of up to 5 mm. The ten stations with the biggest residuals are labeled.

7 Conclusions and Outlook

In time periods with high ionosphere activity, higher-order ionosphere terms should be considered for GNSS global analysis. In times with low TEC, the correction terms are not significant.
The presented implementation using dedicated scaling factor parameters allows to validate the higher-order ionosphere (HOI) model (considering two terms). Moreover, it is possible, among other things, to switch on and off each correction term individually. Finally, the HOI correction model was verified also for direct use of L1 and L2 (instead of LC) observations (commonly used for QIF ambiguity resolution).
In a further step, ray path bending will be considered as a third HOI correction term. The replacement of the currently used geomagnetic dipole field by the IGRF is another important model improvement planned.

References

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