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Higher-Order Ionosphere Modeling for CODE's Next Reprocessing Activities

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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 (BSW, see Dach et al., 2007) used at CODE was expanded with the ability to assign additional scaling parameters to the 2nd and 3rd order ionosphere 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.

BACKGROUND

In order to obtain second and third order ionosphere correction terms for L1, L2 and LC (ionosphere-free) phase observations, the frequency-dependent formulas from Fritsche et al. (2005) were added to the parameter estimation part of the most recent development version of the BSW. The algorithm is based on Bassiri et al. (1993) where the geomagnetic field is characterized by a co-centric tilted magnetic dipole. This model has been replaced by the 11th generation of the more realistic International Geomagnetic Reference Field (IGRF).

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.

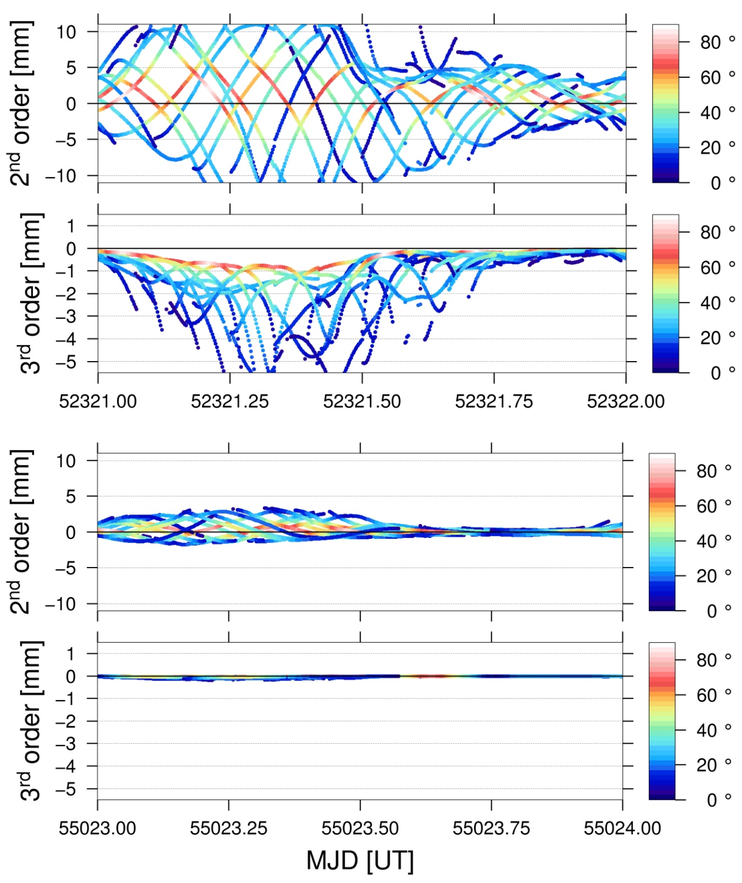

Fig. 1: 2nd and 3rd order HOI corrections in millimeters on LC with 30 seconds of sampling down to 3 degrees elevation at the IGS station NTUS (Singapore, 1.3N/103.7E/73.0m U, see also Fig. 2) on a day with high ionosphere activity, i.e., mean TEC of more than 50 TECU (top panels) and a day with minimal activity (bottom panels). The colors indicate the elevation angle of the observed GPS satellites.

Depending on station latitude, elevation angle and time of the day, the second order correction term of one observation can reach 1cm. 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 1mm in an absolute sense. During quiet ionosphere conditions the only noticeable influence up to 2mm comes from the second-order correction term at low elevation angles.

TEST PERIODS AND STATION NETWORK

Two times one month of data during periods of very high solar and ionosphere activity in 2001 and 2002 were analyzed to study the significance of the higher-order ionosphere terms and the usability of the scaling factors. One week in 2009 with very low activity (global mean TEC of less than 10 TECU) was processed to assess the differences.
The station network for this investigation consists of the available sites of the IGS05 reference frame and some additional stations close to the equator, where the ionosphere effects are most significant, plus available stations close to the poles to obtain a global coverage of the network.

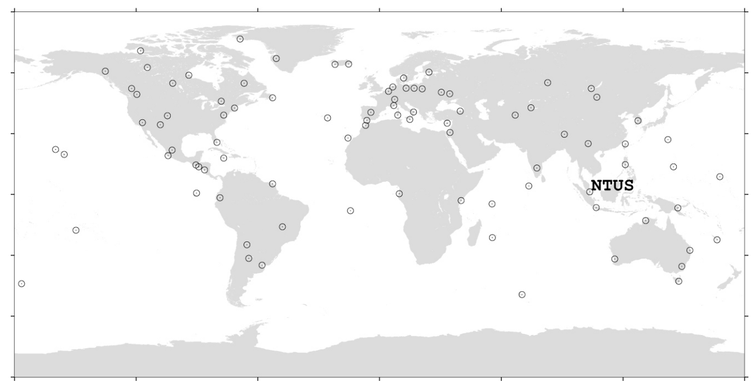

Fig. 2: Experimental station network. The IGS station NTUS is labeled in conjunction with Fig. 1.

HOI SCALING FACTORS

The development version of the BSW 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 stations) or station-wise.

Globally stacked scaling factors

The progress of the daily and weekly globally stacked scaling factors for the second and third order ionosphere terms are shown in **Fig. 3**. The scaling factor of the second order term is in general better determined because its effect is more accentuated.

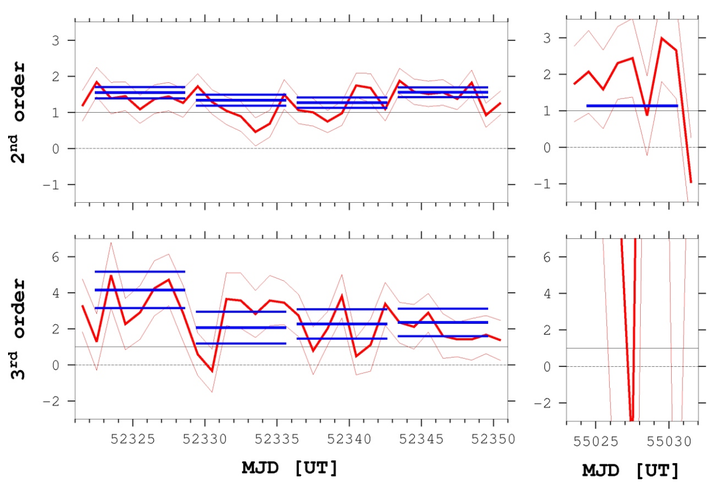

Fig. 3: Daily (red) and weekly (blue) global scaling factors for the second and third order ionosphere terms within an interval of their weighted mean RMS covering four weeks in 2002 (left panels). The situation during one week in July 2009 with low ionosphere activity (right panels) differs remarkably. The daily scaling factors deviate much more for the second as well as for the third order terms than during high ionosphere activity. The weighted mean RMS of the weekly solution exceeds the limits of the plots.

Station-wise, temporally stacked scaling factors

Setting up station-wise scaling factors for the higher-order ionosphere terms allows analyzing 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. 4**. The scaling factors with their mean weighted RMS are plotted against the Z-coordinate.

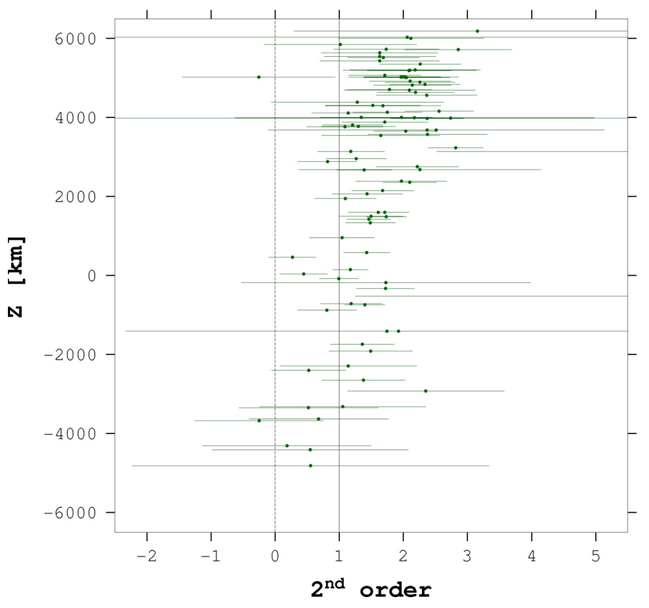

Fig. 4: Station-wise higher-order ionosphere scaling factors and their mean weighted RMS stacked over the two time intervals in 2001 and 2002 (two times four weeks). With this data sample some systematic behavior can already be extracted: The scaling factors, and thus the higher-order ionosphere corrections, of stations close to the equator are better determined (close to unity 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.

EFFECT ON COORDINATES

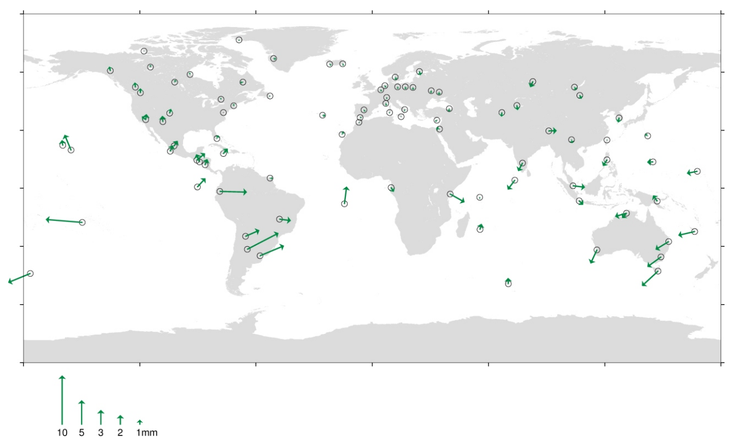

Fig. 5: The combined solution of the two months of data from 2001 and 2002 (mean TEC of more than 50 TECU) applying higher-order ionosphere corrections is compared with the same solution without HOI terms by means of a 7 parameter Helmert transformation. None station on the northern hemisphere is critically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

CONCLUSIONS AND OUTLOOK

In time periods with high ionosphere activity, higher-order ionosphere term should be considered for global GNSS analysis. In times with low TEC, the correction terms are not significant.
The presented implementation using dedicated scaling factor parameters allows validating 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.

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