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Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center · IonSAT · UPC · TUM · gmv INNOVATING SOLUTIONS

Recent activities of IAG working group "Ionosphere Prediction"

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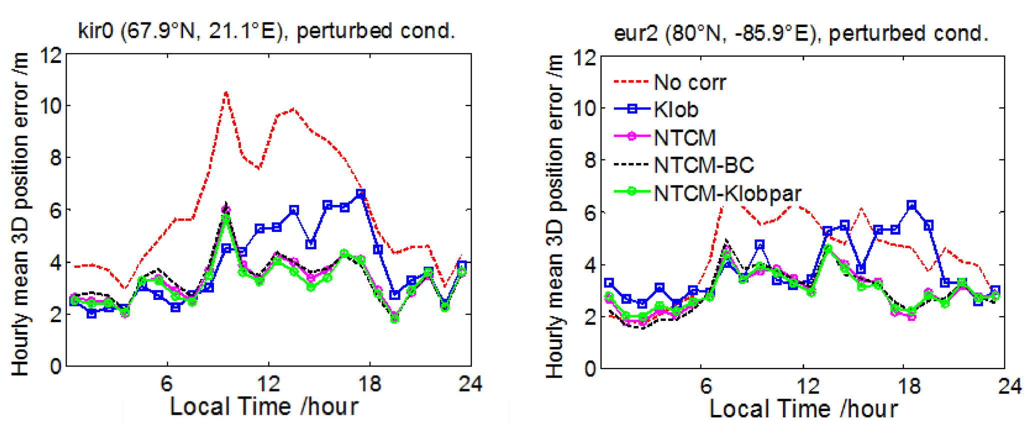
Introduction

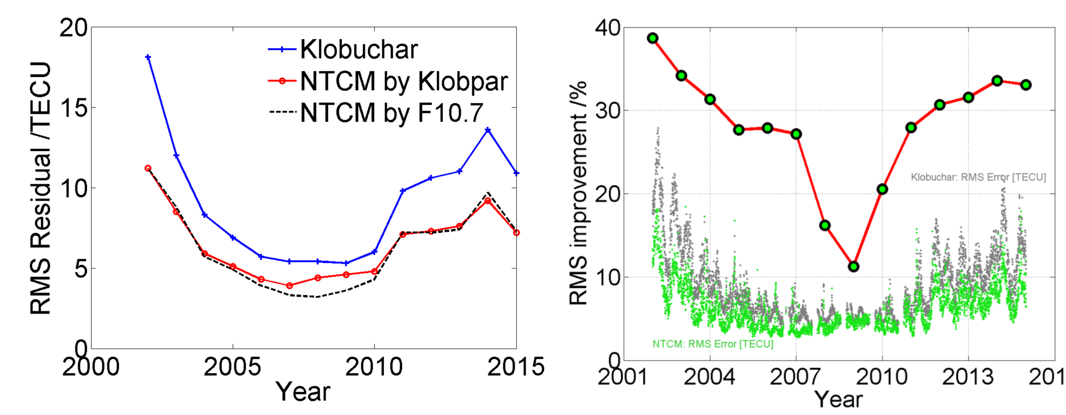
Ionospheric disturbances pose, for instance, an increasing risk on economy, national security, satellite and airline operations, communications networks and the navigation systems. Constructing forecasted ionospheric products with a reliable accuracy is still an ongoing challenge. In this sense, a Working Group (WG) with the title "Ionosphere Prediction" within the International Association of Geodesy (IAG) under Sub-Commission 4.3 "Atmosphere Remote Sensing" of the Commission 4 "Positioning and Applications" has been created and is actively working since 2015 to encourage scientific collaborations on developing models and discussing challenges of the ionosphere prediction problem. Different centers contribute to the WG such as the German Aerospace Center (DLR), Universitat Politècnica de Catalunya (UPC), Technical University of Munich (TUM) and GMV. One of the main focus of the WG is to evaluate different ionosphere prediction approaches and products which are highly depending on solar and geomagnetic conditions as well as on data from different measurement techniques (e.g. GNSS) with varying spatial-temporal resolution, sensitivity and latency. In this contribution, the recent progress of the WG on ionosphere prediction studies including individual and cooperated activities will be presented.

DLR

A family of Neustrelitz Total Electron Content (TEC) models called NTCM has been developed for last two decades at the DLR Institute of Communications and Navigation. Recently the global NTCM model has been modified so that it can be driven by the GPS Klobuchar coefficients instead of the solar flux index F10.7. The model can be used as complementary to the GPS Klobuchar model for improving ionospheric corrections up to 40% especially during high solar activity time. Like the GPS Klobuchar model the NTCM predicts ionospheric corrections 24 hours ahead.



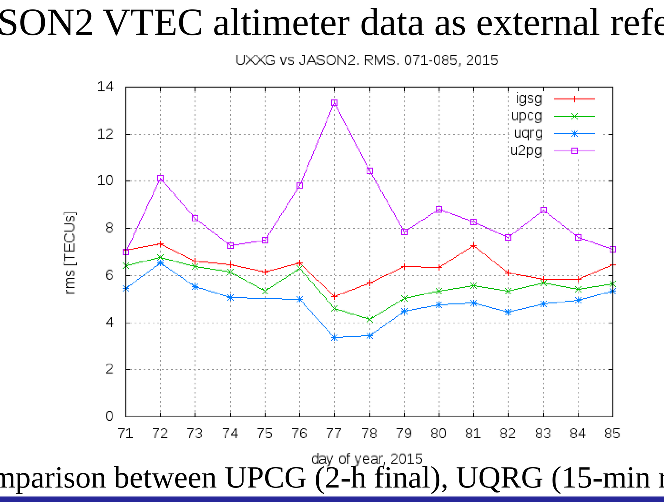
While estimating positioning accuracy we found an improvement in the order of 0.5 m and 1.0 m for unperturbed low solar activity and perturbed medium solar activity conditions, respectively [Hoque et al. 2018].

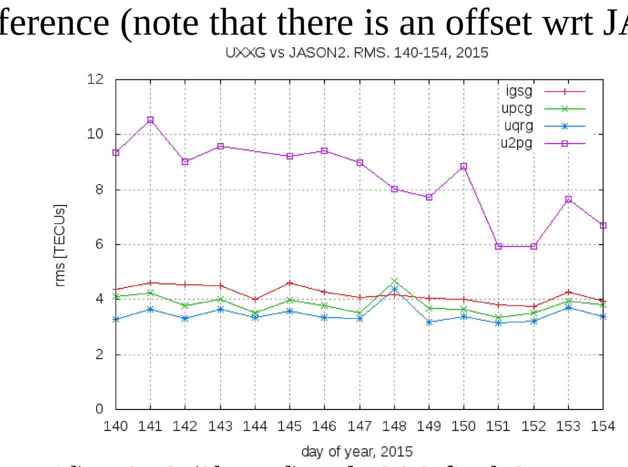


Left panel shows yearly average of RMS residual and right panel gives percentage improvement whereas daily RMS residuals are shown in the background. The RMS TEC errors for NTCM are up to about 40% and 10% less than the Klobuchar model during high and low solar activity period, respectively [Hoque et al. 2017].

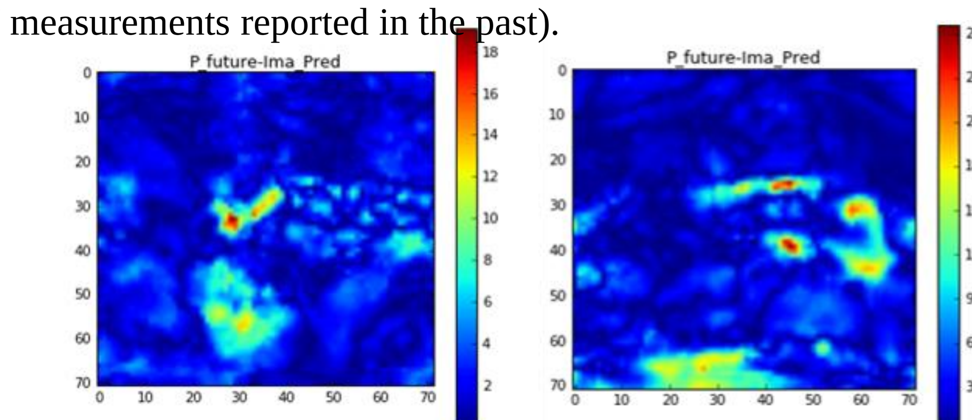
UPC-IonSAT

Former UPC forecast model was based on applying linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain. New approaches are being implemented at the moment to improve both short- and mid-term forecasts. One of these is based on forecasting by means of a linear combination of maps in the recent past together with their corresponding Tangent Spaces, associated to the possible small deformations of TEC changes in space, i.e. rotations, diagonal stretching, vertical/horizontal translations, thinning and thickening, etc. In addition, this method has already been executed in operational conditions based on UPC real-time GIMs (labelled URTG). Preliminary results obtained for the former DCT-based GIMs for both the quiet and perturbed periods in consideration (i.e. 24 to 48h ahead), showed there was potential margin of improvement. These results were compared to JASON2 VTEC altimeter data as external reference (note that there is an offset wrt JASON measurements reported in the past).





Comparison between UPCG (2-h final), UQRG (15-min rapid), U2PG (2h pred) and IGSG final GIMs wrt JASON2



Examples showing the errors are concentrated in the borders of the highest-ionized regions

DGFI-TUM

The DGFI-TUM approach for VTEC modelling is based on a series expansion in tensor products of polynomial B-splines (BS) $N_{k_1}^{J_1}(\varphi)$ in latitude φ and trigonometric B-splines $T_{k_2}^{J_2}(\lambda)$ in longitude λ; see Eq. (1) and Schmidt et al. (2015). For the forecasting of the VTEC values our approach is based on the extraction of important signal components by using a Fourier series representation of the BS coefficients $d_{k_1,k_2}^{J_1,J_2}$ estimated by Kalman filtering (Erdogan et al. 2017). The approach is extended by an ARMA model to take into account the stochastic part. The unknown coefficients a_0, a_i, b_i of the Fourier series and the ARMA model parameters (2) for each BS coefficient are computed at the end of every hour Using the last 5 days data sets. In the current version the Fourier series and the ARMA model are extrapolated to provide the predicted VTEC values.

VTEC representations

$$VTEC(\lambda,\varphi,t) = \sum_{k_1=0}^{K_{J_1-1}} \sum_{k_2=0}^{K_{J_2-1}} d_{k_1,k_2}^{J_1,J_2}(t)\, N_{k_1}^{J_1}(\varphi)\, T_{k_2}^{J_2}(\lambda) \qquad (1)$$

Forecast model

$$d_{k_1,k_2}^{J_1,J_2}(t) = a_0 + \sum_{i=1}^{n} (a_i \cos(\omega_i t) + b_i \cos(\omega_i t)) + s_{k_1,k_2} (2)$$

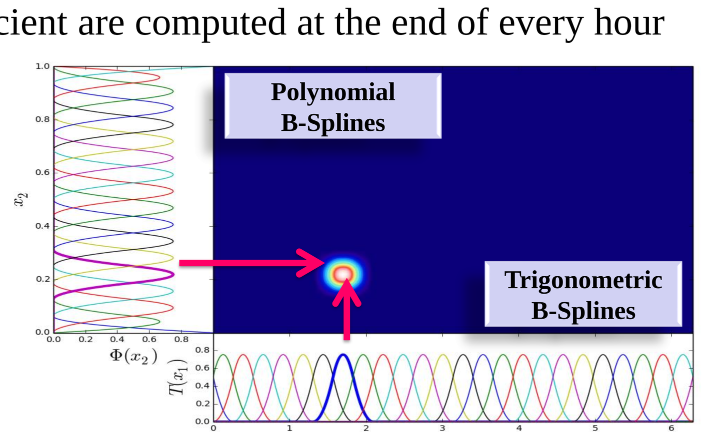


Figure 1: Basis formation with polynomial B-splines of resolution level $J_1 = 4$ and trigonometric B-splines of resolution level $J_2 = 3$..

Forecast model internal performance

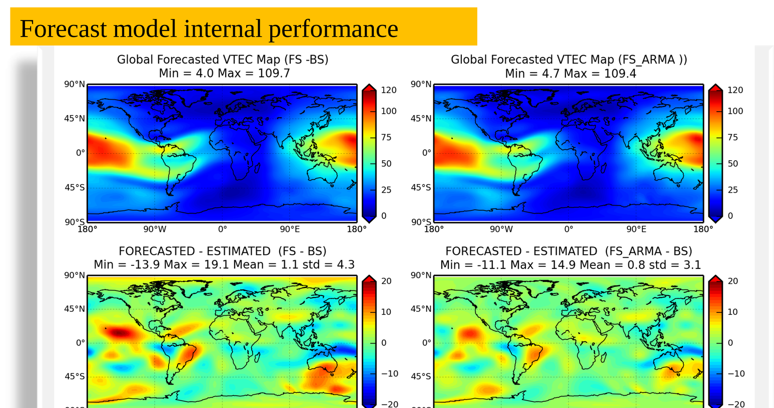


Figure 2: Two hour ahead performance of the forecast models; left: using Fourier series approach only; right: Fourier series and ARMA model approach.

GMV

The forecast algorithm developed by GMV is based on the ionospheric delay estimation from previous epochs using GNSS data and the main dependence of ionospheric delays on solar and magnetic conditions. Since the ionospheric behavior is highly dependent on the region of the Earth, different region-based algorithmic modifications have been implemented in GMV´s magicSBAS ionospheric algorithms to be able to estimate and forecast ionospheric delays worldwide. Further details on the algorithm and on the analyses performed so far can be found in (Cueto et al. 2011) and (Fidalgo et al. 2015).

Ionospheric Delay Forecast Algorithm´s performances have been evaluated by means of several representative scenarios covering different latitudinal regions, space weather conditions and forecasting periods (Europe (18/4/15); Latin American and Caribbean region (18/4/15); Europe & Africa (23/5/14)) have been selected (medium solar activity conditions).

As can be seen in the figures included below, it has been proven that the ionospheric delay forecasting tool is able to provide remarkable good forecasting performances for middle latitudes, with RMS differences between estimated and forecast vertical ionospheric delays below 0.5 m for most of the IGP´s and a forecasting period of 0.5 hours in the analyzed European scenario.

In what respect equatorial regions, the results obtained are quite encouraging, showing GIVD RMS differences below 1.2 m for 0.5 and 1 hour forecasting periods and for most of the IGPs in the analyzed Latin American and Africa scenarios.

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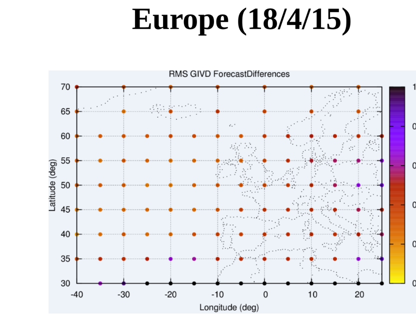
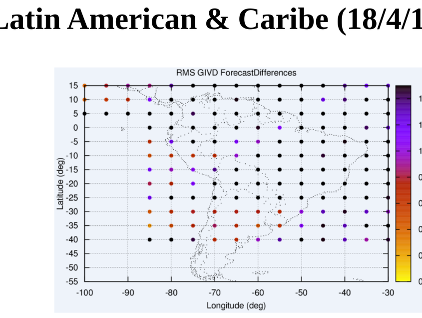
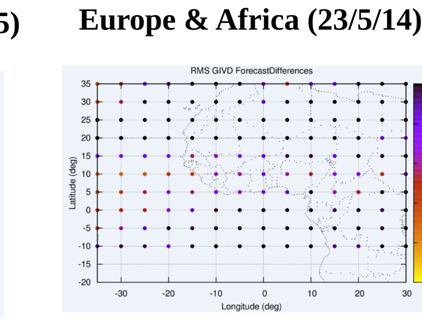
Europe (18/4/15) **Latin American & Caribe (18/4/15)** **Europe & Africa (23/5/14)**







Comparison among different approaches

Center	TEC	TEC prediction approach	TEC prediction performance
DLR	NTCM	The presented approach takes benefit of GPS broadcast Klobuchar coefficients. Like the GPS Klobuchar model the NTCM predicts ionospheric corrections 24 hours ahead.	Global , the RMS TEC errors for NTCM are up to about 40% and 10% less than Klobuchar model during high and low solar activity period, respectively.
UPC	TOMION	linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain	World wide, 24 hour to 48 hour forecast, RMS error wrt to JASON2 altimeter data below 6 and 8 TECUs during quiet and perturbed period, respectively.
DGFI-TUM	B-splines	Fourier series and ARMA model analysis of the B-spline coefficients using the last 5 days data sets	RMS deviations of the daily forecasted maps with respect to IGS final products exhibit around 7 and 5 TECU for the perturbed and the quiet periods.
GMV		ionospheric delay estimated from previous epochs using GNSS data and the main dependence of ionospheric delays on solar and magnetic conditions	Over Europe, 0.5 hour forecast, RMS error below 0.5 meter most cases Over Latin American & Africa, 0.5 & 1hour forecast, RMS error below 1.2 m

Summary & Outlook

Our presented work enables the possibility to compare total electron content (TEC) prediction approaches/results from different centers such as German Aerospace Center (DLR), Universitat Politècnica de Catalunya (UPC), Technische Universität München (TUM) and GMV. Different TEC prediction approaches outlined here will certainly help to learn about forecasting ionospheric ionization. More intensive validation studies using independent TEC data are planned.

Acknowledgements

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