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Ionosphere monitoring and forecast activities within the IAG working group “Ionosphere Prediction”

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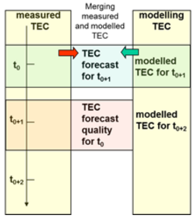
Introduction

Ionospheric disturbances can affect technologies in space and on Earth disrupting satellite and airline operations, communications networks, navigation systems. As the world becomes ever more dependent on these technologies, ionospheric disturbances as part of space weather pose an increasing risk to the economic vitality and national security. Therefore, having the knowledge of ionospheric state in advance during space weather events is becoming more and more important. To promote scientific cooperation we recently formed a Working Group (WG) called “Ionosphere Predictions” within the International Association of Geodesy (IAG) under Sub-Commission 4.3 “Atmosphere Remote Sensing” of the Commission 4 “Positioning and Applications”. The general objective of the WG is to promote the development of ionosphere prediction algorithm/models describing the electron density and/or the total electron content (TEC). Our presented work enables the possibility to compare total electron content (TEC) prediction approaches/results from different centers contributing to this WG such as German Aerospace Center (DLR), Universitat Politècnica de Catalunya (UPC), Technische Universität München (TUM) and GMV.

DLR SWACI

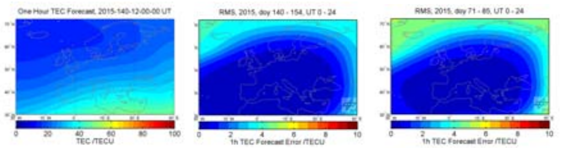
DLR developed a model-assisted TEC forecast algorithm taking benefit from actual trends of the TEC behavior at each grid point. Since during perturbations, characterized by large TEC fluctuations or ionization fronts, this approach may not work properly, the trend information is merged with the current background model which provides a stable climatological TEC behavior. The data reconstructed at grid point (k, l) at epoch i, are merged in the following way (Jakowski et al. 2011a, b):

$$TEC^{fci}(k,l) = (1-\eta)TEC^{fci}_{NTCM-XXj}(k,l) + \eta\left(\Delta TEC^{i}_{j}(k,l)/\Delta t\right)\cdot T^{fc}$$



with $\Delta t = t^{i} - t^{i-1}$, where $TEC^{fci}(k,l)$ is the forecasted TEC at grid point (k,l) for T^{fc} hours ahead, the parameter η ($0 \leq \eta \leq 1$) is a weight factor controlling weight of model and actual trend and t^{i} is the time at measurement epoch i.

The figures show an example one hour TEC forecast map and RMS errors ($TEC_{SWACI\text{-}Forecast} - TEC_{SWACI\text{-}Realtime}$) during selected quiet period (20 May – 3 June 2015) and perturbed period (12-26 March 2015).



The presented solution is a first step to regularly provide forecasted TEC services via SWACI/IMPC by DLR.

UPC-IonSAT

UPC forecast model is based on applying linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain. Performance tests are being conducted at the moment in order to improve UPC predicted products for 1- and 2-day ahead (labelled U1PG and U2PG, respectively). In addition, UPC is working to enable short-term predictions based on UPC real-time GIMs (labelled URTG) and implementing an improved prediction approach. Preliminary results are obtained for U2PG GIMs for both the quiet and perturbed periods in consideration (i.e. 24 to 48h ahead), showing there is potential margin of improvement. These results are compared to JASON2 VTEC altimeter data as external reference (note that there is an offset wrt JASON measurements reported in the past).

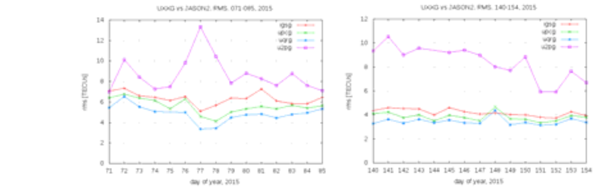
$$C_{p,q} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} V_{m,n}\cos\frac{\pi(2m+1)p}{2M}\cos\frac{\pi(2n+1)q}{2N}$$

$$0 \leq p \leq P-1,\ 0 \leq q \leq Q-p$$

DCT coefficients of a given map represented by the VTEC values Vm,n

$$\widehat{C_{p,q}}[t+\Delta t] = \omega_{p,q}[0] + \sum_{u=1}^{U}\omega_{p,q}[u]\cdot C_{p,q}[t-u+1]$$

Predicted value is computed by performing a dot product between the regression coefficients $w_{p,q}$ and the sequence of input DCT coefficients.



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

DGFI-TUM

The DGFI-TUM approach for VTEC modelling is based on series expansions in tensor products of polynomial B-splines $N^{J_1}_{k_1}(\varphi)$ in latitude φ and trigonometric B-splines $T^{J_2}_{k_2}(\lambda)$ in longitude λ; see Eq. (1). For the prediction of the VTEC maps we apply a Fourier series analysis of the B-spline (BS) coefficients $d^{J_1,J_2}_{k_1,k_2}$ estimated by Kalman filtering. The unknown coefficients C_0, C_i, S_i of the Fourier series (2) for each B-spline coefficient are computed at the end of every hour using the last 5 days data sets.

In the current version the Fourier series are extrapolated to provide the predicted VTEC values.

VTEC representations

$$VTEC(\lambda,\varphi,t) = \sum_{k_1=0}^{K_{J_1}-1}\sum_{k_2=0}^{K_{J_2}-1} d^{J_1,J_2}_{k_1,k_2}(t)\, N^{J_1}_{k_1}(\varphi)\, T^{J_2}_{k_2}(\lambda) \qquad (1)$$

Deterministic forecast model

$$d^{J_1,J_2}_{k_1,k_2}(t) = C_0 + \sum_{i=1}^{n}\left(C_i\cos(\omega_i t) + S_i\cos(\omega_i t)\right) \qquad (2)$$

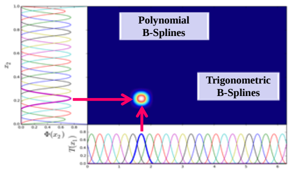


Figure 1: Basis formation with polynomial B-splines of resolution level $J_1 = 4$ and trigonometric B-splines of resolution level $J_2 = 3$..

Preliminary Forecast results

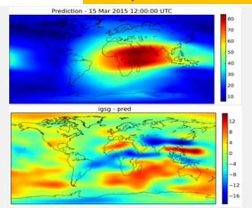


Figure 2: Forecasted VTEC map 1 hour ahead (left) .and the differences with respect to the IGS VTEC map (left).

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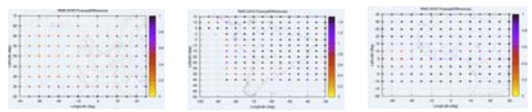
Europe (18/4/15) | Latin American & Caribe (18/4/15) | Europe & Africa (23/5/14)



Comparison among different approaches

Center	TEC	TEC prediction approach	TEC prediction performance
DLR	NTCM	model-assisted (27-day median) TEC forecast algorithm taking benefit from actual trends of the TEC behavior at each grid point	over Europe,1 hour forecast, RMS error is below 4 and 5 TECU during quiet (20 May – 3 Jun 2015) and perturbed period (12-26 Mar 2015), respectively
UPC	TOMION	linear regression to a temporal window of TEC maps in the Discrete Cosine Transform (DCT) domain	global, up to 48-hour forecast, RMS discrepancy of U2PG wrt IGSG below 6 and 8 TECU during quiet & perturbed period, resp., considering JASON2 data as reference
DGFI-TUM	B-splines	Fourier series analysis of the B-spline coefficients using the last 5 days data sets	global, RMS deviations of the forecasted maps with respect to IGS final products exhibit around 5 and 7 TECU for the quiet and perturbed periods, respectively
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 3 TECU and over Latin American & Africa, 0.5 & 1 hour forecast, RMS error below 8 TECU

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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