Combination of Space Geodetic Observations in a Kalman Filter for an Estimation of the Global Vertical Total Electron Content

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Introduction

Most of the up-to-date global geodetic ionosphere VTEC models …

... are limited by the use of globally defined base functions that require a homogeneous data distribution, namely spherical harmonics,

... are computed with a uniform resolution,

... are driven by GNSS data and suffer from large data gaps, e.g. over the oceans,

Distribution of ionospheric pierce points (IPP) based on GPS observation of November 11, 2014, 7:00 UT - 8:00 UT.
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... do not consider data from other space-geodetic/geoscientific observation techniques,

... allow only for the computation of ionospheric products with a low temporal resolution (e.g. 1h or even 2h),

... provide historical or instant information but no predictions,

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DGFI-TUM

localising base functions

multi-scale approach

data adaptive techniques

data combination techniques

Kalman filter processing

sophisticated dynamic model

e.g. Sun observations
Improved Concepts

• Our approach aims on the development of an adaptive global VTEC model (including regional densifications) to generate
  – low latency global VTEC maps as well as
  – predictions for several days into the future.

• The model parameters will be computed from a combination of various space geodetic (geoscientific) observation techniques.

• The parametrization will be set up by B-spline functions adapted to the distribution of the input observations.

• The sequential data processing model is driven by a Kalman filter which allows for temporally high resolution outputs.

• To consider solar phenomena such as CMEs and flares Sun observations are incorporated.
Observation Techniques: Overview

CMEs, Flares,…

Jason-2

Formosat-3/COSMIC

GLONASS

GPS

Radio occultation

VTEC

STEC

STEC

STEC

STEC

STEC
Observation Techniques: GNSS Preprocessing

- Distribution of **ionospheric pierce points** (IPP) based on the **hourly observation** batch of February 11, 2016, 12:00 UT - 13:00 UT.

- The figures show exemplarily the **spatial resolution** of GPS and GLONASS during the time interval of 1 hour.
Observation Techniques: Altimetry Preprocessing

- **Jason-2 hourly batch** as observed on January 3, 2014 between 21:00 and 22:00 UT

- Left: **Original VTEC** (red), **median filtered** (blue),

- **Measurements** over water surfaces along satellite track
Observation Techniques: DORIS Preprocessing

- DORIS biased STEC observations through a pass of the satellite observed on January 1, 2015.
Observation Techniques: Radio Occultation (RO)

- Dual-frequency signal tracking of occultation events (signal elevation in LEO < 0°)
- Retrieval of electron density profiles below the LEO orbit

F-3/C orbit altitude (≈ 800 km)

Global distribution of electron density profiles observed by the six F-3/C satellites on 2015/01/01
Observation Techniques: Overall Data Distribution

- Figure shows the **data distribution** from different space geodetic techniques on February 12, 2016, between 11:30 UT and 12:30 UT

- Terrestrial **GPS and GLONASS** observations provide a **high-resolution coverage** of continental regions.

- Large **data gaps** still exist especially over the oceans.
Observation Techniques: Process Flowchart

- Parallelized processes
- Python based
- C++

- Altimetry Preprocessing
- GNSS Preprocessing
- DORIS Preprocessing
- LEO Preprocessing

Database (HDF)
Observation Techniques: Process Flowchart

Parallelized processes  
Python based  
C++

Altimetry Preprocessing  
GNSS Preprocessing  
DORIS Preprocessing  
LEO Preprocessing

Database (HDF)

Modeling

IONEX

Sun observations Preprocessing

analytical  
stochastic
VTEC Representation: Uniform B-splines (UBS)

- VTEC is parametrized in tensor products of trigonometric B-spline functions $T_{J_2,k_2}^2$ for longitude $\lambda$ and polynomial B-spline functions $N_{J_1,k_1}^2$ for latitude $\varphi$

\[
VTEC(\lambda, \varphi) = \sum_{k_1=0}^{K_1-1} \sum_{k_2=0}^{K_2-1} d_{k_1,k_2}^{J_1,J_2} N_{J_1,k_1}^2(\varphi) T_{J_2,k_2}^2(\lambda)
\]

Polynomial B-spline functions $N_{3,k_1}^2$

\[
J_1 = 3, K_3 = 10, k_1 = 0, 1, \ldots, 9
\]

Trigonometric B-spline functions $T_{2,k_2}^2$

\[
J_2 = 2, K_2 = 14, k_2 = 0, 1, \ldots, 13
\]
VTEC Representation: UBS Model Resolution

- Tensor products of polynomial B-spline functions $N_{J_1,k_1}^2$ and trigonometric B-spline functions $T_{J_2,k_2}^2(\lambda)$
  - Left figure: levels $J_1 = 4, J_2 = 2$
  - Right figure: levels $J_1 = 5, J_2 = 3$

- The higher the chosen level values, the finer the structures could be modeled.
Sequential Processing: Measurement Model

Overall state vector of the unknown parameters

\[
\begin{align*}
\gamma_{GPS} + e_{GPS} &= m(z) \cdot VTEC + b_{r, GPS} + b_{s, GPS} \\
\gamma_{GLO} + e_{GLO} &= m(z) \cdot VTEC + b_{r, GLO} + b_{s, GLO} \\
\gamma_{ALT} + e_{ALT} &= VTEC + b_{ALT} \\
\gamma_{IRO} + e_{IRO} &= VTEC + b_{IRO} \\
\gamma_{DOR} + e_{DOR} &= m(z) \cdot VTEC + b_{DOR}
\end{align*}
\]

\[
VTEC(\lambda, \varphi) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} d_{k_1, k_2} J_{J_1, k_1}(\varphi) T_{J_2, k_2}^{0}(\lambda)
\]

\[
\beta = \begin{bmatrix}
\begin{array}{c}
d \\
b_{GPS} \\
b_{GLO} \\
b_{ALT} \\
b_{IRO} \\
b_{DOR}
\end{array}
\end{bmatrix}
\]
A Kalman filter is used to estimate the unknown parameters sequentially.

The state vector of the unknown parameters is updated every minute with the new observations.

Currently, the random walk model is used for time variation of the filter (prediction or time update).
Validation during an Ionospheric Storm: Comparisons to IGS and ACs Final Products

A case study for St. Patrick storm (DOY 76, 2015)
Validation during an Ionospheric Storm: Comparisons to Jason-2 Altimetry data

A case study for St. Patrick storm

- Altimetry sensor on Jason-2 allows acquisition of direct VTEC measurements which can be used for quality assessments of the VTEC products.

\[ d = VTEC_{AC} - VTEC_{JASON-2} \]

Median Filtered VTEC time series from Jason-2 satellite

Interpolated VTEC data from IONEX files of different analysis centres (ACs)

Differences between ACs VTECs and Altimetry VTEC data
Validation during an Ionospheric Storm: Comparisons to Jason-2 Altimetry data

A case study for St. Patrick storm

Summary of statistics for the daily differences between 14 March 2015 (DOY 73) and 17 March 2015 (DOY 76)

\[ d = VTEC_{AC} - VTEC_{JASON-2} \]
Validation during an Ionospheric Storm: Self Consistency Analysis

- Self consistency analysis is based on a comparison of STEC values computed from GPS geometry free phase measurements $L_c$ along a continuous arc and STEC values computed from VTEC products (maps).

\[ L_c = L_1 - L_2 = STEC + b \]

- Computation of the differences

\[ d = [L_c(t_k) - L_c(t_{ref})] - [STEC_p(t_k) - STEC_p(t_{ref})] \]

- Differential STEC computed from measurements

- Differential STEC computed from VTEC products ($p$)
Validation during an Ionospheric Storm: Self Consistency Analysis

### Mean RMS

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Summary

- One of the key points of our approach is to compute global VTEC maps with
  - **low latency** and
  - **high accuracy**.
- Therefore, modeling approaches which require
  - **post-processed products**
  are not used.
- Considering the **hourly GNSS observations** with an
  - increased number and an
  - improved distribution
  of observation sites, **near-real time products** are an **alternative** to the **traditional VTEC products**.
- **Conclusion**: VTEC products in near real time using a **sequential** (e.g. Kalman) filter will play an important role in the near future.