The impact of low-latency DORIS data on near real-time VTEC modeling

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Motivation

- Ionospheric modeling is important for various applications, e.g. correcting space-based microwave observations; space weather;
- Today, most models are computed based on GNSS measurements; e.g. IGS GIM
- Other space-based geodetic techniques also provides valuable data sets, e.g. DORIS.
- DORIS may help to improve the data coverage and to fill data gaps.

Problem: DORIS is only usable for post-processed products, since today, no NRT data sets are available (current latency = around 3 days).

Aim of this presentation:
- investigate the impact of DORIS for NRT VTEC models by means of simulations
Introduction

- **Electron density:**
  \[ N_e(\lambda, \varphi, h, t) \]

- **Slant total electron content (STEC):**
  \[ STEC(t) = \int_{R}^{S} N_e(\lambda, \varphi, h, t) ds \]
  determinable by GNSS and DORIS geometry-free observations

- **Vertical total electron content (VTEC):**
  \[ VTEC(IPP(t)) = \int_{H} N_e(\lambda, \varphi, h, t) dh \]
  \[ = MF(z) \cdot STEC(t) \]

IPP: Ionospheric pierce point
Observation Techniques: Overview

CMEs, Flares,…

Jason-2/3

Saral

HY-2A

Formosat-3/COSMIC

GLONASS

GPS

STEC

VTEC

Radio occultation

STEC

STEC

STEC

STEC
Observation distribution

- The figure shows the **data distribution** of the different space geodetic observation techniques on July 23, 2016:

![Observation distribution map]

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

- The additional techniques, i.e. DORIS, satellite altimetry and radio occultation **cannot repair** the problem of **data gaps**, but **reduce it**.
Data extracted from **Jason-2, Jason-3, Saral, HY-2A** are used for ionosphere modelling.

In near future, **Cryosat-2** and **Sentinel** missions are planned to be incorporated into the modelling approach.
DORIS Ionsopheric Observable: Example Saral

- DORIS biased STEC observations (shifted w.r.t. first observation) through a pass of the **Saral satellite** observed on August 23, 2016 between at 13:00:01 and 13:07:21
Extracting Ionosphere Data from DORIS Observations

Carrier-phase measurement

\[ \lambda \Phi = \rho^r_t + c(\Delta t^r - \Delta t_t) + \Delta_{Tropo} - \Delta_{Iono} + C P B + D + \epsilon_\Phi \]

Geometric distance
Clock errors
Tropospheric delay
Ionospheric delay
Carrier phase bias
Phase Centre Offset

Linear combination of carrier-phase measurements for two different frequency

\[ L_4 = \lambda_1 \Phi_1 - \lambda_2 \Phi_2 = \Delta_{Iono,L_4} + C P B_4 + \Delta D + \epsilon_\Phi \]

- Ionosphere data
- Carrier-phase bias
- Geometric Correction

- Geometric corrections are determined in the data pre-processing step whereas carrier phase biases are estimated by a Kalman filter.
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 $\varphi$

$$VTEC(\lambda, \varphi) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} d_{k_1,k_2}^{J_1,J_2} N_{J_1,k_1}^2(\varphi) T_{J_2,k_2}^2(\lambda)$$

Polynomial B-spline functions $N_{J_1,k_1}^2$

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

Trigonometric B-spline functions $T_{J_2,k_2}^2$

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

UBS; Sun-fixed coordinate system
• Level $J_1 = 3$ in longitude
• Level $J_2 = 4$ in latitude

- Base functions are only different from zero in a local environment (compact support).
- The compact support can allow:
  - modification of present data and
  - incorporation of new measurements without causing global effect
- Data gaps can be handled appropriately.
- The approach can be applied for global, regional and combined modelling,
- The approach can be used in an Earth- or Sun-fixed geographical or geomagnetic coordinate system.
A **Kalman filter** is used to estimate the unknown parameters *sequentially*.

The **state vector** of the unknown parameters is *updated at every 10 minutes* with the new observations.

Currently, a **random walk** model is used to model time variations of the filter (prediction or time update).
• … to combine space geodetic data acquired with different latencies without re-processing of all data set

• … to propagate model improvements obtained from latent data set to the (near)real-time

• … to use data as soon as possible

✔ In this study, only GNSS and DORIS are considered.
✔ GNSS and altimetry combined VTEC solutions are just used for validation
Multi-filter approach:

**GNSS only filter**

- $t_i - 4h$
- $t_i - 3h$
- $t_i - 2h$
- $t_i - 1h$
- $t_i$

**GNSS + DORIS filter with simulated latency of 3 hour (similar to altimetry) and 2 days**

- $t_i - 2\,\text{days}$
- $t_i - 4h$
- $t_i - 3h$
- $t_i - 2h$
- $t_i - 1h$
- $t_i$

**DORIS filter with latency (3 hours)**

- $t_i - 2\,\text{days}$
- $t_i - 4h$
- $t_i - 3h$
- $t_i - 2h$
- $t_i - 1h$
- $t_i$

**DORIS filter with latency (2 days hours)**

- $t_i - 2\,\text{days}$
- $t_i - 4h$
- $t_i - 3h$
- $t_i - 2h$
- $t_i - 1h$
- $t_i$
Case study: September 2017, during high and low solar activity

Data Set:

- **GNSS-only solution**: the data acquired from GPS and GLONASS receivers

- **GNSS and DORIS solution**: In addition to the GNSS data, the estimation model exploits data acquired from DORIS system on-board of Jason-2, Saral, Jason-3 and HY-2A satellites.

Comparison:

- **Altimetry Jason-2/3**: VTEC maps obtained by combining GNSS and Jason-2/3 data are used for validation of VTEC maps derived from GNSS+DORIS.

Case study: September 2017

Low solar activity
September 6, 2017

High solar activity
September 8, 2017

Direction of the IMF (Bz) on Wednesday, 6 September 2017

Direction of the IMF (Bz) on Friday, 8 September 2017

Sources:
- Direction of the IMF (Bz) on Wednesday: https://www.spaceweatherlive.com/en/archive/2017/09/06/aurora
- Direction of the IMF (Bz) on Friday: https://www.spaceweatherlive.com/en/archive/2017/09/08/aurora
Case Study: Example, September 6

GNSS

GNSS + DORIS

GNSS + latent DORIS

DORIS data collected between 19:00-20:00 was assimilated.
After 20:00 the model coefficients were propagated to 21:40.
GNSS + latent DORIS solution is slightly better than the GNSS solution, but can not exceed the performance of GNSS + DORIS solution.
Case Study: Example, September 6

- **Time Line**
  - 19:00 to 20:00
  - 20:00 to 21:00: latency (3 hours)
  - 21:00 to 22:00: latency (1 hour)
  - 22:00 to 23:00: latency (hour)

**GNSS + DORIS solution:**

DORIS has the same latency with GNSS

- **Epoch Data (06 Sep 2017 19:50:00 UTC):**

**GNSS + latent DORIS solution:**

DORIS has different latency

- **DORIS data collected between 19:00-20:00 was assimilated.**
Case Study: Example, September 8

GNSS + DORIS solution:
DORIS has the same latency with GNSS

Epoch Data (08 Sep 2017 01:40:00 UTC)

DORIS data collected between 00:00-01:00 was assimilated.
After 01:00 the model coefficients were propagated to 01:40
GNSS + latent DORIS solution is slightly better than the GNSS solution, but far away from the performance of GNSS + DORIS solution.
Summary and outlook

• A multi-filter approach based on Kalman filtering was presented.

• To consider the individual latencies of the applied observation techniques we setup our approach by one main filter based on GNSS data and additional filters for satellite DORIS data with simulated latencies.

• In the first study case, the latency of DORIS data is set to 1 hour, i.e. identical to the near real-time GNSS data latency. Results show that DORIS significantly improves the VTEC maps, at least in regions that are less or not supported by GNSS data.

• In the second case, the latency is set to 3 hours. Improvements of GNSS-only solutions are less pronounced but still visible. The impact depends on the dissemination time of DORIS data (with respect to the modeling epoch).

• Extensive validation studies covering more and longer data sets will be performed next and shown in near future. These validations will also cover latencies between 1 and 3 hours.