High-precision and high-resolution VTEC maps based on B-spline expansions and GNSS data

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OPTIMAP
Operational Tool for Ionosphere Mapping and Prediction

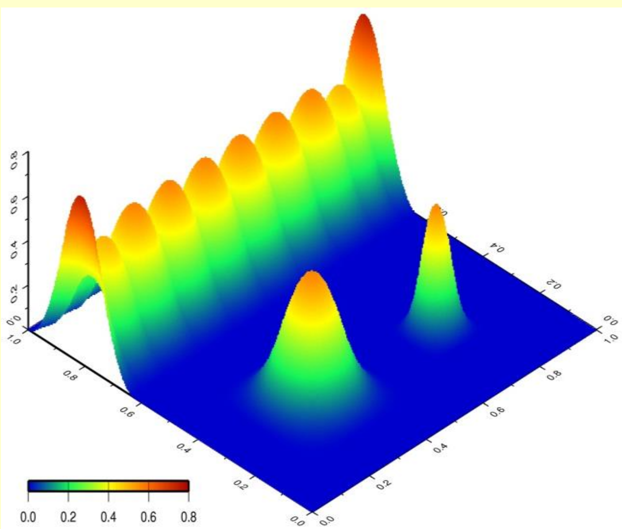
Introduction

- Large volumes of **GNSS data**, which are acquired from continuously operating terrestrial GNSS receivers and distributed worldwide, allow for monitoring and modelling the **Vertical Total Electron Content** (VTEC) of the ionosphere with an increasing spectral, temporal and spatial resolution as well as accuracy.
- Many analysis centres are providing VTEC products with different **latencies** (e.g. real-time, hourly, daily) and **quality**.
- The VTEC model of DGFI-TUM is based on tensor products of **trigonometric** and **polynomial B-splines**. The unknown parameters of the model are sequentially estimated by assimilating **GNSS observations** using a **Kalman filter**.
- The application of B-spline functions allows for handling **data gaps** and the generation of a **multi-scale representation**, i.e. the view of VTEC under different spectral resolutions.
- In this study, the **performance** of the VTEC maps derived within the project **OPTIMAP** (OPerational Tool for Ionospheric Mapping And Prediction) at DGFI-TUM is assessed.

Ionosphere modelling:
VTEC representation based on B-spline expansions

- VTEC is represented as a series expansion in tensor products of **B-spline functions** defined separately for **longitude** and **latitude**

2-D B-Spline Functions

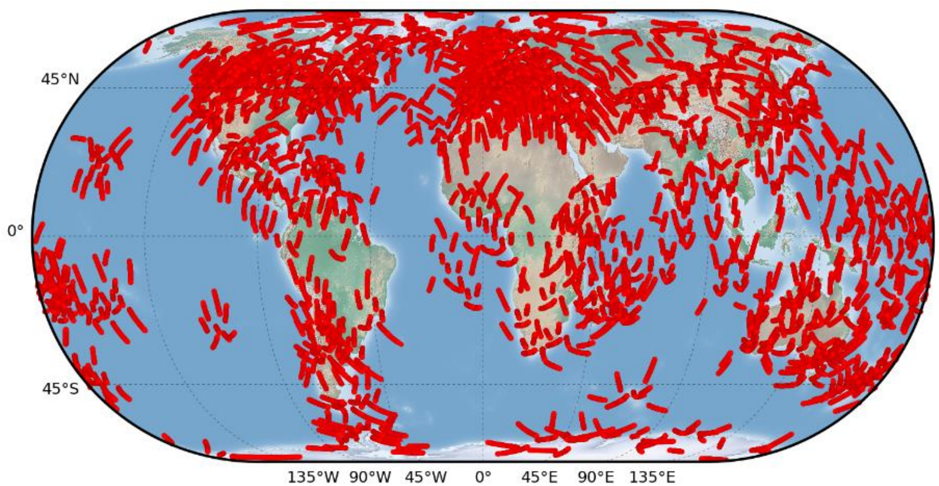


- The B-spline functions are different from zero only in a local environment, i.e. they are characterized by a **compact support**
- In opposite to a spherical harmonics (SH) representation the compact support allows for
  - a modification of input data and
  - the incorporation of new measurements

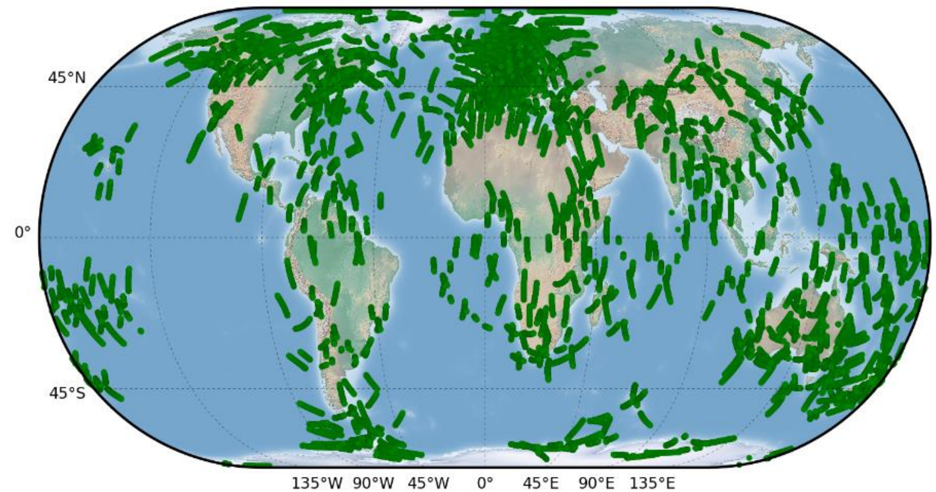
  without causing a **global effect**
- Data gaps can be handled **appropriately,**
- The approach can be applied for **global, regional** and **combined** modelling.

GNSS data distribution

GPS

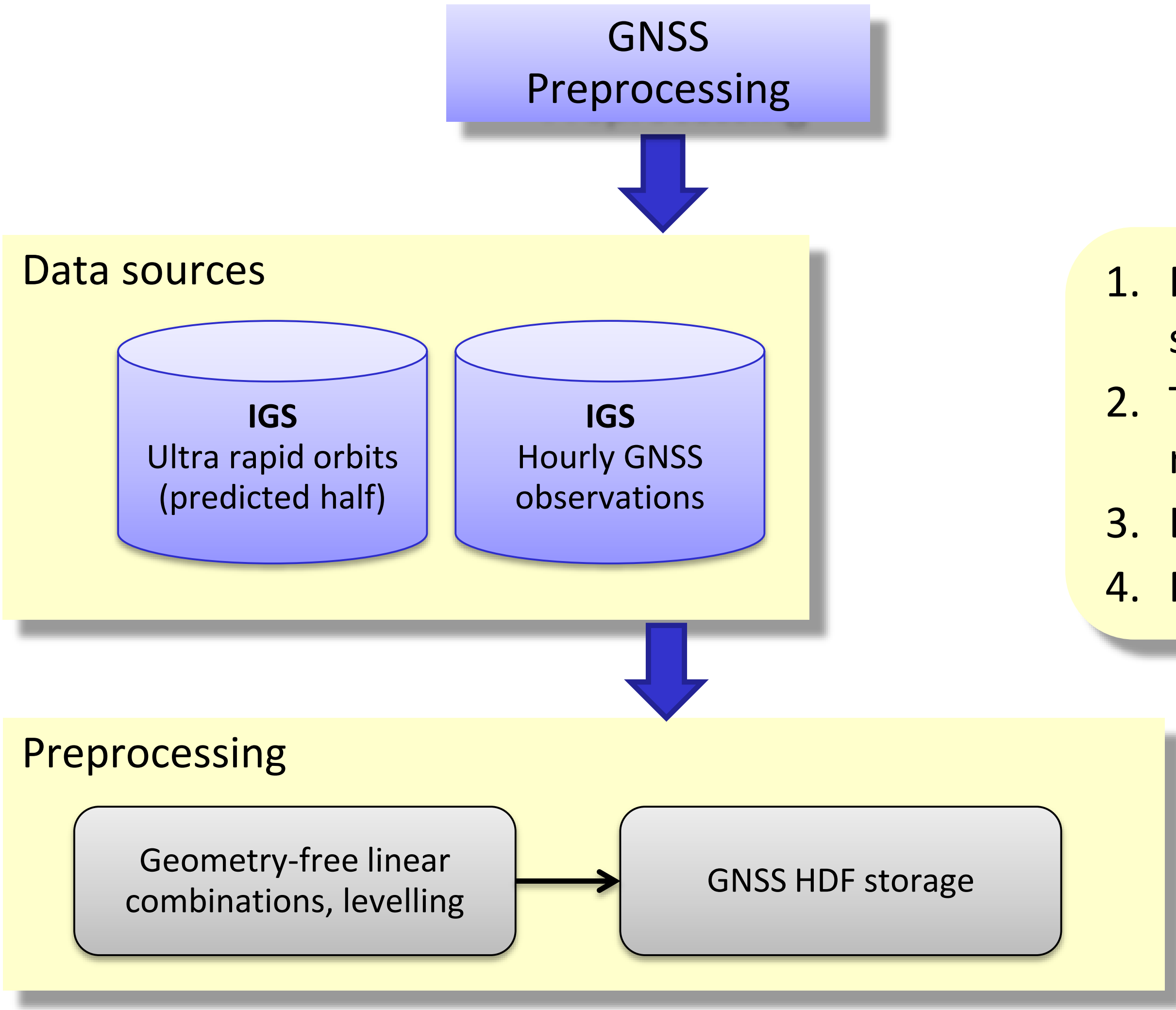


GLONASS



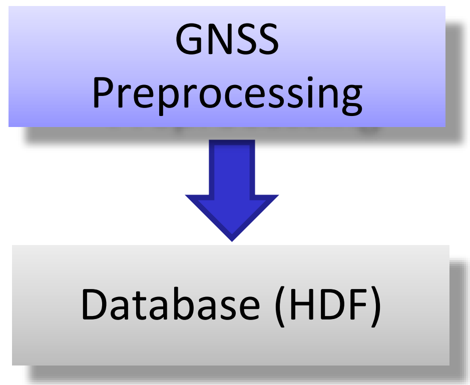
- Distribution of **ionospheric pierce points** (IPP = intersection point of the signal ray path with the single-layer model in a certain altitude) based on the **hourly observation** batch of February 11, 2016, 12:00 UT - 13:00 UT.
- The figures show exemplarily the **spatial resolution** of GPS and GLONASS during the time interval of 1 hour.

Process flowchart

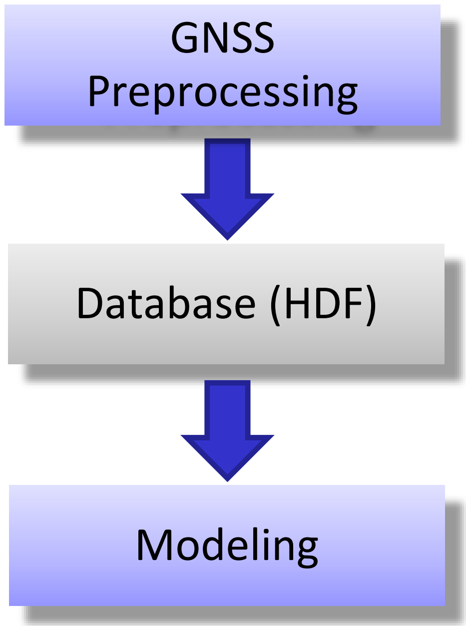


1. Number of GNSS stations: ~ 360
2. Temporal resolution: 30 sec.
3. Latency: ~ 1 hour
4. Functional: STEC

Process flowchart



Process flowchart

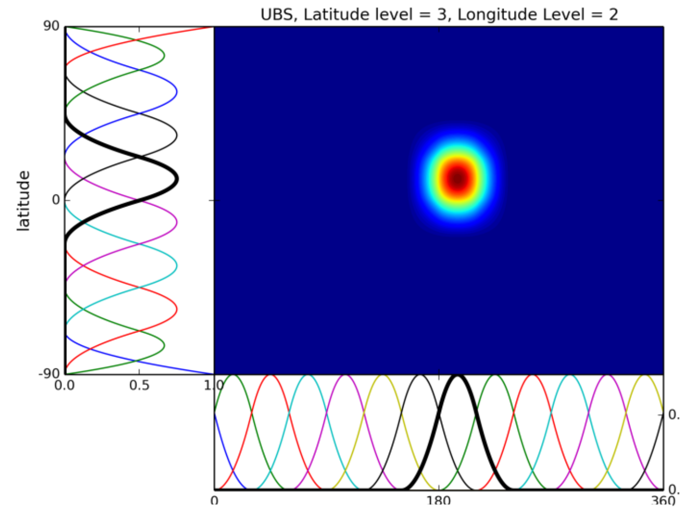


Ionosphere modelling:
OPTIMAP approach of VTEC representation

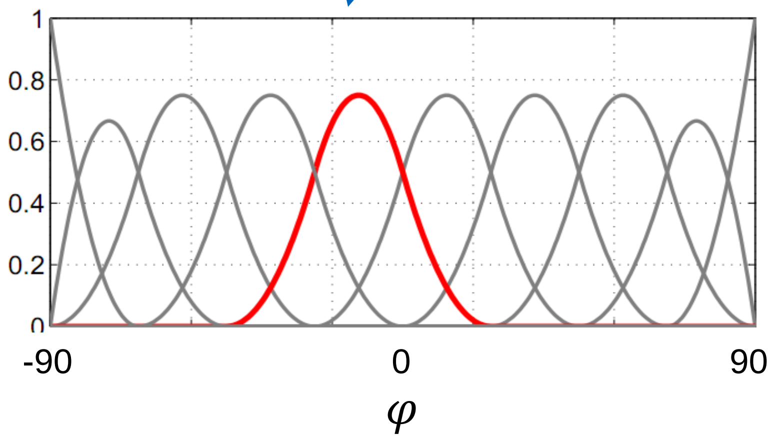
- Use of **polynomial** and **trigonometric** B-splines

unknown coefficients

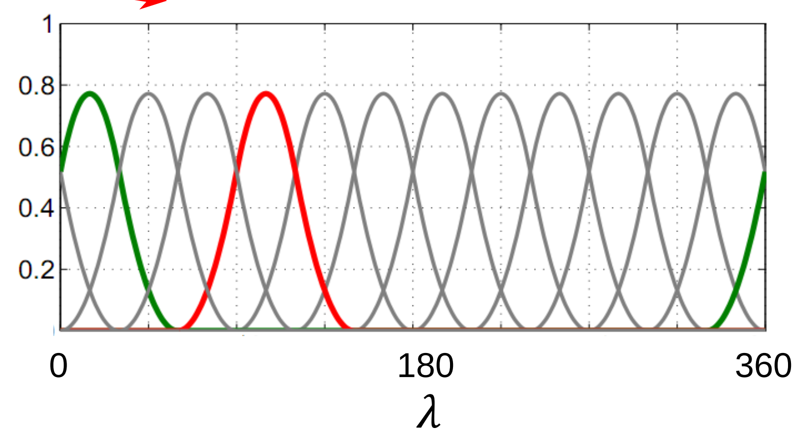
$$VTEC(\varphi,\lambda,t) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} d_{k_1,k_2}^{J_1,J_2}(t)\; N_{J_1,k_1}^2(\varphi)\; T_{J_2,k_2}^2(\lambda)$$



Polynomial B-splines **Trigonometric B-splines**



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



$J_2 = 2,\ K_2 = 14,\ k_2 = 0,1,\dots,13$

B-spline expansion for VTEC modelling

Why using B-splines?

1. Due to the **localizing feature** of the B-spline functions **data gaps** (oceans, deserts, etc.) can be handled appropriately
2. B-spline functions generate a **multi-scale analysis**, i.e. the representations on different resolution levels are related to each other by **linear equation systems**, represented by **linear operators** ($\mathcal{P}$ = low-pass filter, $\mathcal{Q}$ = band-pass filter)

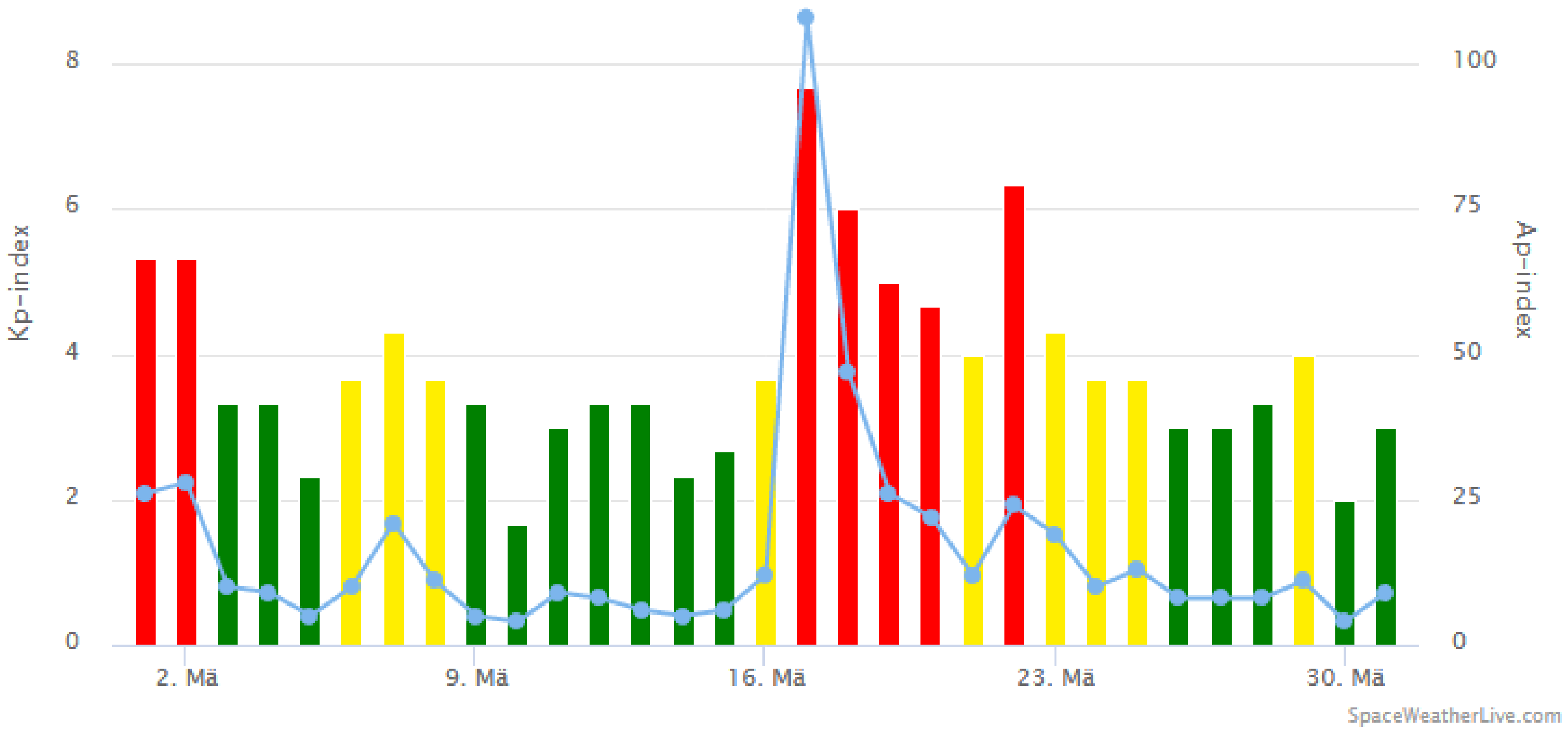
$$VTEC(J_1 = 4, J_2 = 3) = \mathcal{P}\{VTEC(J_1 = 5, J_2 = 3)\}$$

$$G(J_1 = 4, J_2 = 3) = VTEC(J_1 = 5, J_2 = 3) - VTEC(J_1 = 4, J_2 = 3)$$
$$= \mathcal{Q}\{VTEC(J_1 = 5, J_2 = 3)\}$$

Consequently, the high resolution VTEC map $(J_1 = 5, J_2 = 3)$ includes also the lower resolution VTEC map $(J_1 = 4, J_2 = 3)$; see the following example for the St. Patrick Storm day

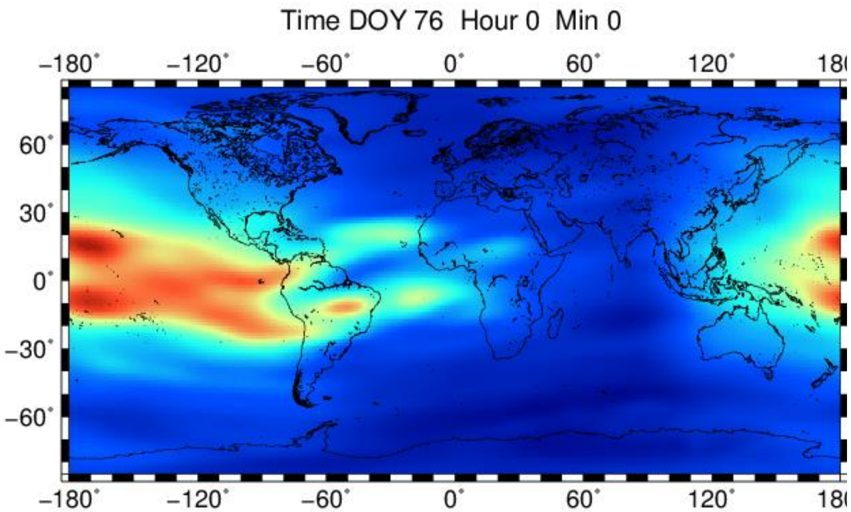
Example: St. Patrick Storm days

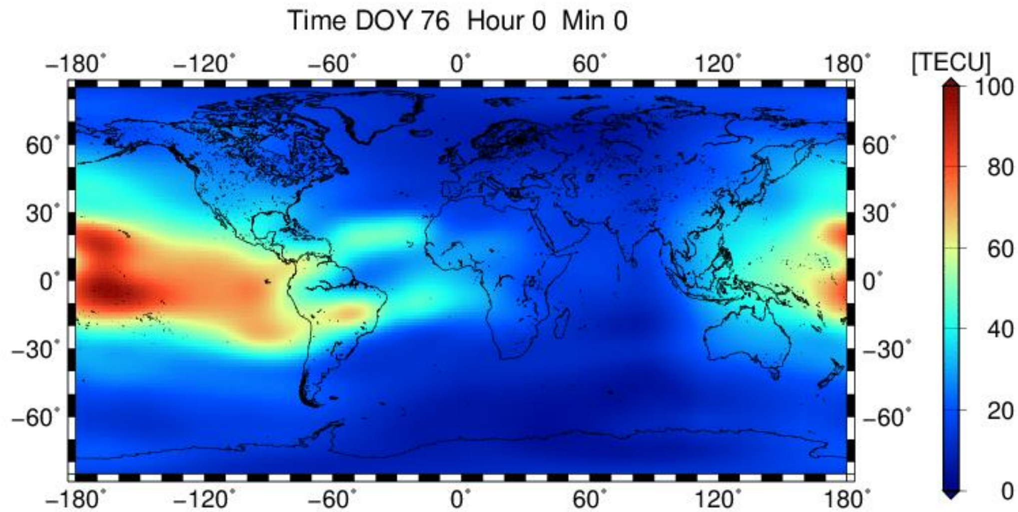
- The Kp index is a measure for the **magnetic effect** of the solar particle radiation.
- It is provided by measurements of 13 **magnetic observatories**.



DOY 76 = March 17, 2015

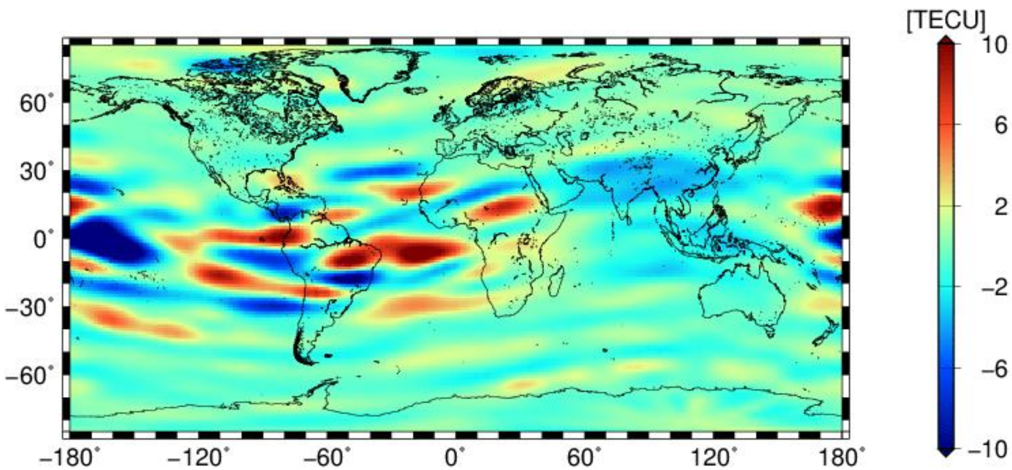
VTEC maps of different spectral resolutions





VTEC map at St.Patrick storm day with **high levels** $J_1 = 5, J_2 = 3$ (comparable with SH degree $n_{max} = 30$).

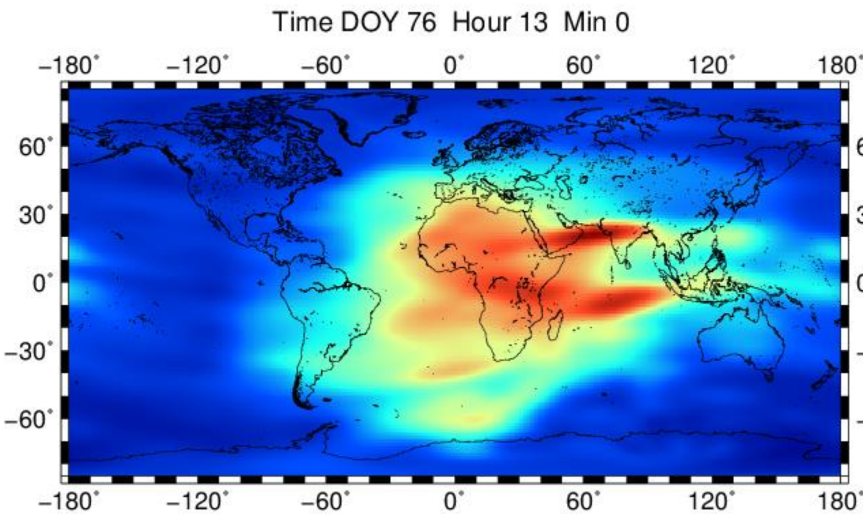
VTEC map at St.Patrick storm day with **lower levels** $J_1 = 4, J_2 = 3$ (comparable with SH degree $n_{max} = 15$).

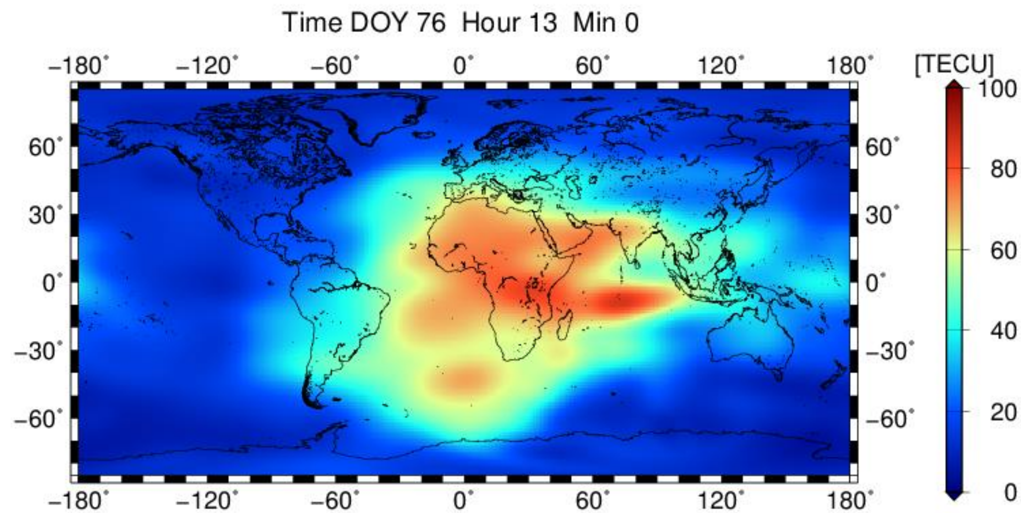


Detail signal G at St.Patrick storm day with levels $J_1 = 4, J_2 = 3$).

Detail signal G means the difference between the signals shown above.

VTEC maps of different spectral resolutions





VTEC map at St.Patrick storm day with **high levels** $J_1 = 5, J_2 = 3$ (comparable with SH degree $n_{max} = 30$).

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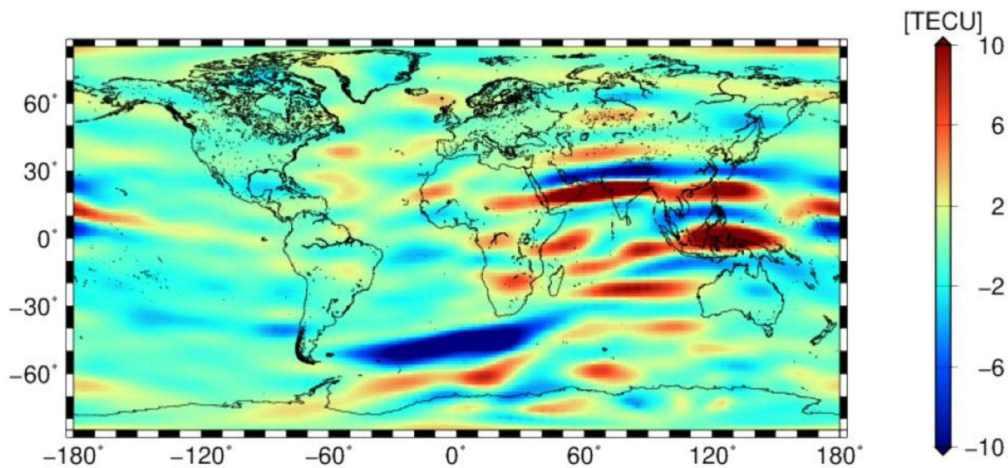
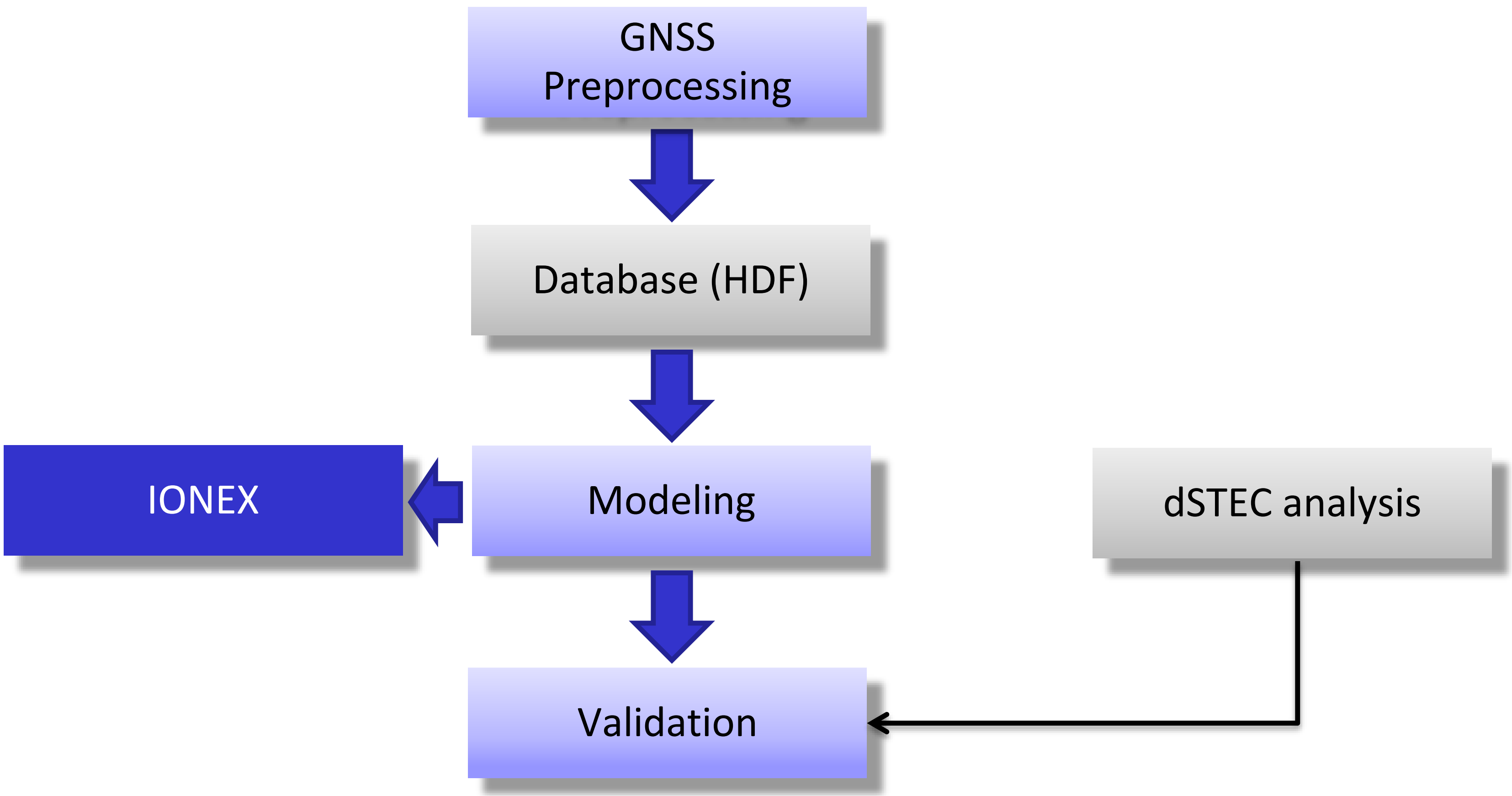


Detail signal G at St.Patrick storm day with levels $J_1 = 4, J_2 = 3$).

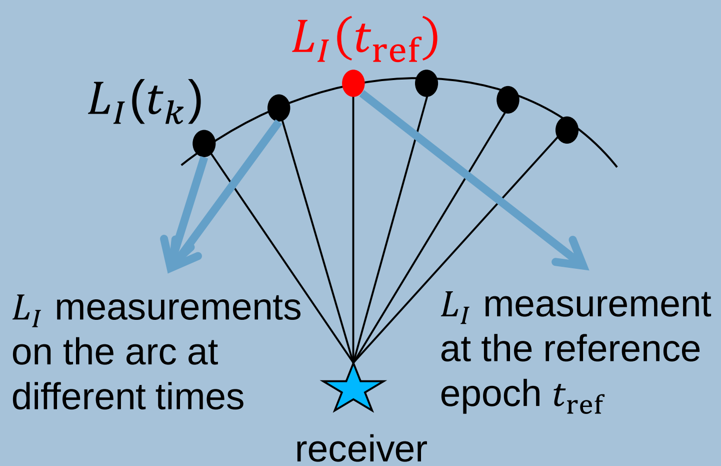
Detail signal G means the difference between the signals shown above.

Comparison of the VTEC maps of different spectral resolutions



Comparison of the VTEC maps of different spectral resolutions

- A comparison for the **test period** including the **St. Patrick's storm** (17 March 2015) was performed.
- The validation method is based on the **self-consistency analysis** (**dSTEC**); see Orus et al. (2007) and Feltens et al. (2011)



Analysis of the $\boldsymbol{dSTEC}_{\mathbf{obs,k}}$ values from a continuous arc by subtracting a reference observation

- The self consistency analysis is based on the comparison of

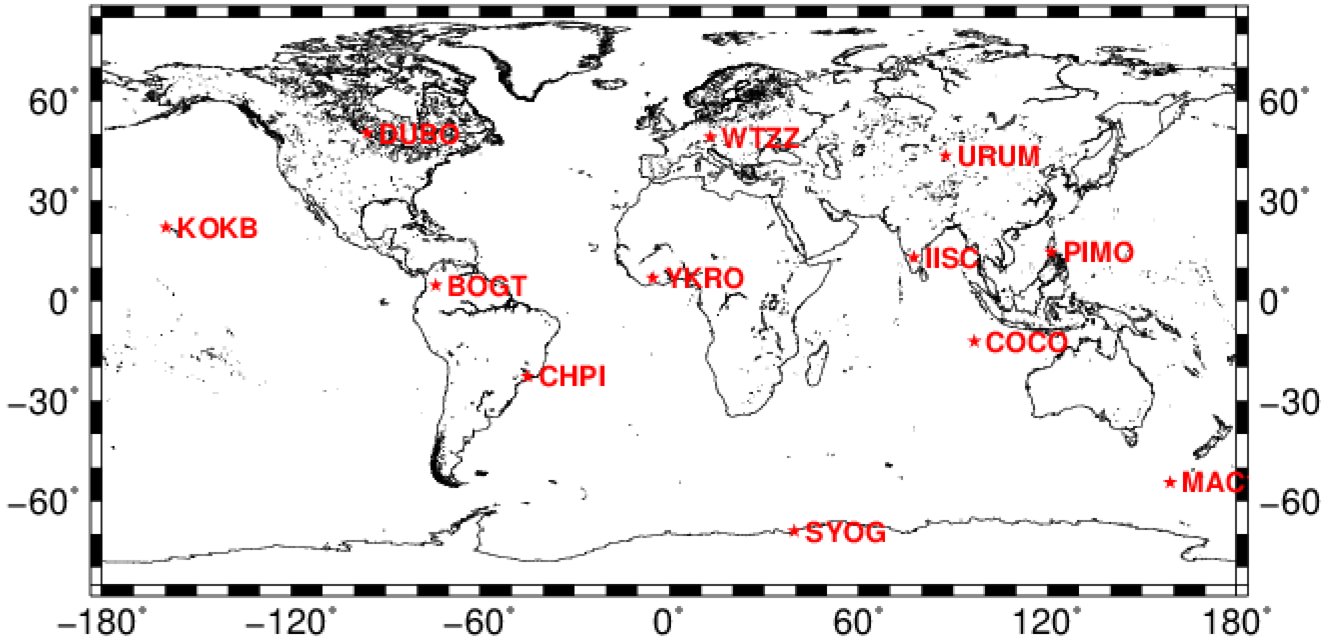
…differenced STEC values computed from the **GPS geometry-free linear combination** of carrier-phase observables (along a phase-continuous arc): $dSTEC_{\mathrm{obs,k}}$

…and **differenced STEC values computed from VTEC maps:** $dSTEC_{\mathrm{map,k}}$

$$dSTEC_{\mathrm{k}} = dSTEC_{\mathrm{obs,k}} - dSTEC_{\mathrm{map,k}}$$

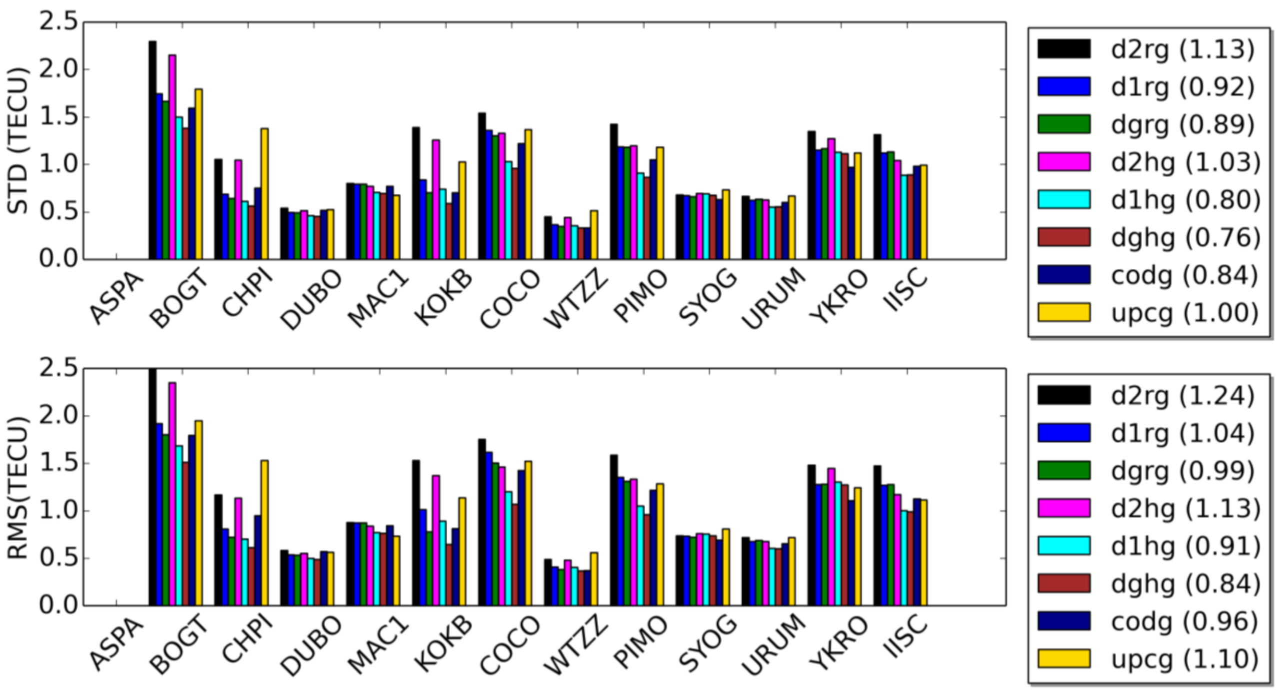
Comparison of the VTEC maps of different spectral resolutions

- The geographical locations of the **stations selected** for the analysis are shown in the figure
- The test receivers chosen globally are located at **low** and **high latitudes**, which can estimate the VTEC model accuracy at regions characterized by **strong variable VTEC activity**.



Comparison of the VTEC maps of different spectral resolutions

- **Summary of the statistics**: **average standard deviation (STD)** and **average RMS deviations** of 8 VTEC models with different **spectral** and **temporal resolutions** presented at 12 stations covering the St. Patrick storm day from dSTEC analysis



d2rg = VTEC($J_1 = 4, J_2 = 3$), 2h temporal resolution

d1rg = VTEC($J_1 = 4, J_2 = 3$), 1h temporal resolution

dgrg = VTEC($J_1 = 4, J_2 = 3$), 10 min temporal resolution

d2hg = VTEC($J_1 = 5, J_2 = 3$), 2h temporal resolution

d1hg = VTEC($J_1 = 5, J_2 = 3$), 1h temporal resolution

dghg = VTEC($J_1 = 5, J_2 = 3$), 10 min temporal resolution

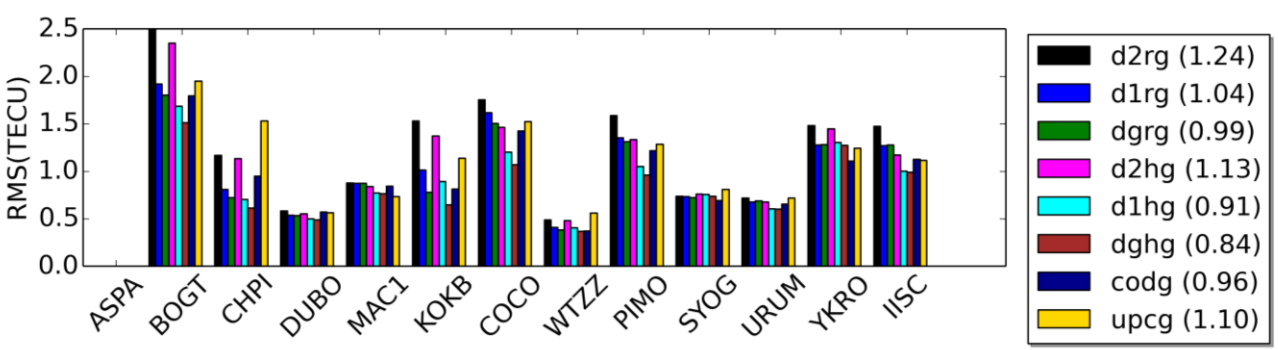
codg = final product CODE, 1h temporal resolution

upcg = final product UPC, 1h temporal resolution

- The values in brackets show overall average values computed from all receivers at the given 12 stations

Comparison of the VTEC maps of different spectral resolutions

- **Summary of the statistics**: **average standard deviation (STD)** and **average RMS deviations** of 8 VTEC models with different **spectral** and **temporal resolutions** presented at 12 stations covering the St. Patrick storm day from dSTEC analysis
- The **DGFI-TUM** VTEC model '**dghg**' with **3h latency, level values** $J_1 = 5, J_2 = 3$ and **10 min temporal resolution** is the best.
- The **DGFI-TUM** VTEC model ‚**dgrg**' with **3h latency, level values** $J_1 = 4, J_2 = 3$ and **10 min temporal resolution** is as expected a bit worse.



- The final product ‚**codg**' with **2 weeks latency, SH degree** $n_{max} = 15$, **1h temporal resolution** is comparable with 'dgrg'.

d2rg = VTEC($J_1 = 4, J_2 = 3$),
2h temporal resolution
d1rg = VTEC($J_1 = 4, J_2 = 3$),
1h temporal resolution
dgrg = VTEC($J_1 = 4, J_2 = 3$),
10 min temporal resolution
d2hg = VTEC($J_1 = 5, J_2 = 3$),
2h temporal resolution
d1hg = VTEC($J_1 = 5, J_2 = 3$),
1h temporal resolution
dghg = VTEC($J_1 = 5, J_2 = 3$),
10 min temporal resolution
codg = final product CODE,
1h temporal resolution
upcg = final product UPC,
1h temporal resolution

Summary and outlook

- We presented the **global VTEC model** approach of **DGFI-TUM** developed within the **OPTIMAP project**.
- It is based on
  - **GNSS** observations only, namely **GPS** and **GLONASS**
  - **localizing B-spline functions** to handle **data gaps** appropriately
  - the **multi-scale representation** providing VTEC maps of **various spectral resolutions** by **linear transformations**
  - the **Kalman filter** to estimate the unknown model parameters, in particular the **B-spline coefficients.**
- The approach provides VTEC maps **in around 3.5 hours**, i.e. in **near real-time (NRT)**
- The presented approach allows for the application of an **additional forecasting procedure** applied to the series coefficients of the B-spline expansion
- Besides the VTEC maps **full error information** is provided by **„standard deviation“ maps**.