Deutsches Geodätisches Forschungsinstitut (DGFI-TUM)
Technische Universität München

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

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International Association of Geodesy (IAG), Commission 4 Symposium
Positioning and Navigation

Wroclaw, Poland, September 04-07, 2016

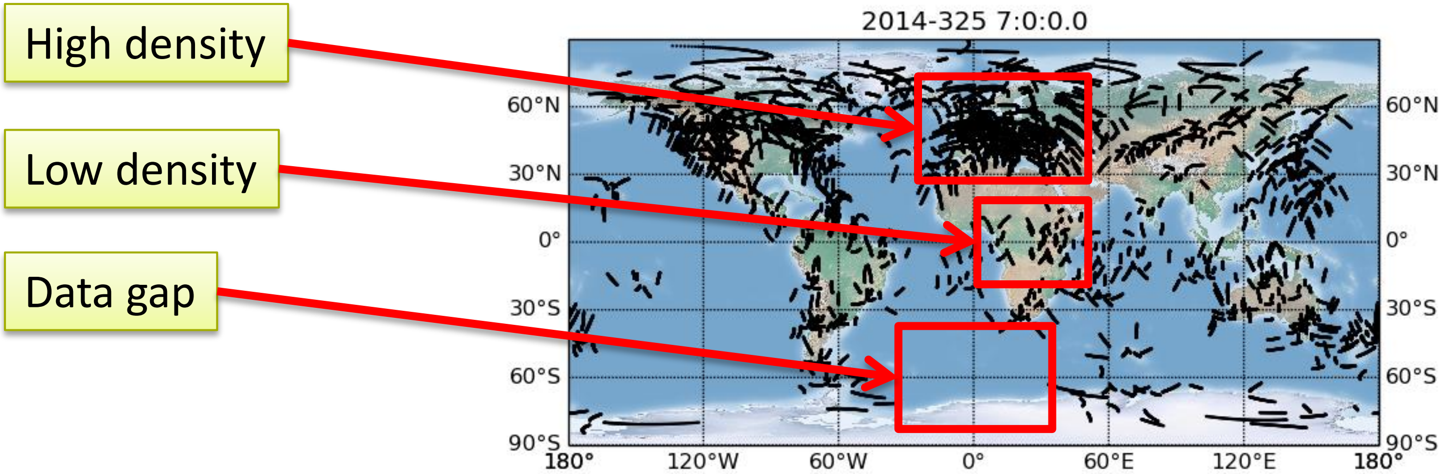
Introduction

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.

Introduction

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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,**

… do not allow the incorporation of **additional data.**

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DGFI-TUM

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- … do not allow the incorporation of **additional data.**

localising base functions

multi-scale approach

data adaptive techniques

data combination techniques

Kalman filter processing

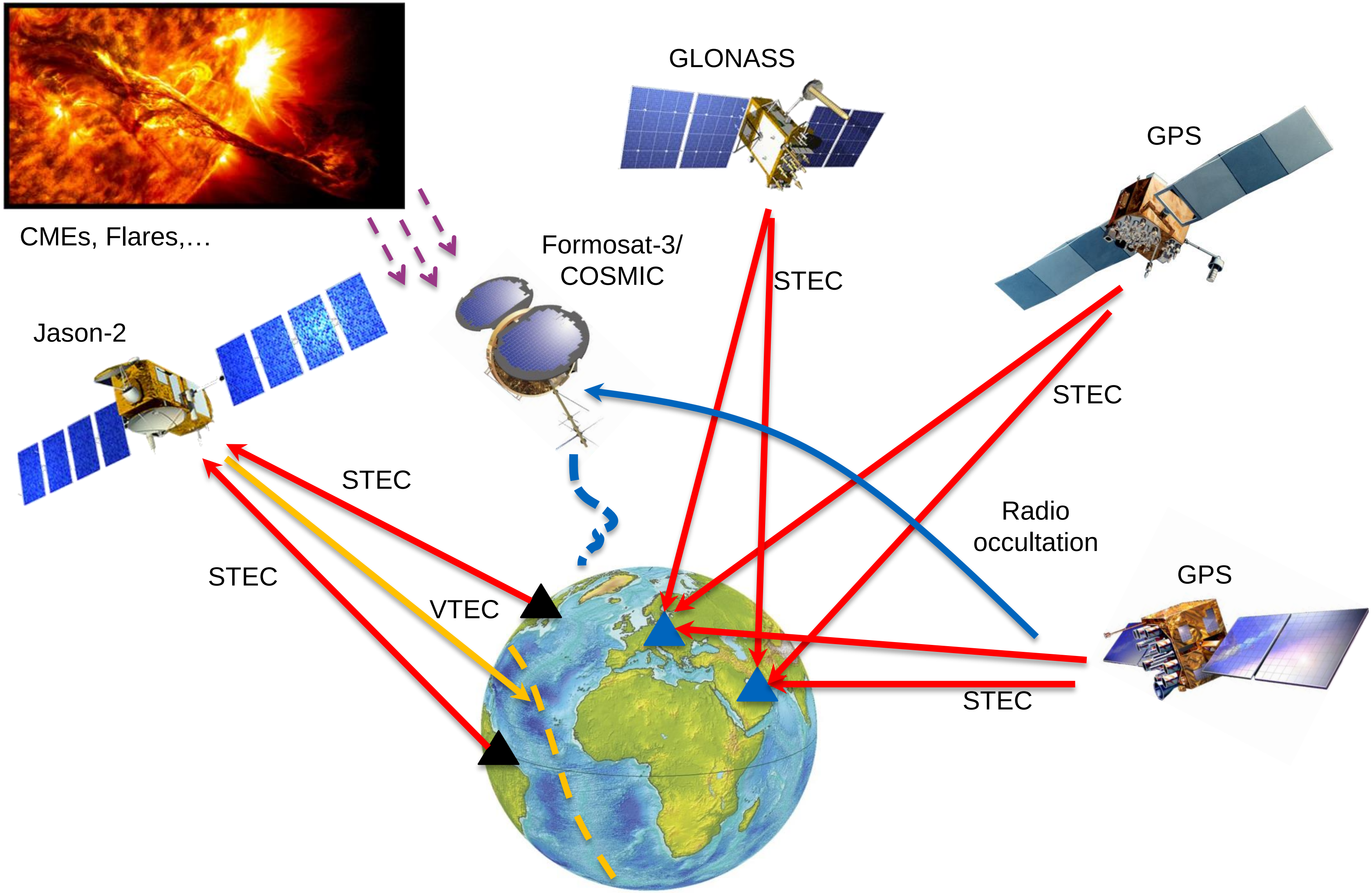
sophisticated dynamic model

e.g. Sun observations

Improved Concepts

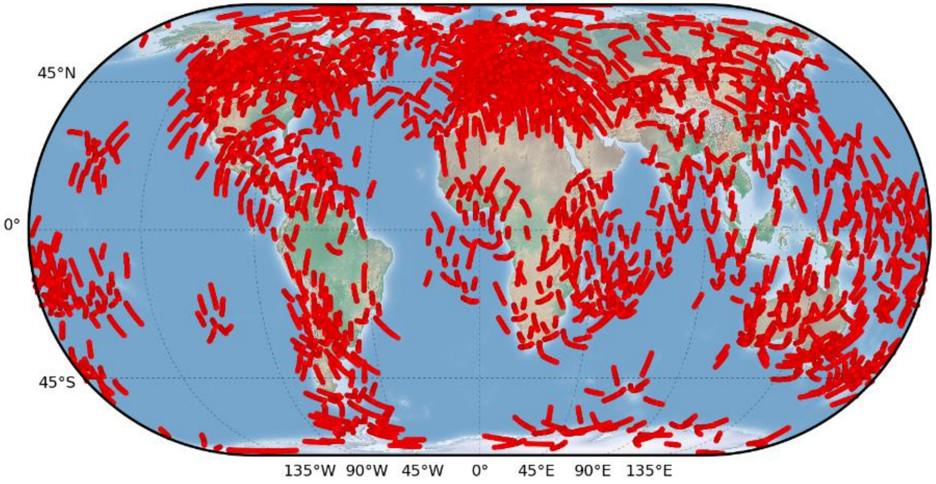
- Our approach aims on the development of an **adaptive global VTEC model** (including **regional densifications**) to generate
  - **low latency global VTEC** maps as well as
  - predictions **for several days into the future.**
- The model parameters will be computed from a **combination** of various **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

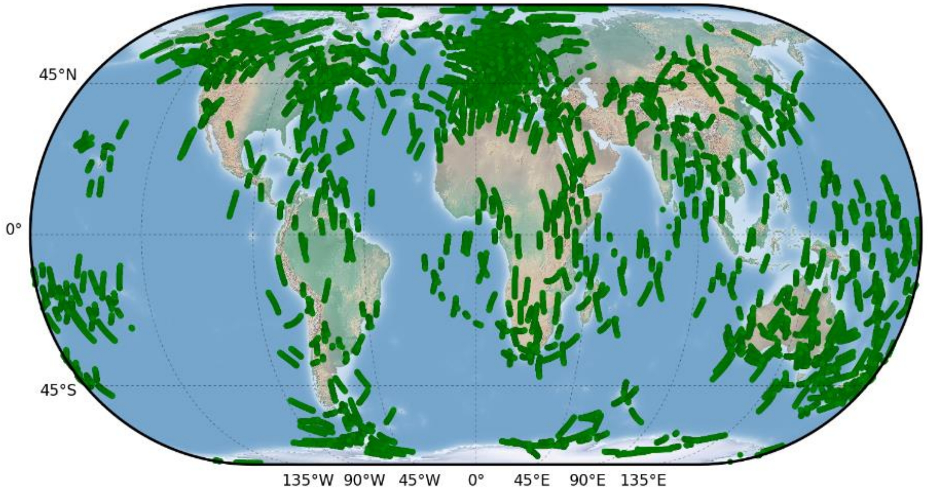


Observation Techniques: GNSS Preprocessing

GPS

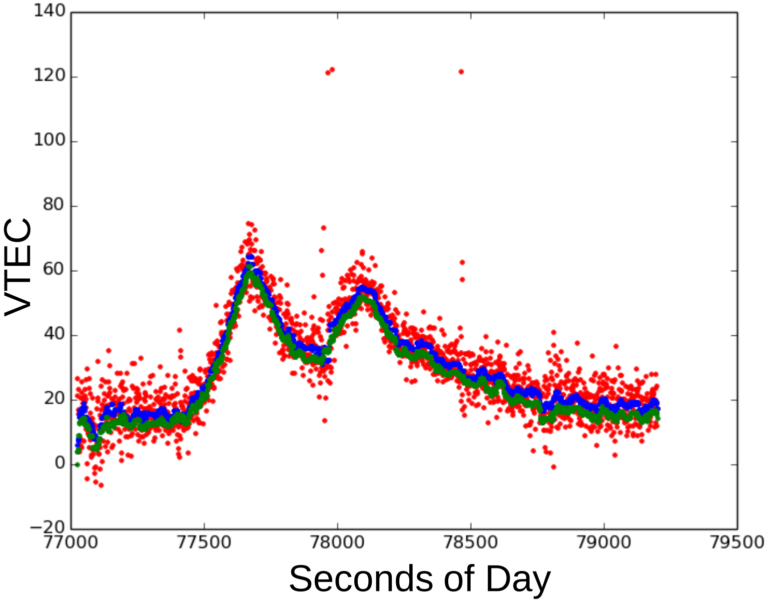


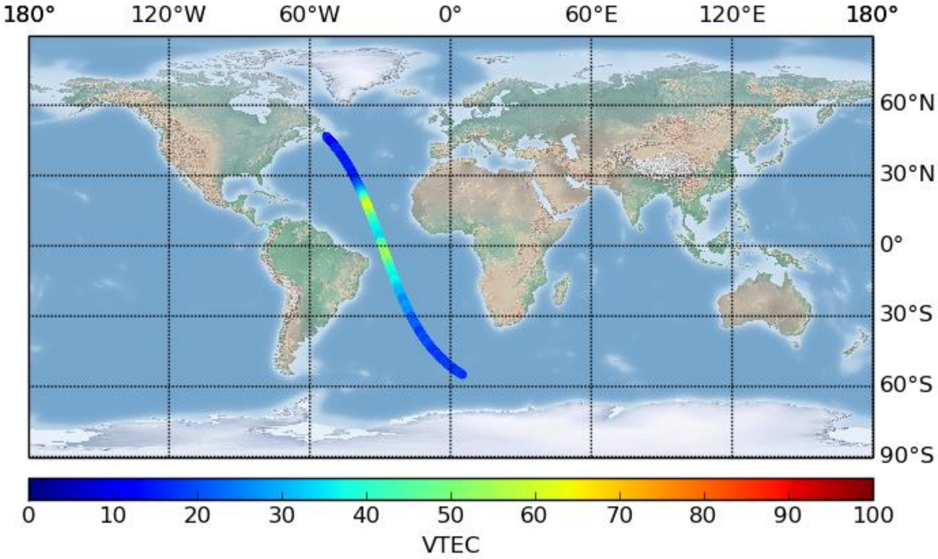
GLONASS



- 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.

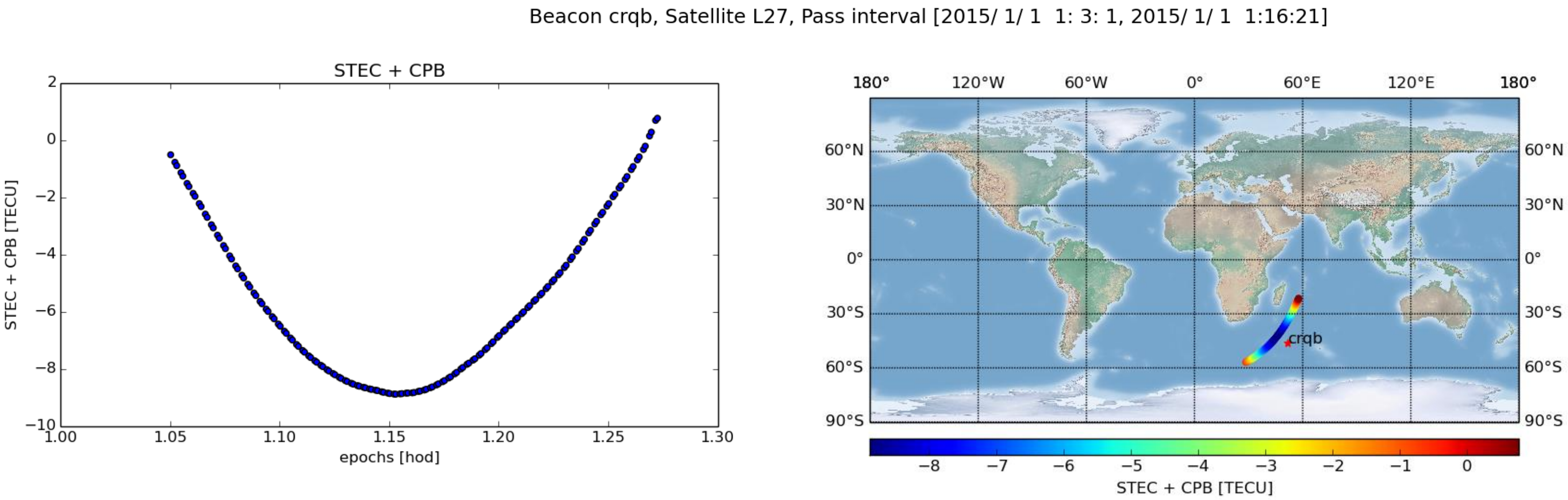
Observation Techniques: Altimetry Preprocessing





- **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



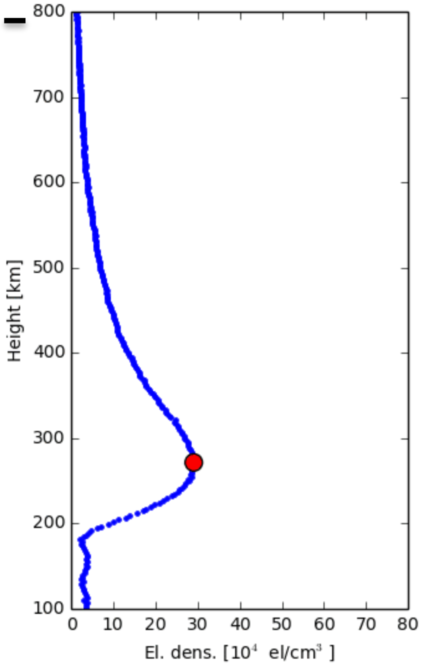
- DORIS **biased STEC** observations through a pass of the satellite observed on January 1, 2015.

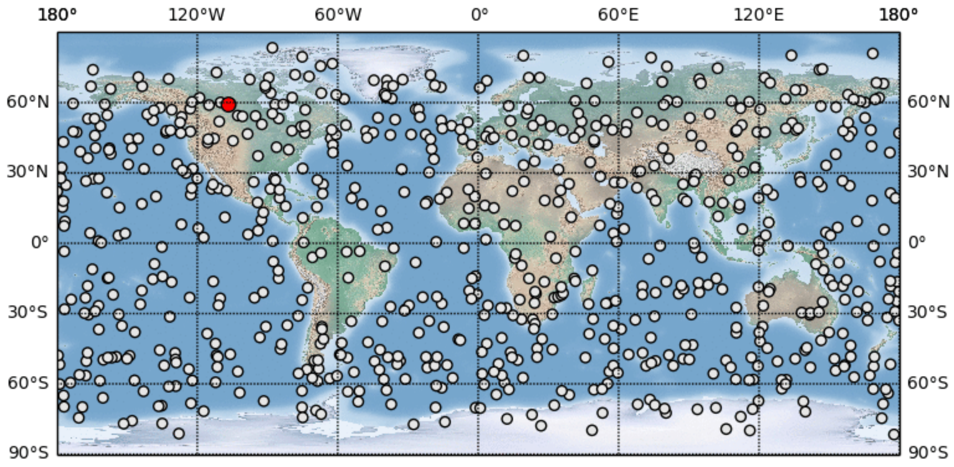
Observation Techniques: Radio Occultation (RO)

- 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)

Occultation event between F-3/C 05 and GPS 01

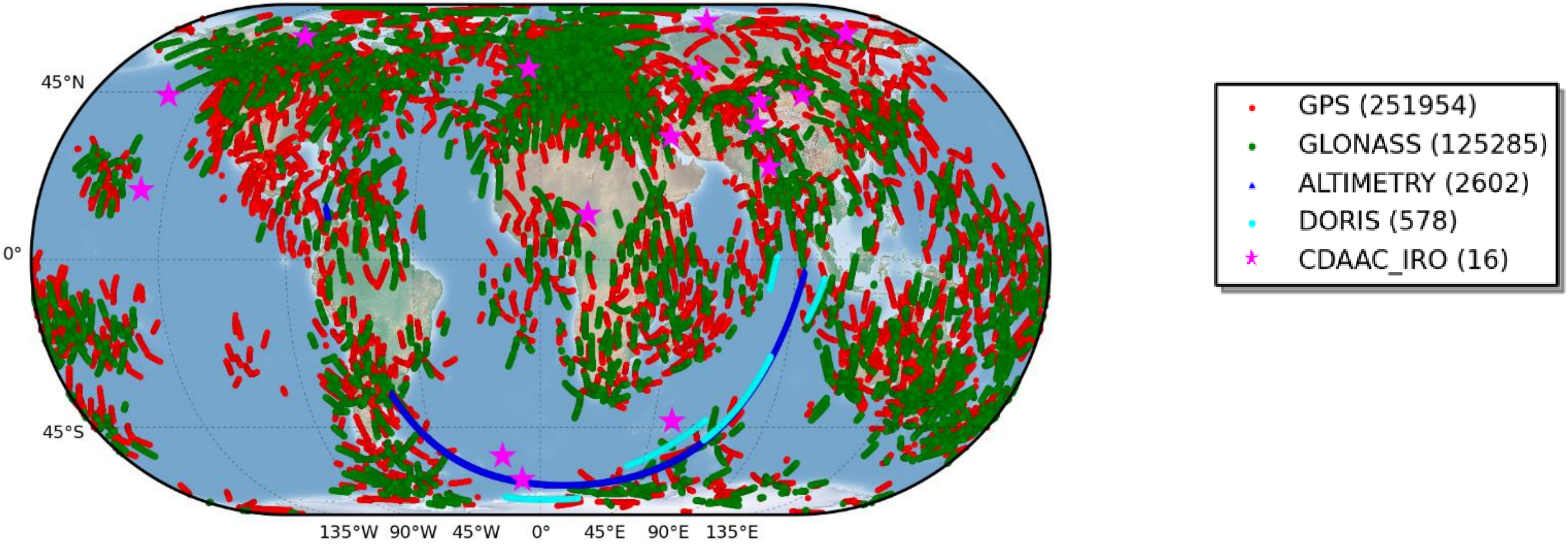




Global distribution of electron density profiles observed by the six F-3/C satellites on 2015/01/01

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



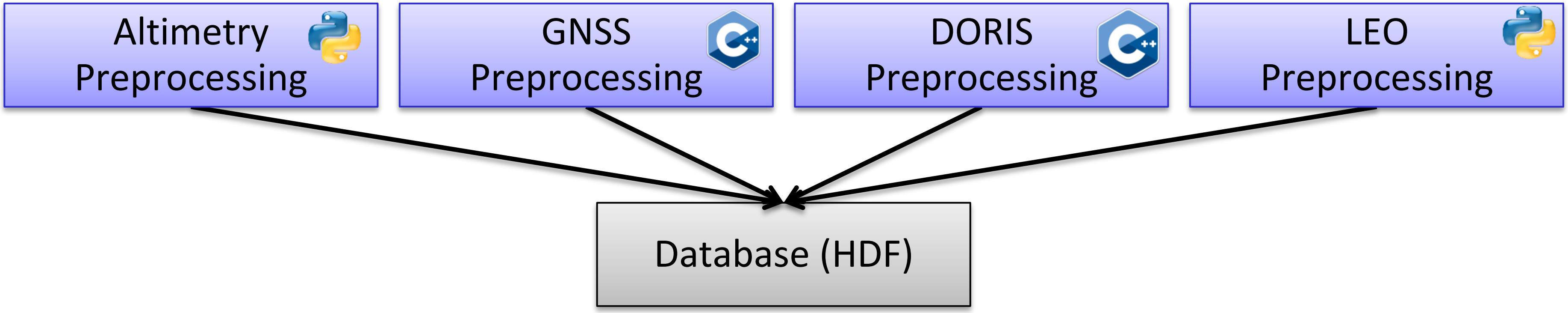
- Terrestrial **GPS and GLONASS** observations provide a **high-resolution coverage** of continental regions.
- Large **data gaps** still exist especially over the oceans.

Observation Techniques: Process Flowchart

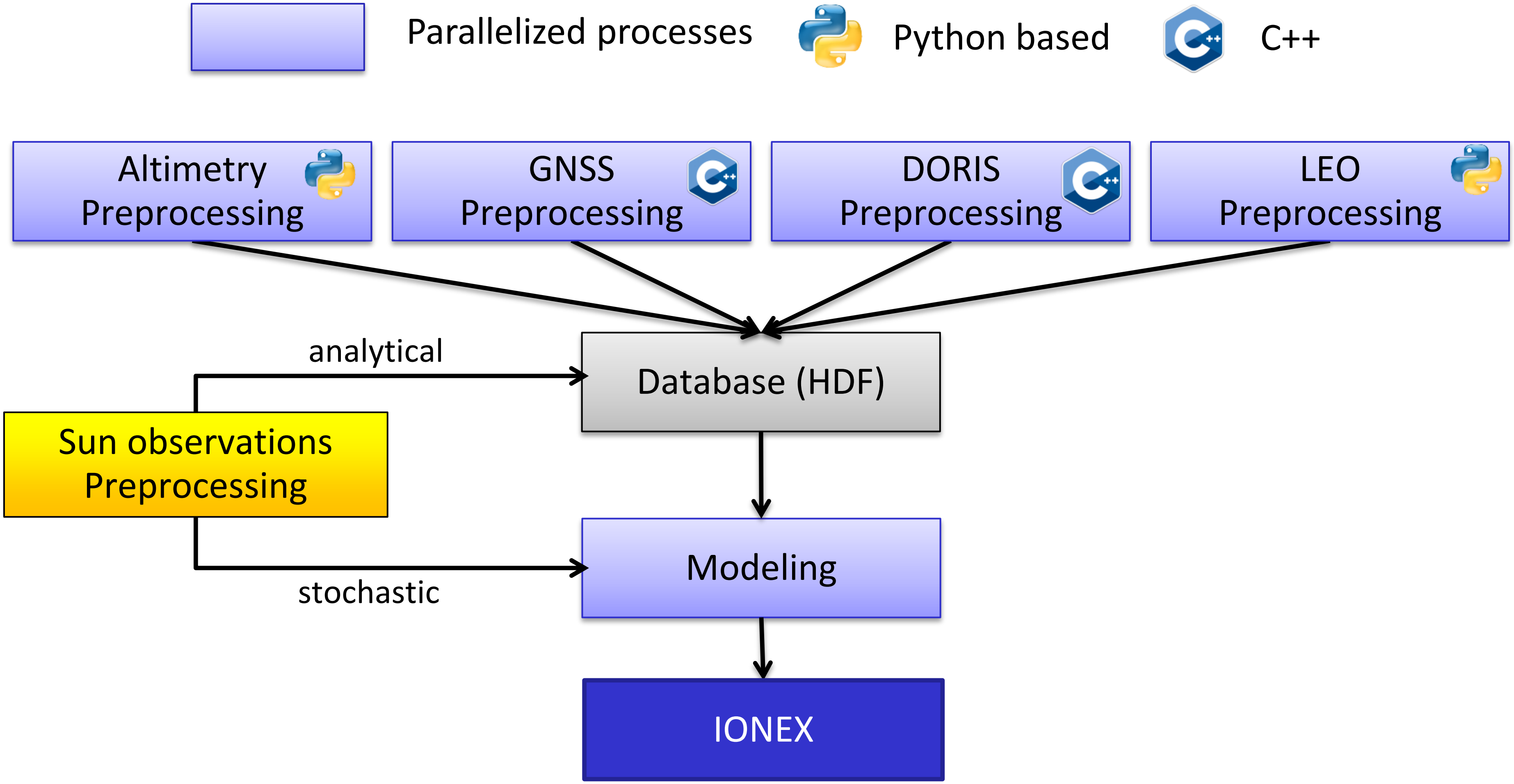
🟦 Parallelized processes

Python based

C++



Observation Techniques: Process Flowchart



Parallelized processes

Python based

C++

Altimetry Preprocessing

GNSS Preprocessing

DORIS Preprocessing

LEO Preprocessing

Database (HDF)

analytical

Sun observations Preprocessing

stochastic

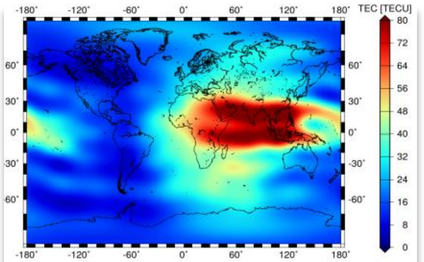
Modeling

IONEX

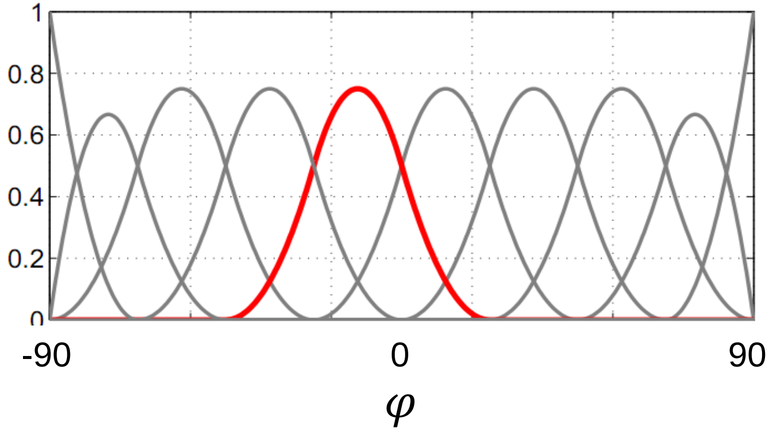
VTEC Representation: Uniform B-splines (UBS)

- VTEC is parametrized in tensor products of **trigonometric B-spline functions** $T^2_{J_2,k_2}$ for longitude λ and **polynomial B-spline functions** $N^2_{J_1,k_1}$ for latitude φ

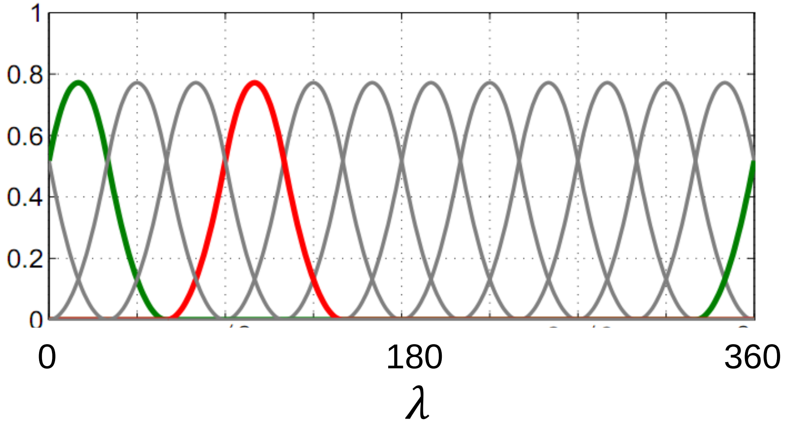
$$VTEC(\lambda,\varphi) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} d^{J_1,J_2}_{k_1,k_2} \boxed{N^2_{J_1,k_1}(\varphi)} \boxed{T^2_{J_2,k_2}(\lambda)}$$



Polynomial B-spline functions N^2_{3,k_1}



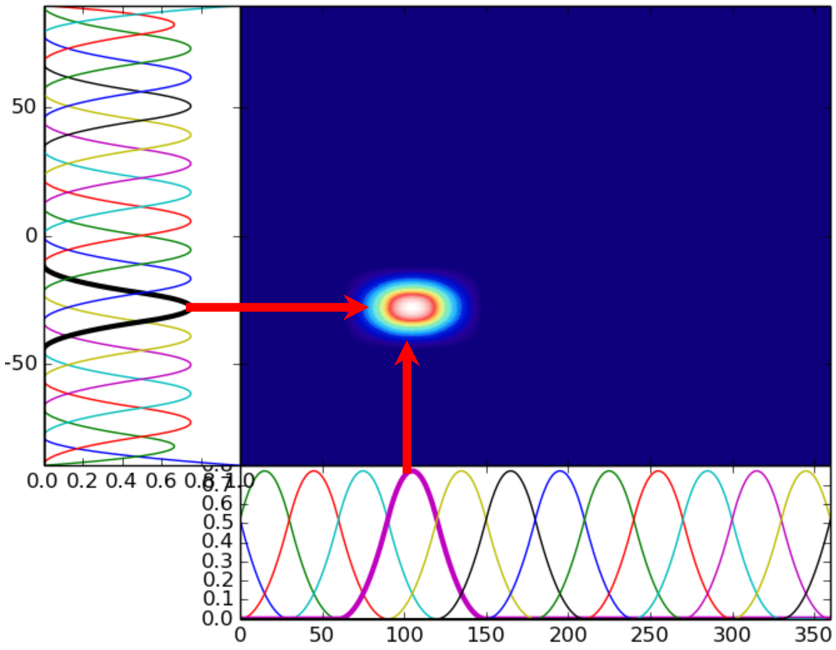
Trigonometric B-spline functions T^2_{2,k_2}

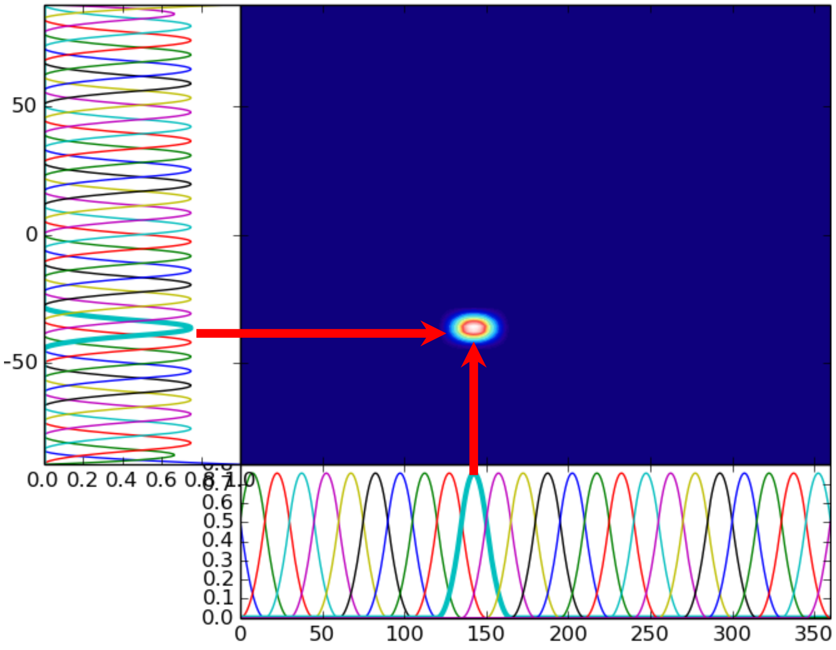


$J_1 = 3, K_3 = 10,\ k_1 = 0,1,\dots,9$

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

VTEC Representation: UBS Model Resolution





- Tensor products of polynomial B-spline functions $N^2_{J_1,k_1}$ and trigonometric B-spline functions $T^2_{J_2,k_2}(\lambda)$
  - 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

$$y_{GPS} + e_{GPS} = m(z)\,VTEC + \boxed{b_{r,GPS}} + \boxed{b^{s}_{GPS}}$$

$$y_{GLO} + e_{GLO} = m(z)\,VTEC + \boxed{b_{r,GLO}} + \boxed{b^{s}_{GLO}}$$

$$y_{ALT} + e_{ALT} = VTEC + \boxed{b_{ALT}}$$

$$y_{IRO} + e_{IRO} = VTEC + \boxed{b_{IRO}}$$

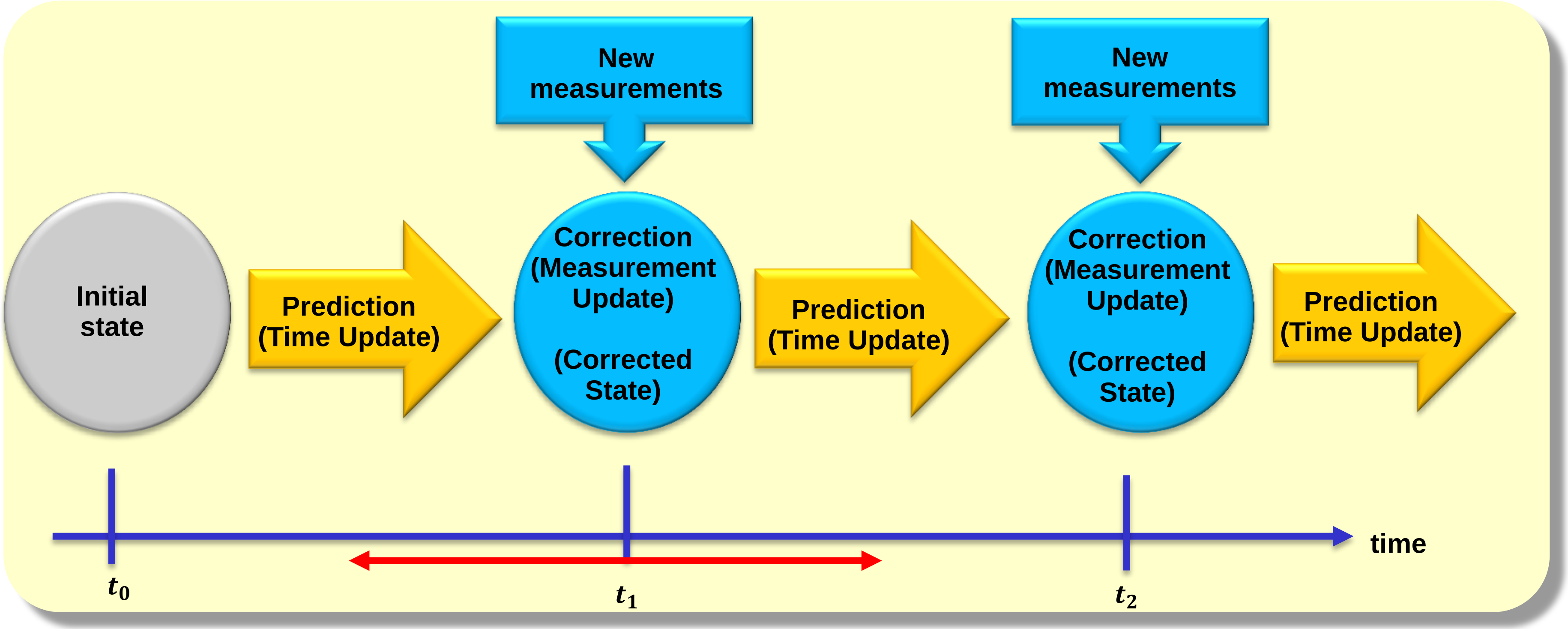
$$y_{DOR} + e_{DOR} = m(z)\,VTEC + \boxed{b_{DOR}}$$

$$VTEC(\lambda, \varphi) = \sum_{k_1=0}^{K_{J_1}-1} \sum_{k_2=0}^{K_{J_2}-1} \boxed{d^{J_1,J_2}_{k_1,k_2}}\, N^2_{J_1,k_1}(\varphi)\, T^2_{J_2,k_2}(\lambda)$$

Overall state vector of the unknown parameters

$$\boldsymbol{\beta} = \begin{bmatrix} \boxed{\boldsymbol{d}} \\ \boxed{\boldsymbol{b}_{GPS}} \\ \boxed{\boldsymbol{b}^{GPS}} \\ \boxed{\boldsymbol{b}_{GLO}} \\ \boxed{\boldsymbol{b}^{GLO}} \\ \boxed{b_{ALT}} \\ \boxed{b_{IRO}} \\ \boxed{\boldsymbol{b}_{DOR}} \end{bmatrix}$$

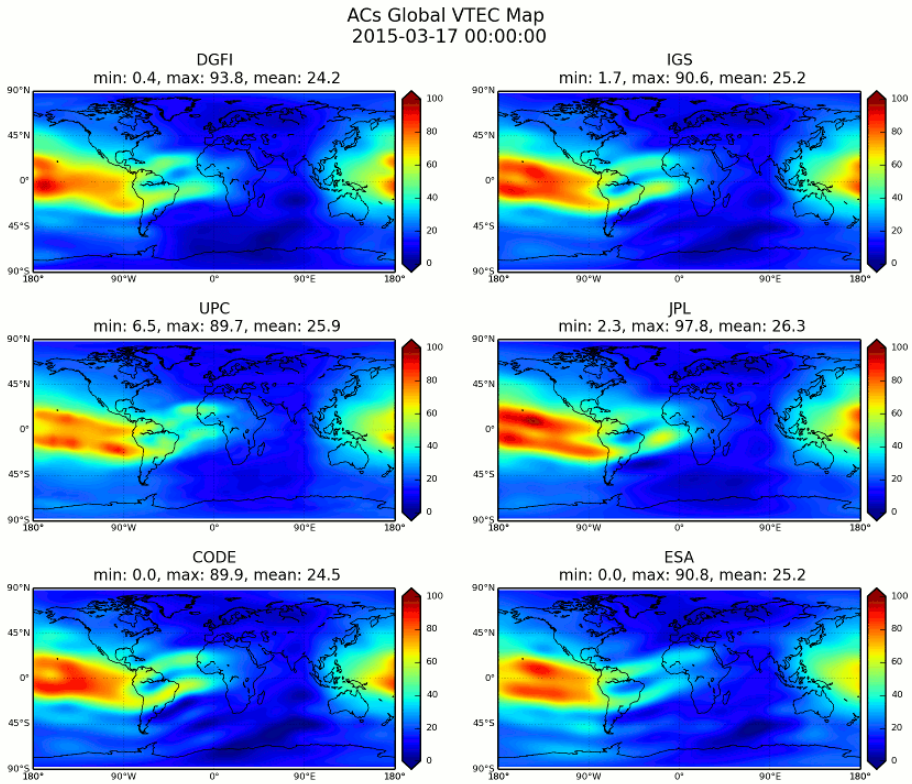
Sequential Processing: Kalman Filter

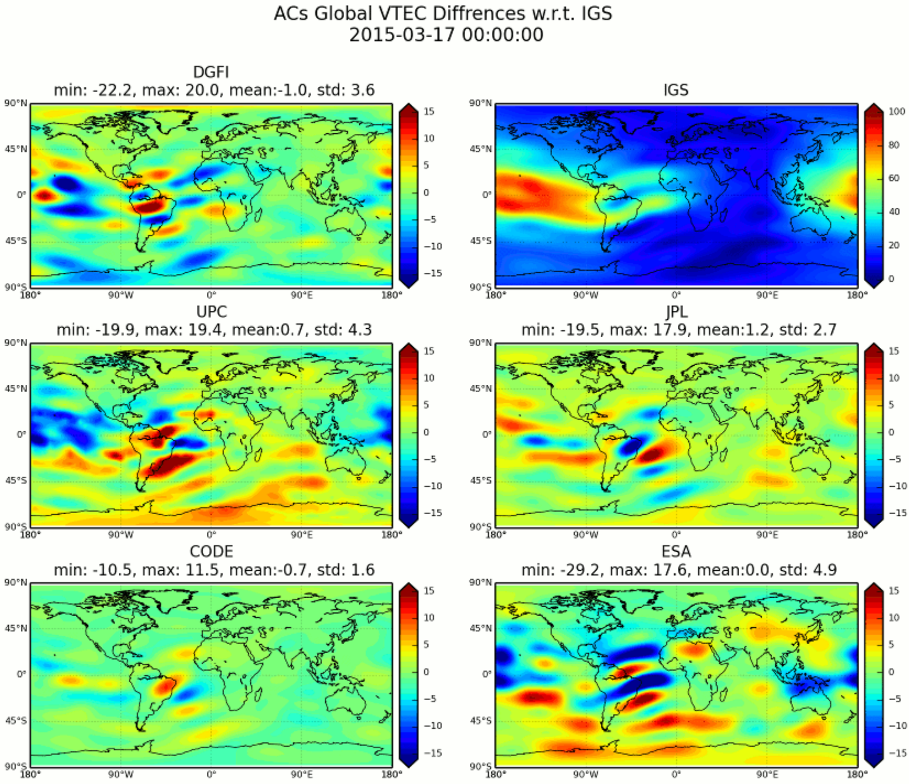


- A **Kalman filter** is used to estimate the unknown parameters **sequentially**.
- The **state vector** of the unknown parameters is **updated every minute** with the new observations.
- Currently, the **random walk** model is used for time variation of the filter (prediction or time update).

Validation during an Ionospheric Storm: Comparisons to IGS and ACs Final Products

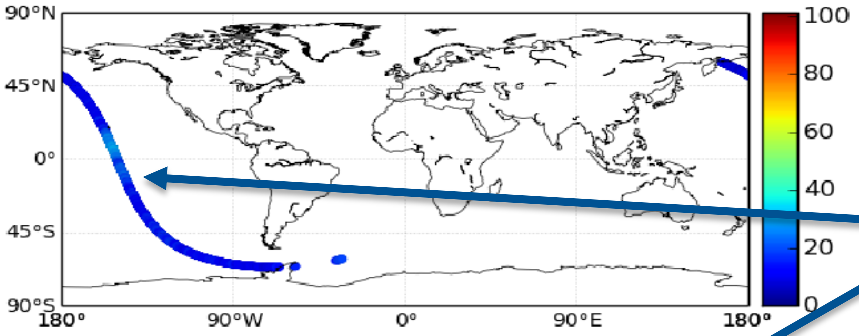
A case study for St. Patrick storm (DOY 76, 2015)





Validation during an Ionospheric Storm: Comparisons to Jason-2 Altimetry data

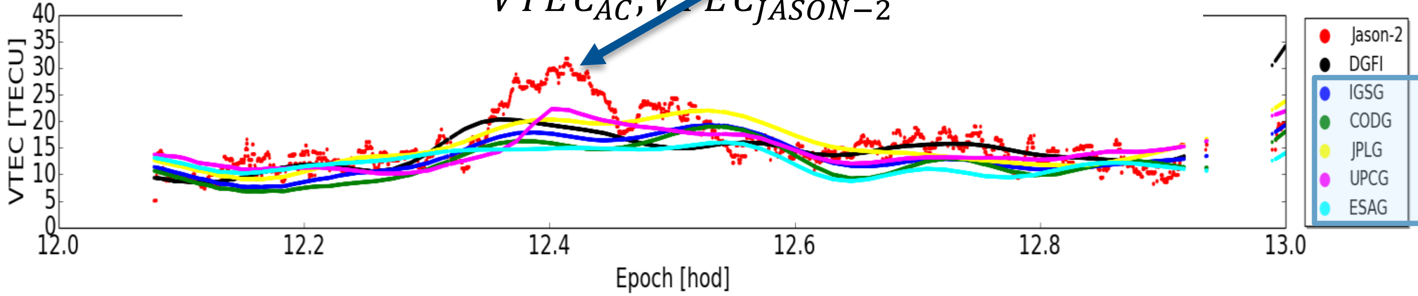
A case study for St. Patrick storm



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

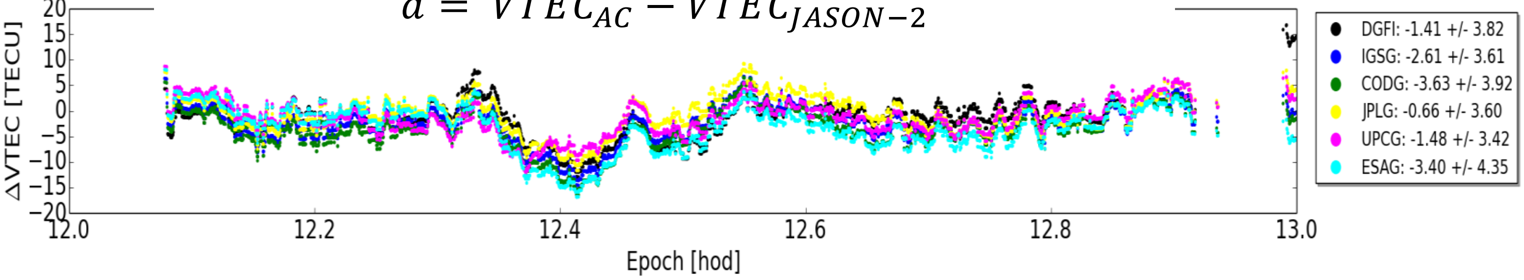
Median Filtered VTEC time series from Jason-2 satellite

$$VTEC_{AC}, VTEC_{JASON-2}$$



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

$$d = VTEC_{AC} - VTEC_{JASON-2}$$



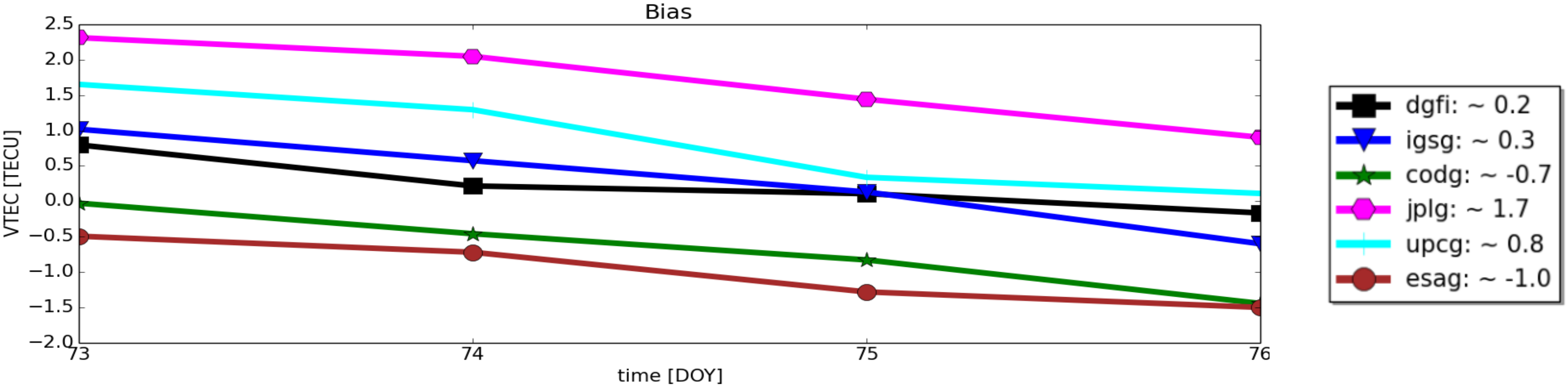
Differences between ACs VTECs and Altimetry VTEC data

Validation during an Ionospheric Storm: Comparisons to Jason-2 Altimetry data

A case study for St. Patrick storm

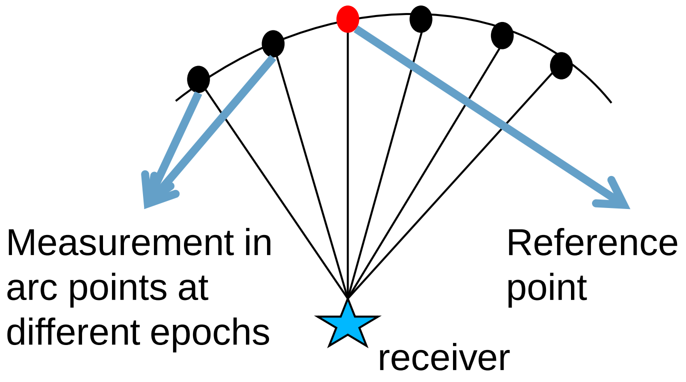
Summary of statistics for the daily differences between 14 March 2015 (DOY 73) and 17 March 2015 (DOY 76)

$$d = VTEC_{AC} - VTEC_{JASON-2}$$



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)**



$$L_c = L_1 - L_2 = STEC + b$$

GPS L1 phase measurements

GPS L2 phase measurements

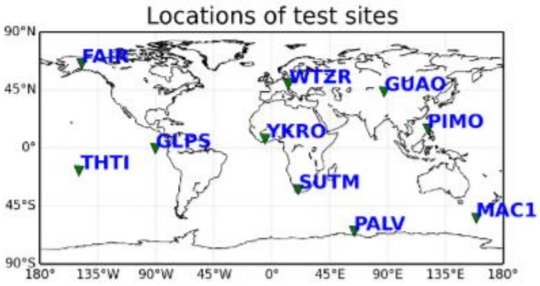
Slant total electron content

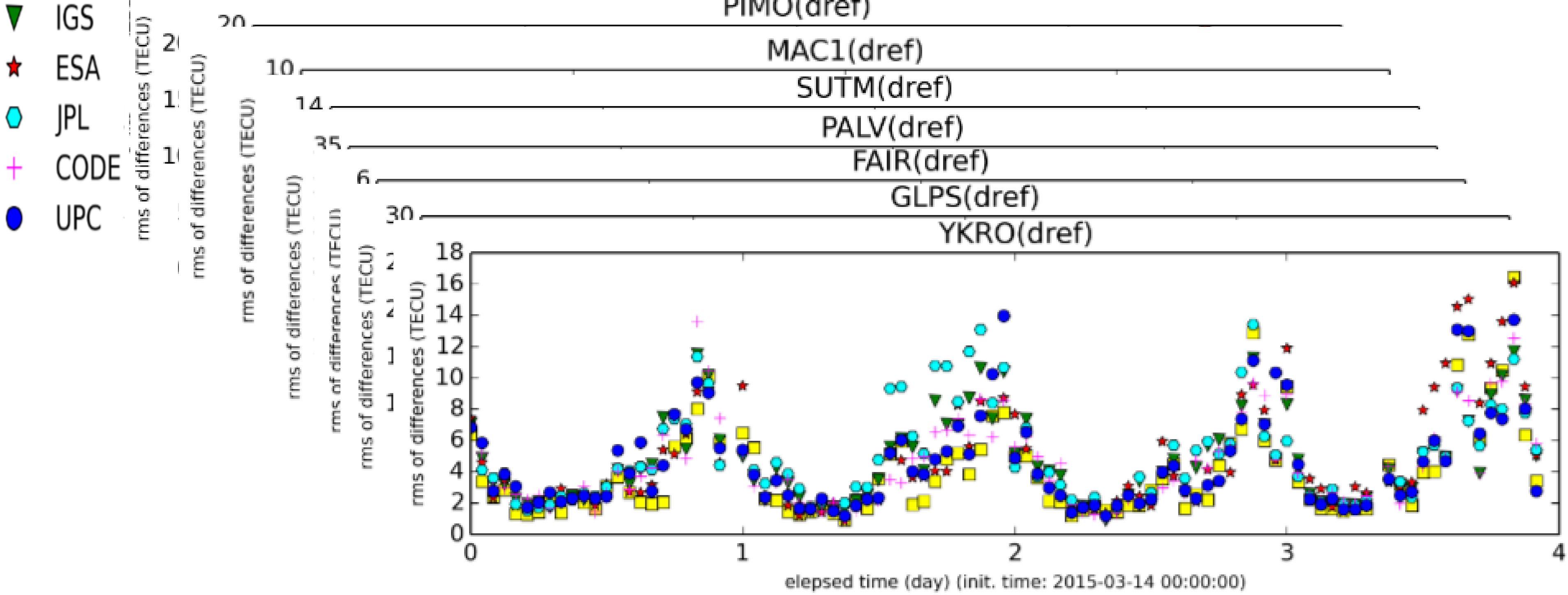
Bias (constant along the arc)

- Computation of the differences

$$d = \underbrace{\left[L_c(t_k) - L_c(t_{\mathrm{ref}})\right]}_{\textbf{Differential STEC computed from measurements}} - \underbrace{\left[STEC_p(t_k) - STEC_p(t_{\mathrm{ref}})\right]}_{\textbf{Differential STEC computed from VTEC products } (p)}$$

Validation during an Ionospheric Storm: Self Consistency Analysis





Mean RMS	WTZR	THTI	PIMO	MAC1	SUTM	PALV	FAIR	GLPS	YKRO
DGFI	1.4	5.9	4.6	3.1	1.6	2.5	1.8	6.5	4.0
IGS	1.9	5.0	4.3	2.9	1.9	2.4	1.8	5.1	4.7
ESA	2.1	6.6	4.2	3.2	2.9	2.8	2.1	5.6	4.8
JPL	1.6	5.2	4.8	2.6	1.8	2.6	1.8	5.5	5.0
CODE	1.5	4.7	3.8	3.4	1.8	2.5	1.8	4.7	4.5
UPC	1.8	5.8	3.8	2.6	2.0	2.1	1.7	4.8	4.6

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.