Estimation of Global Ionosphere VTEC Maps by the Combination of Satellite Observation Techniques based on Kalman-Filtering

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OPTIMAP
Operational Tool for Ionosphere Mapping and Prediction

Outline

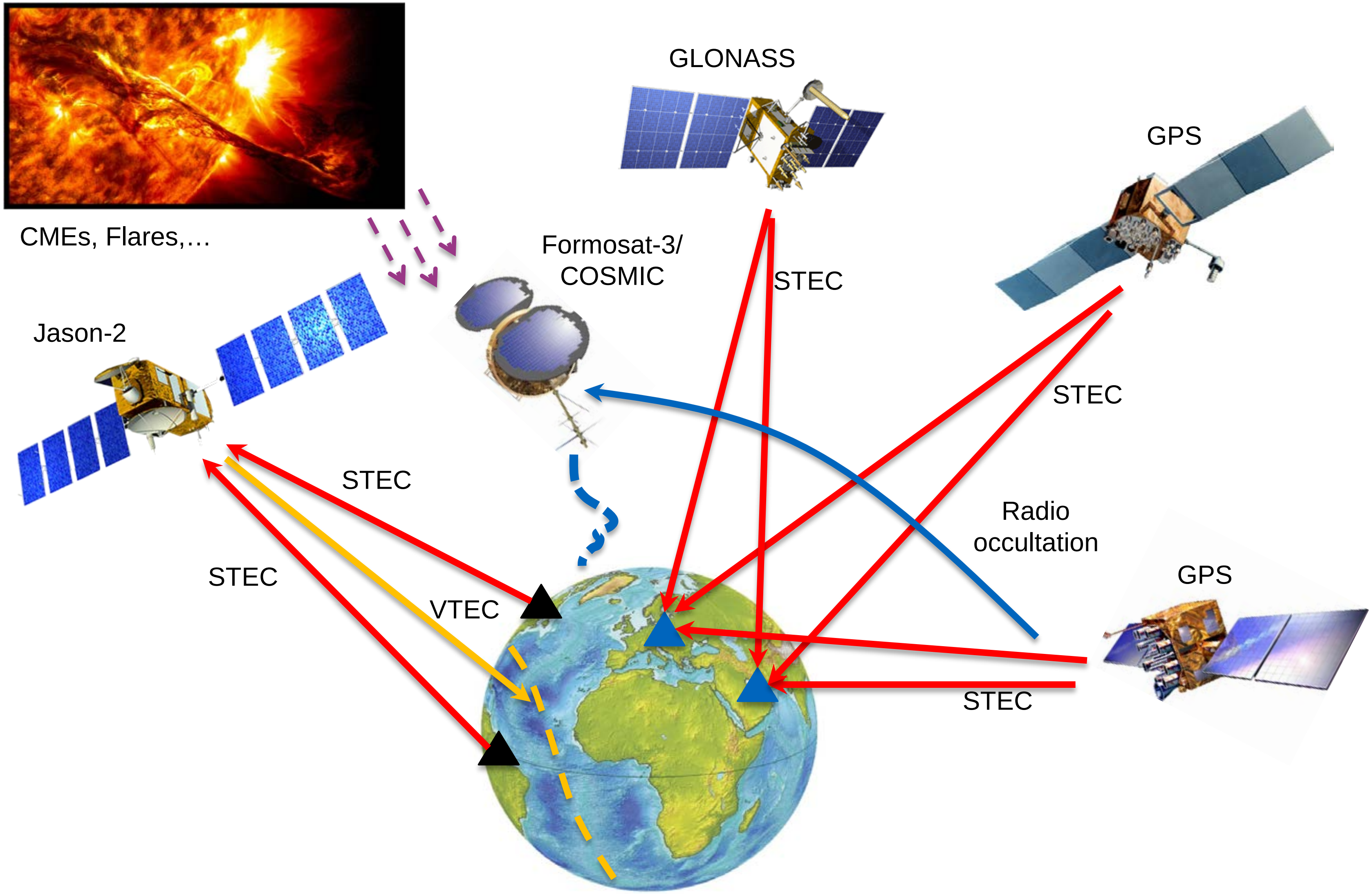
Introduction

- Within the project Optimap we aim on the development of an operational ionospheric monitoring and modeling tool to provide
  - VTEC maps (**global and regional**),
  - VTEC maps on the basis of **electron density modeling** (global and regional),
  - VTEC values for the **ephemerides** of low Earth orbiting (LEO) satellites,
  - VTEC **forecasts** for several days.

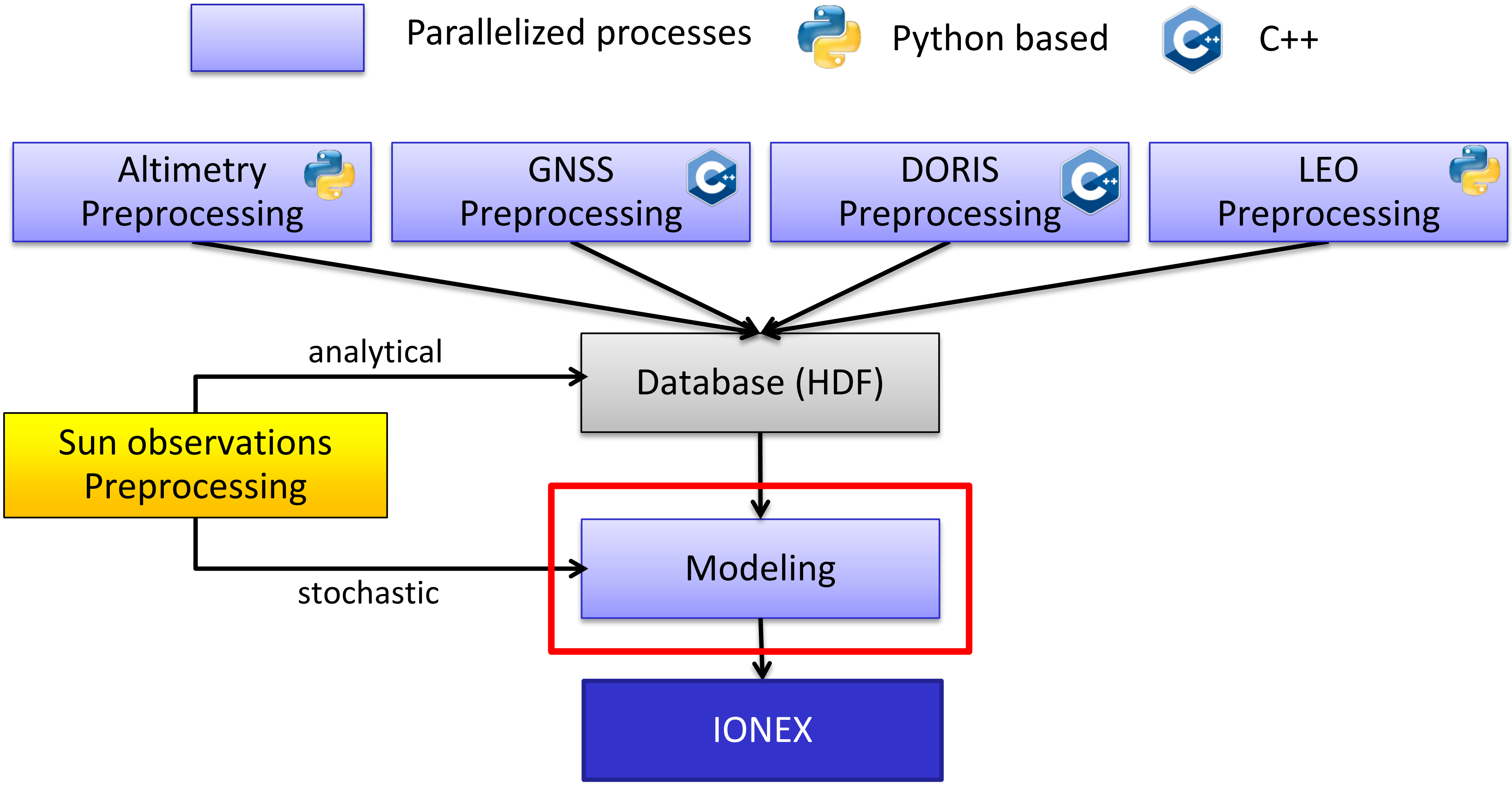
- For achieving these goals different issues have to be implemented:
  - **combination** of different space geodetic observation techniques,
  - **sequential** data processing,
  - incorporation of **Sun observations**.

- Project Partners
  - German Geodetic Research Institute of the Technical University of Munich (DGFI-TUM)
  - Institute of Astrophysics at the University of Göttingen (IAG)
  - German Space Situational Awareness Centre (GSSAC)
  - Bundeswehr GeoInformation Centre (BGIC)

Observation Techniques: Overview

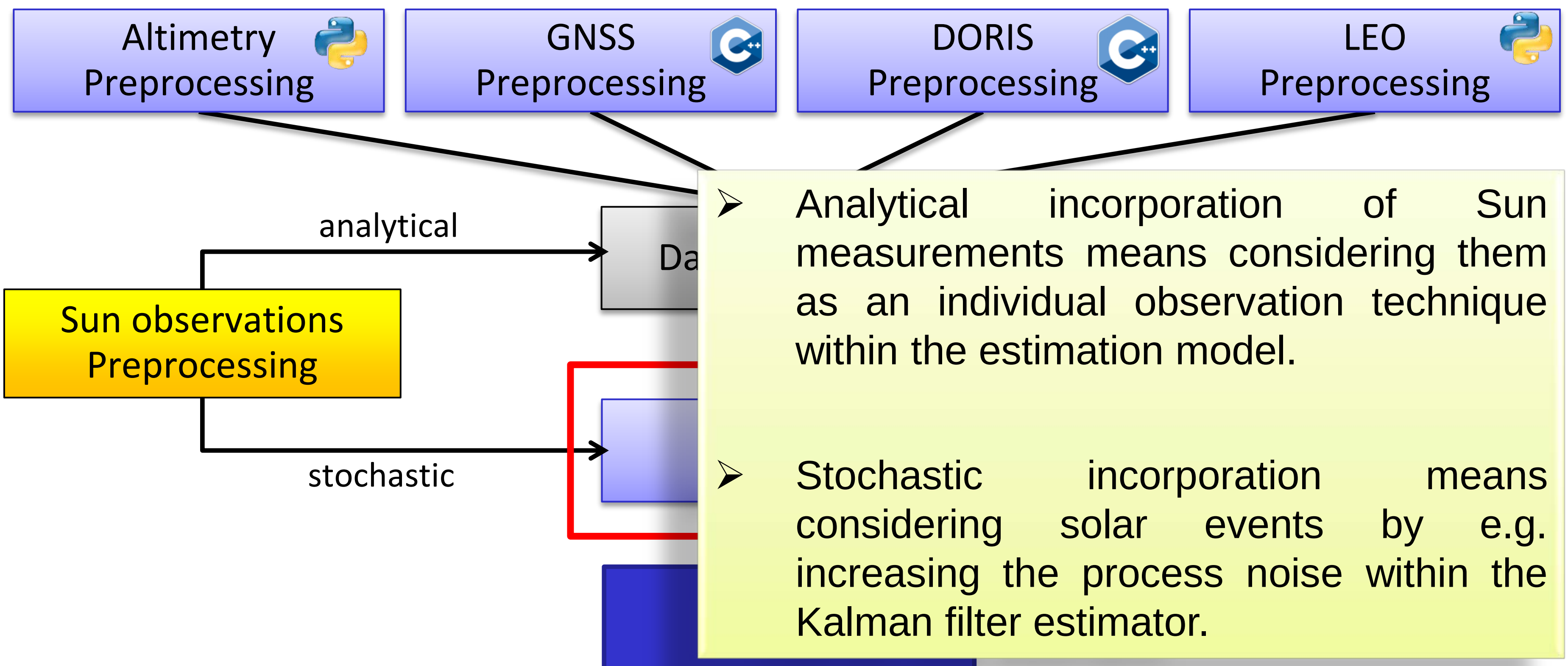


Observation Techniques: Process Flowchart



Observation Techniques: Process Flowchart

Parallelized processes | Python based | C++

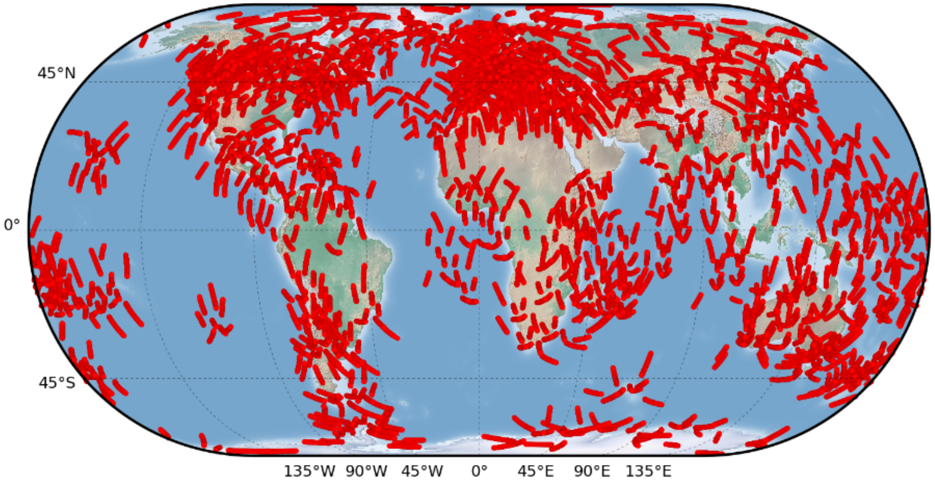


- Analytical incorporation of Sun measurements means considering them as an individual observation technique within the estimation model.

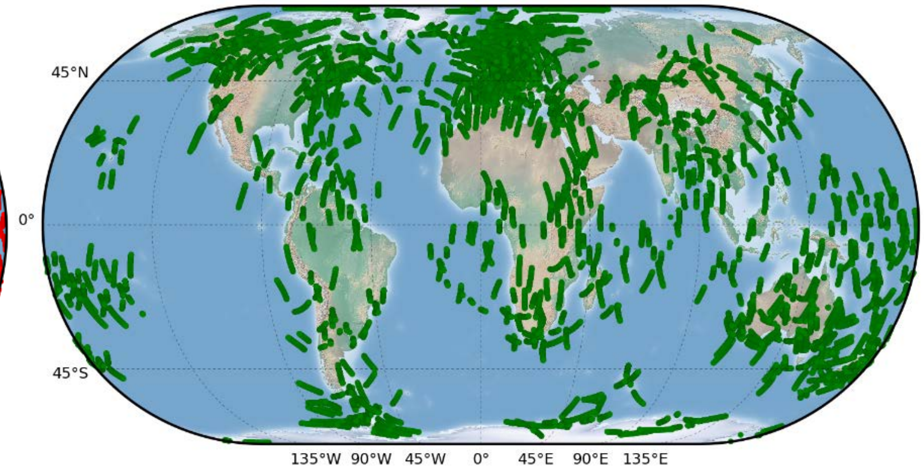
- Stochastic incorporation means considering solar events by e.g. increasing the process noise within the Kalman filter estimator.

Observation Techniques: GNSS Preprocessing

GPS

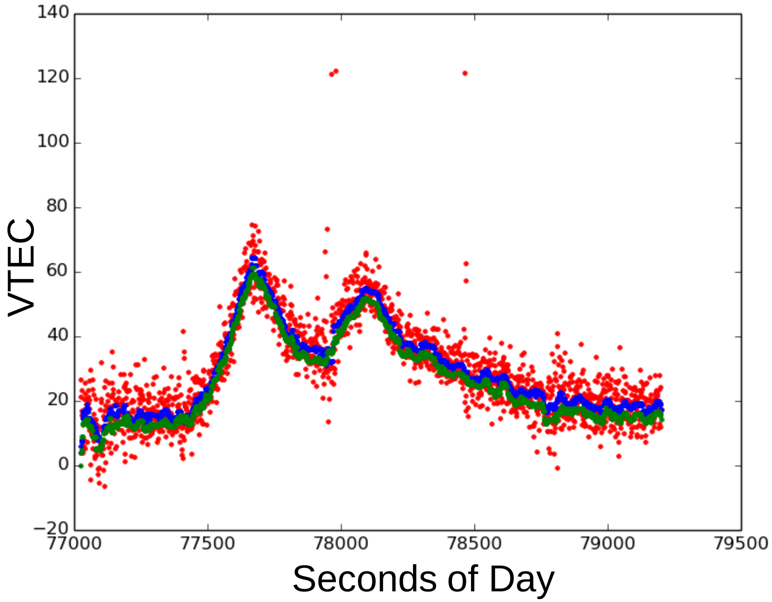


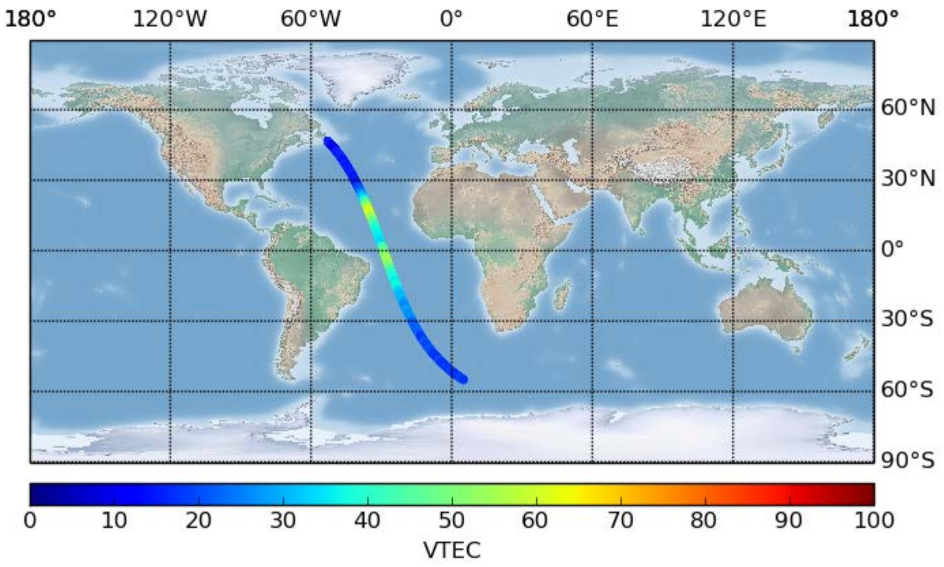
GLONASS



- 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.

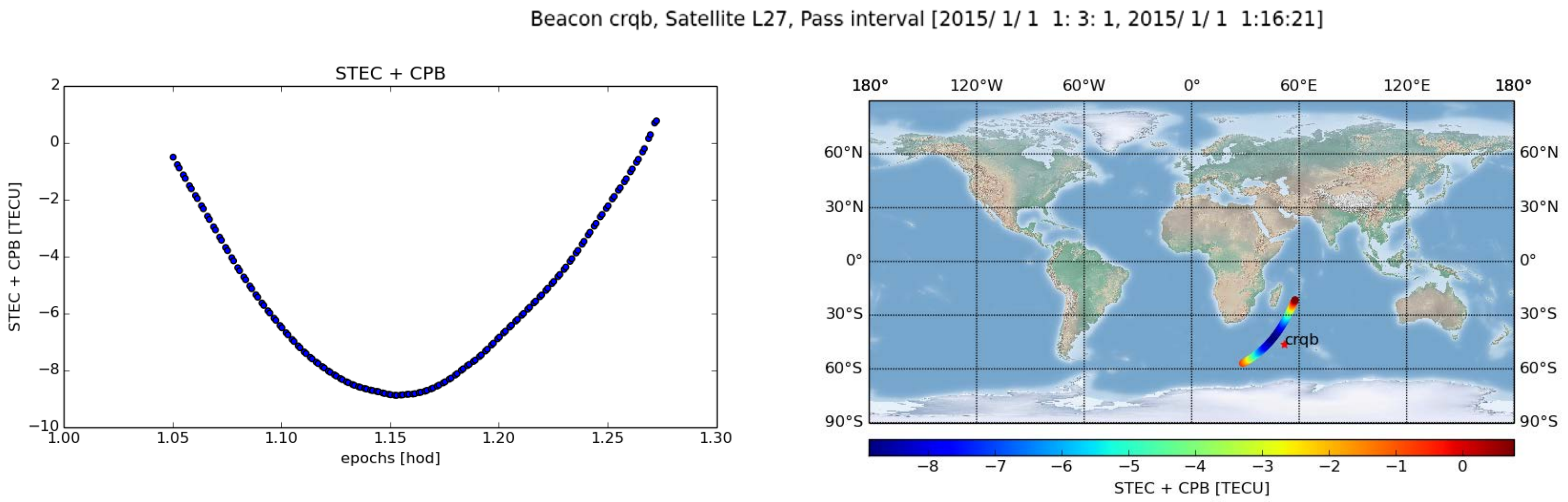
Observation Techniques: Altimetry Preprocessing





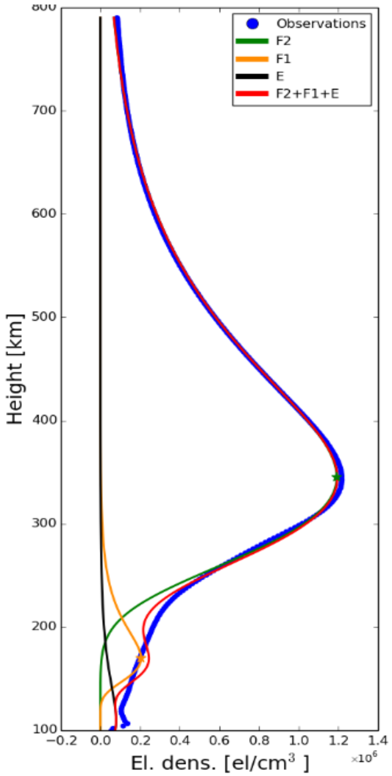
- **Jason-2 hourly batch** as observed on January 3, 2014 between 21:00 and 22:00 UT
- Left: **Original VTEC** (red), **median filtered** (blue)
- **Measurements** over water surfaces along satellite track

Observation Techniques: DORIS Preprocessing

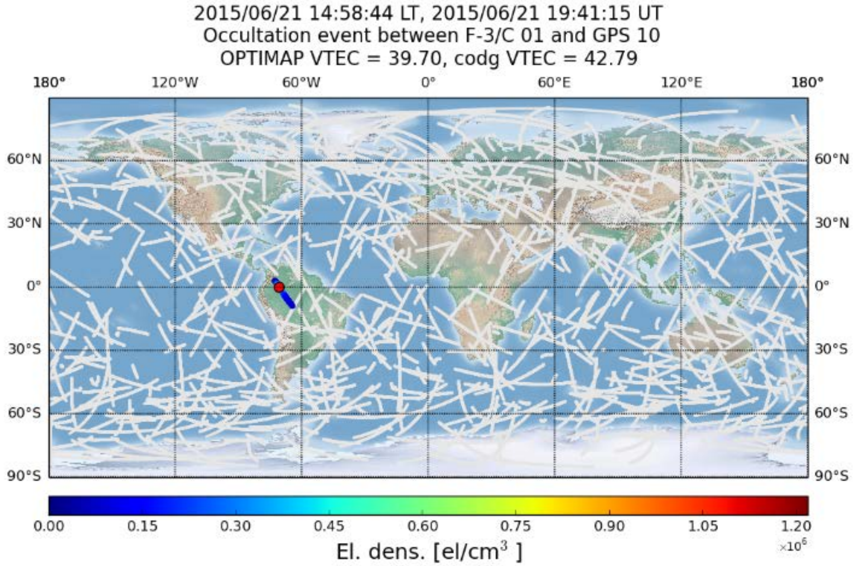


➢ DORIS **biased STEC** observations through a pass of the satellite observed on January 1, 2015.

Observation Techniques: Radio Occultation (RO)



➢ RO measurements from the Formosat-3/COSMIC) mission provide **electron density profiles**, then VTEC is obtained by **integrating** the electron density along the height.



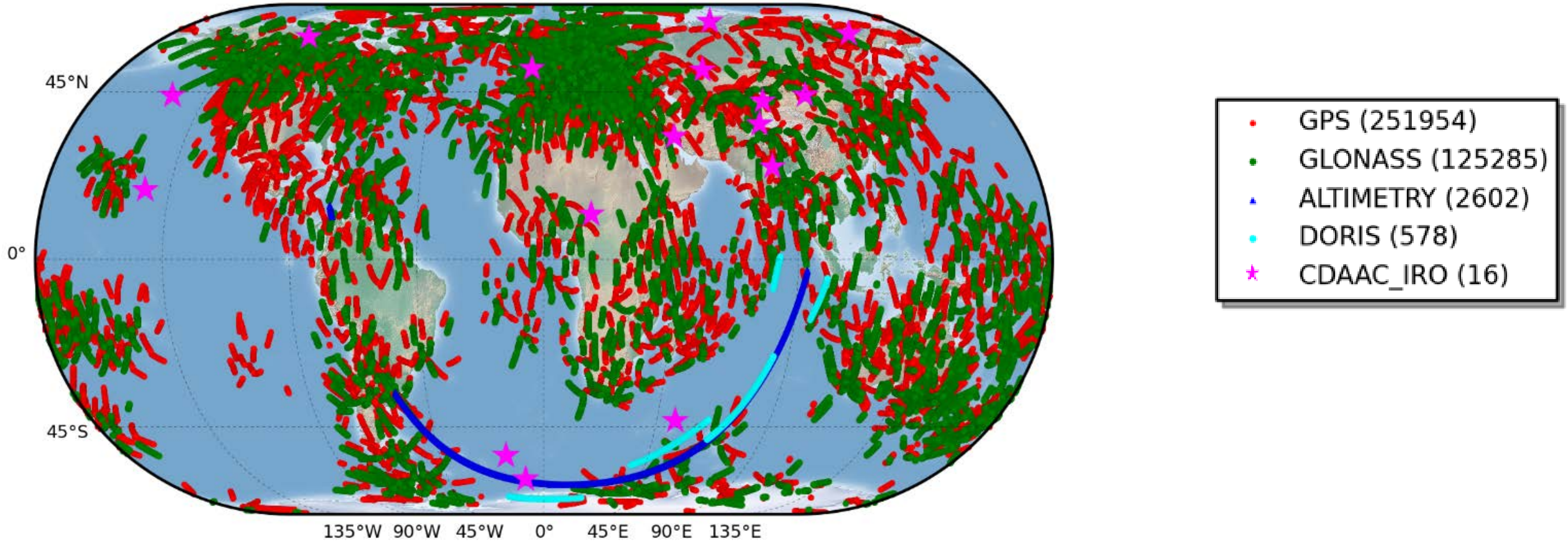
➢ Figure on the left side shows a sample density profile from F-3/C mission on June 21, 2015. Blue dots represents the observations.

➢ Figure on the right side shows the location of the density observation and estimated Multi - Chapman functions

➢ Assumption: profiles are vertical with their F2 peak as a localization point, i.e .: $\mathrm{VTEC} = \int_{h_1}^{h_2} N_e dh$

Observation Techniques: Overall Data Distribution

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



- Terrestrial **GPS and GLONASS** observations provide a **high-resolution coverage** of continental regions.
- Large **data gaps** exist especially over the oceans.
- Additional satellite-based techniques can mitigate the data gap problem as well as contribute to a data densification on the terrestrial regions

Observation Techniques: Overall Data Distribution

- It should be noted that, the key point of the project is to provide Ionosphere products with **low latency** and **high accuracy**.

- ***Therefore, modelling approaches which require post-processed products are not used.***

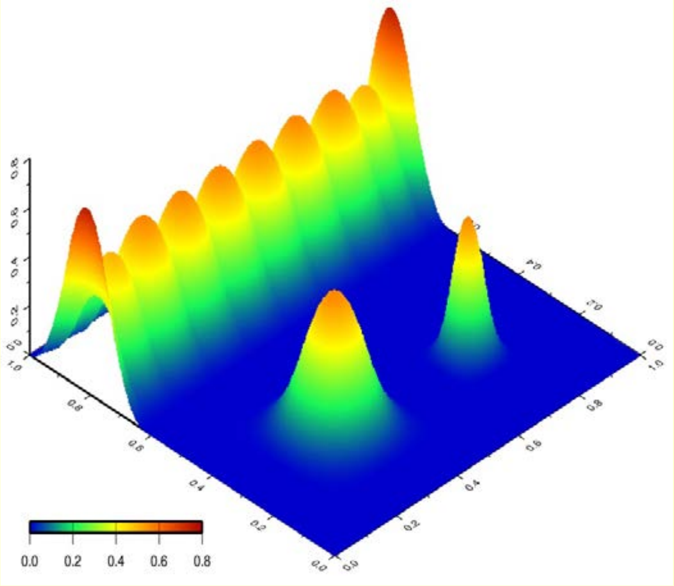
- Considering the **hourly GNSS observations** with improving number and distribution, **near-real time products** would be an alternative to the traditional ones.

- In this sense, providing TEC products in near real time using a **Kalman filter** plays an important role in the project.

VTEC Representation: Uniform B-splines (UBS)

- 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

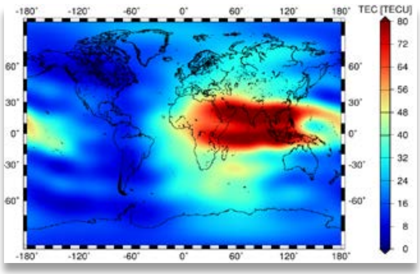


- Base functions are only different from zero in a local environment (compact support)
- The compact support can allow:
  - modification of present data and
  - incorporation of new measurements **without causing global effect**
- Data gaps can be handled appropriately,
- The approach can be applied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

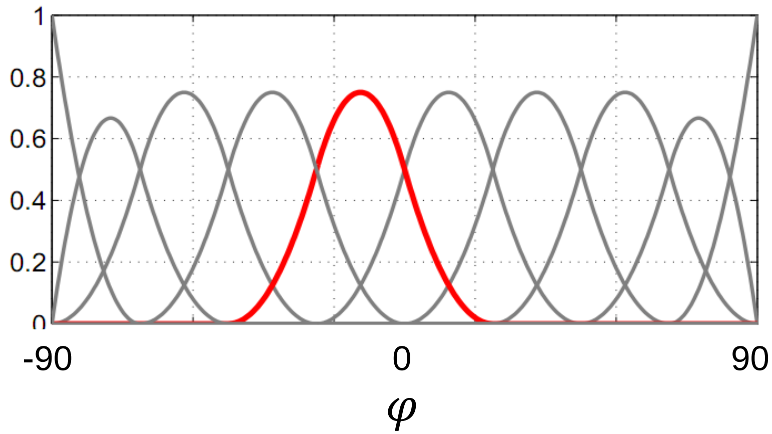
VTEC Representation: Uniform B-splines (UBS)

- 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

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

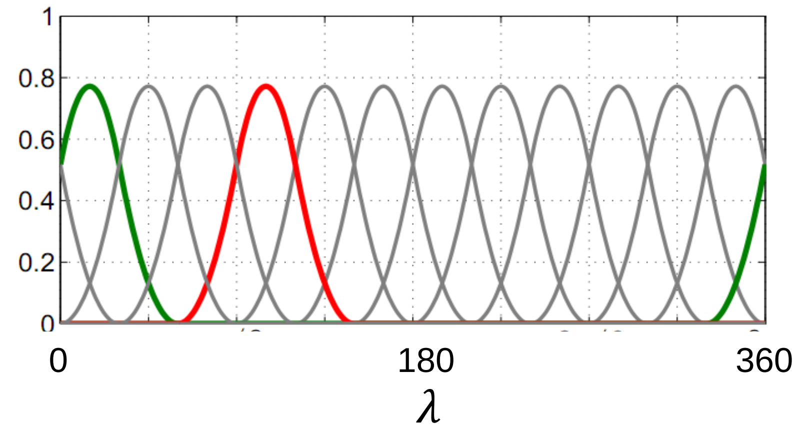


Polynomial B-spline functions N^2_{3,k_1}



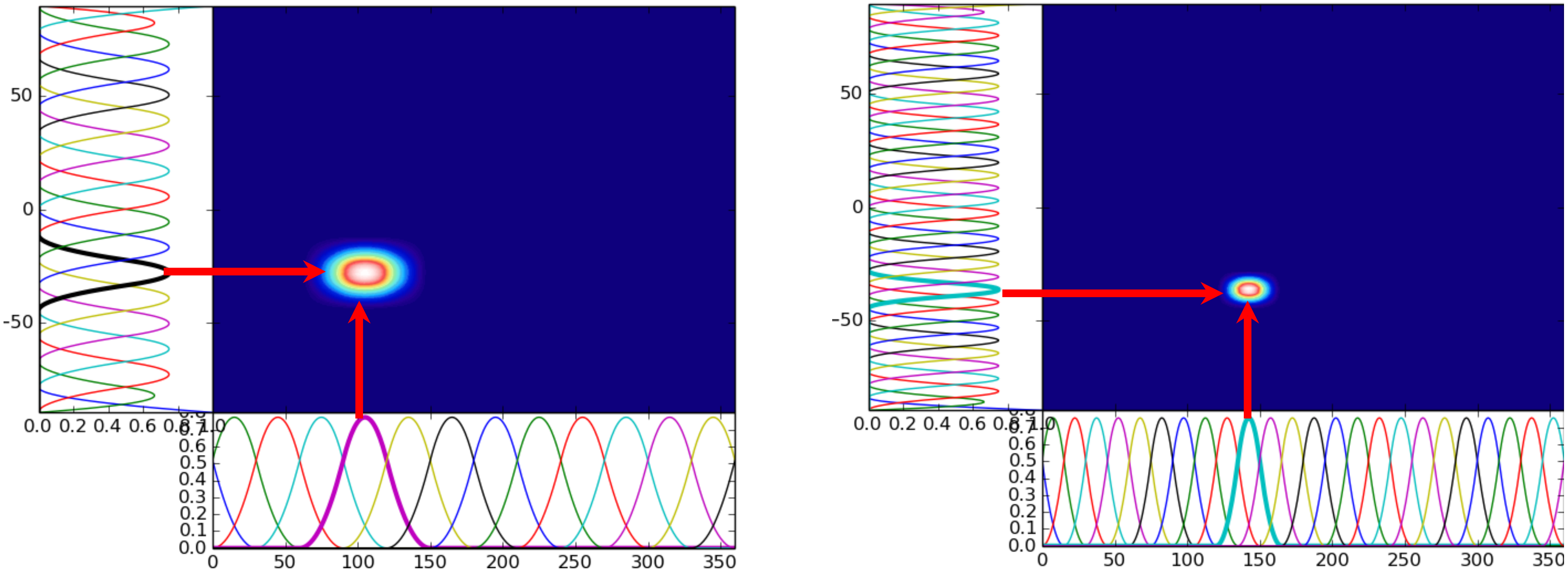
$J_1 = 3, K_3 = 10,\ k_1 = 0,1,\ldots,9$

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



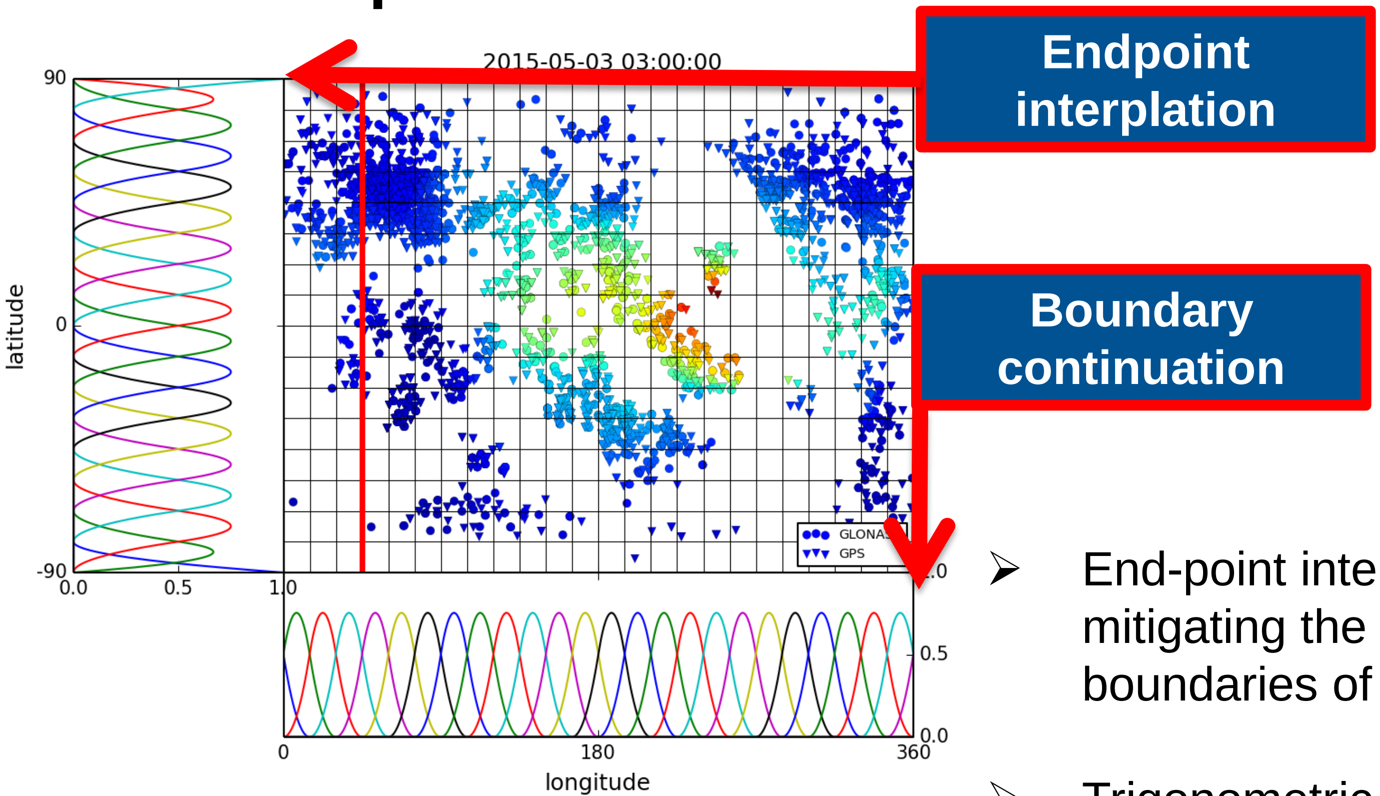
$J_2 = 2,\ K_2 = 14,\ k_2 = 0,1,\ldots,13$

VTEC Representation: UBS Model Resolution



- Tensor products of polynomial B-spline functions $N^2_{J_1,k_1}$ and trigonometric B-spline functions $T^2_{J_2,k_2}(\lambda)$
  - Left figure: levels $\boldsymbol{J_1 = 4, J_2 = 2}$
  - Right figure: levels $\boldsymbol{J_1 = 5, J_2 = 3}$
- The **higher** the chosen level values, the **finer** the structures could be modeled.

Uniform B-splines



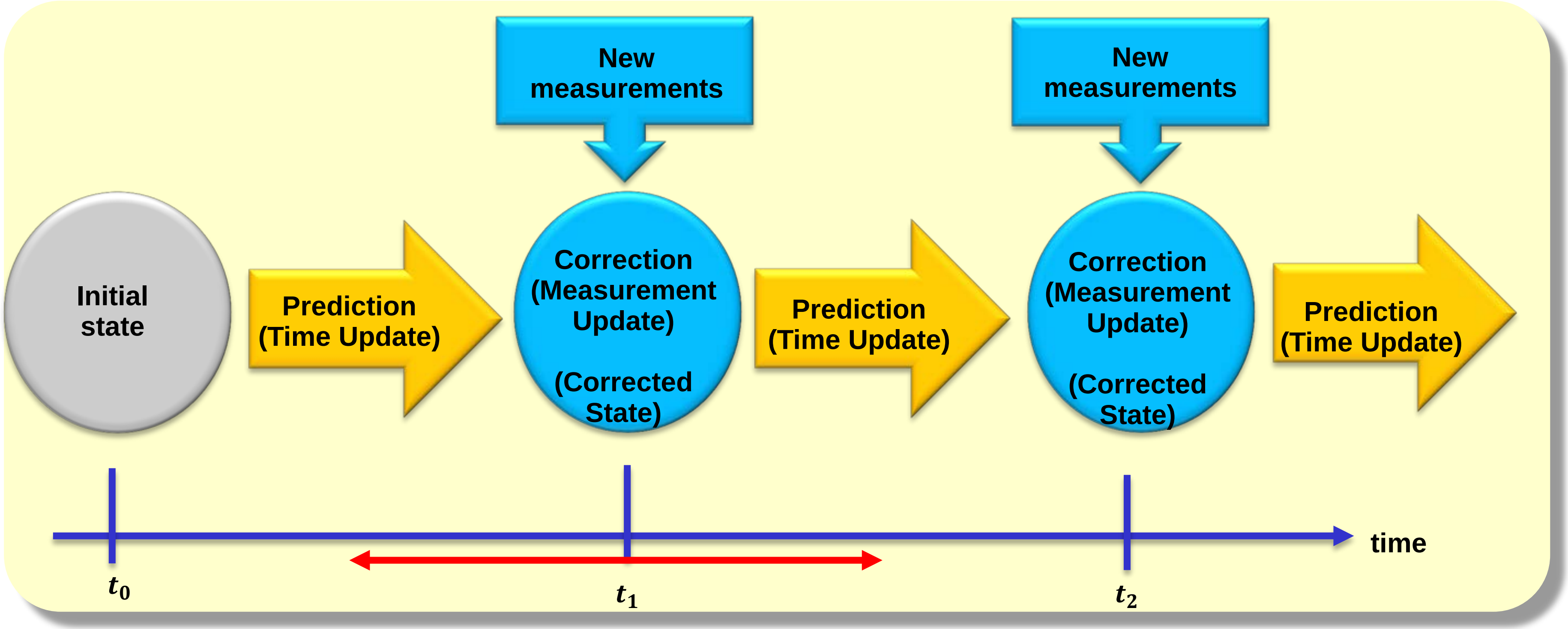
UBS; Sun-fixed coordinate system

- Level $J_1 = 3$ in longitude
- Level $J_2 = 4$ in latitude

➢ End-point interpolation is for mitigating the edge effect at the boundaries of the modelling area.

➢ Trigonometric B-spline functions are useful to preserve continuities at the boundaries of the modelling area

Sequential Processing: Kalman Filter



- A Kalman filter is used to estimate the unknown parameters **sequentially**.
- The state of the filter consisting 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).

Sequential Processing: Kalman Filter

- General formulation of a time varying system

$$\beta_k^- = f(\hat{\beta}_{k-1}, w_k)$$

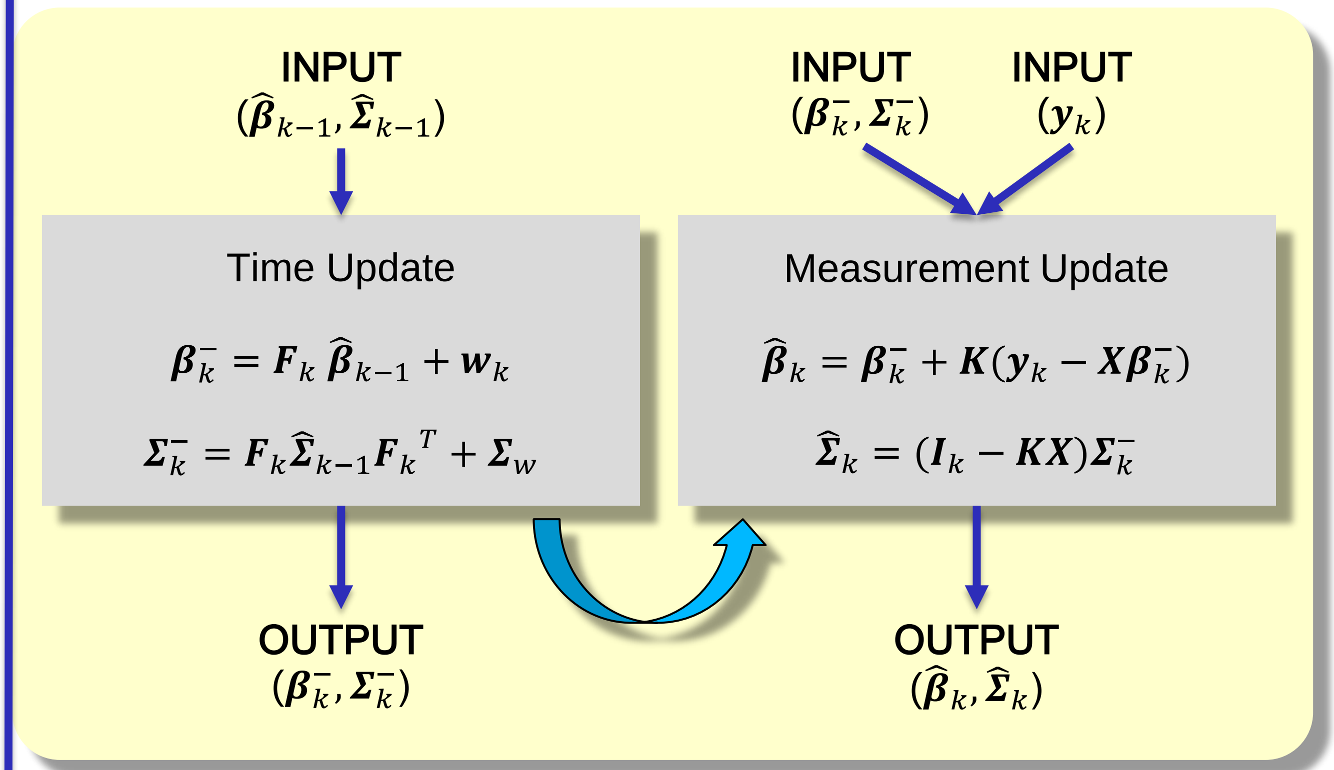
$$y_k = h(\beta_k, e_k)$$

- Measurement error e_k and process noise w_k are assumed to be Gaussian white noise with the following properties

$$\mathrm{E}(e_i\, e_j^T) = \Sigma_e \delta_{i,j}$$

$$\mathrm{E}(w_i\, w_j^T) = \Sigma_w \delta_{i,j}$$

$$\mathrm{E}(e\, w^T) = 0$$



Sequential processing with **discrete time Kalman Filter**

Sequential Processing: Measurement Model

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

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

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

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

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

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

Overall state vector for the unknown parameters

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

Sequential Processing: Prediction Model

- Ionosphere modelling problem is handled in a **Sun-fixed reference** system
- Ionosphere changes much more slowly in the Sun-fixed frame, because the **effect of the Earth's diurnal motion** is mitigated.
- This approach allows use of simple models to represent the time variation of the VTEC model parameters (e.g. random walk)

$$\boldsymbol{\beta}_k = \boldsymbol{F} \; \boldsymbol{\beta}_{k-1} + \boldsymbol{w}_{k-1}$$

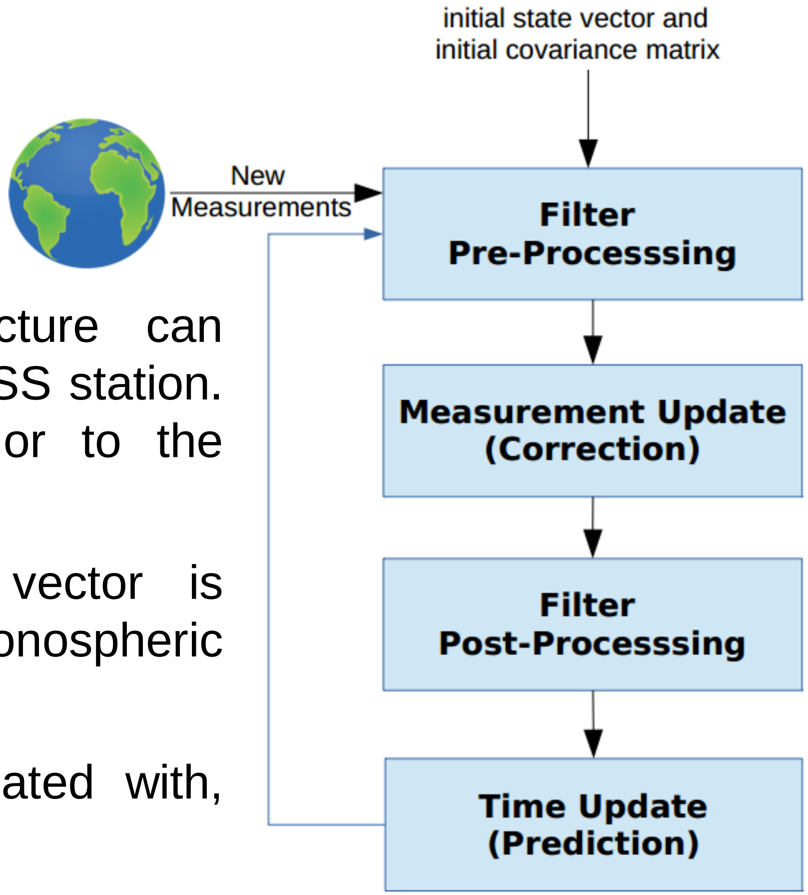
$$\begin{bmatrix} d \\ \boldsymbol{b}_{GPS} \\ \boldsymbol{b}^{GPS} \\ \boldsymbol{b}_{GLO} \\ \boldsymbol{b}^{GLO} \\ b_{alt} \\ b_{IRO} \\ b_{DOR} \end{bmatrix}_k \qquad \begin{bmatrix} d \\ \boldsymbol{b}_{GPS} \\ \boldsymbol{b}^{GPS} \\ \boldsymbol{b}_{GLO} \\ \boldsymbol{b}^{GLO} \\ b_{alt} \\ b_{IRO} \\ b_{DOR} \end{bmatrix}_{k-1}$$

$$\boldsymbol{F} = \boldsymbol{I}$$

The state transition matrix $\boldsymbol{F}$ is equal to an identity matrix $\boldsymbol{I}$

Sequential Processing : Overview of Filtering Step

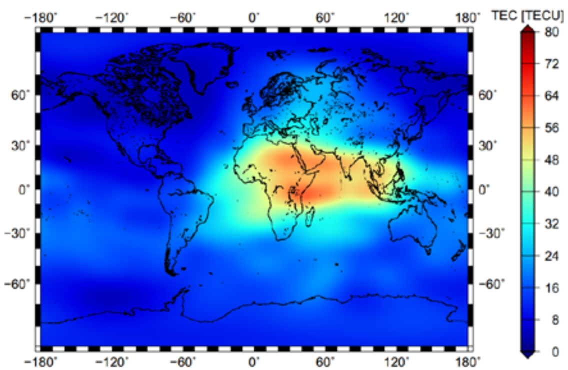
- All the observations are assimilated in a Kalman filter (KF) for modeling the global VTEC distribution. The KF allows for the **sequential processing** of measurements.



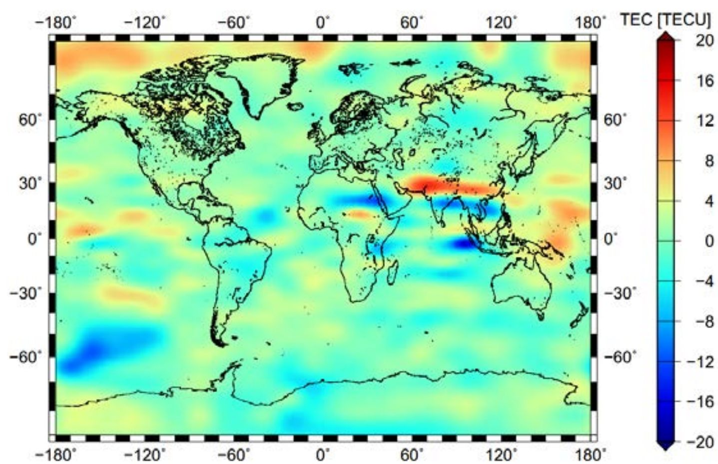
- **Pre-processing step:** The filter structure can change in time, e.g. by adding a new GNSS station. Therefore, the filter state is edited prior to the measurement update.
- **Measurement Update:** the current state vector is corrected immediately with new ionospheric observations.
- **Post-processing step:** This step is related with, e.g., storing the computed parameters
- **Time Update:** Once the filter state is corrected, the state is propagated to the next epoch using a proper prediction method.

Initial Results

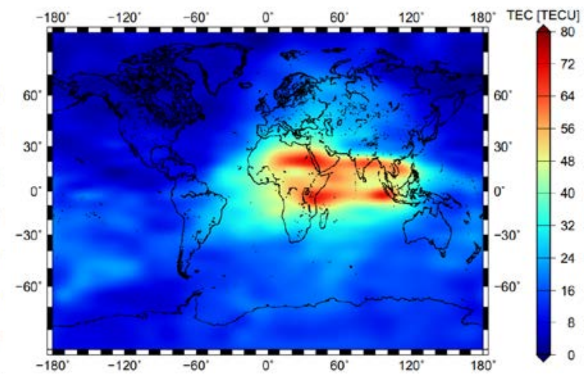
- Here, **first results** regarding the monitoring of global VTEC maps derived from **combination of different space geodetic techniques** are presented.
- For validation the post-processed IGS VTEC products with high accuracy are taken into account as a reference for comparisons.



IGS Final GIM



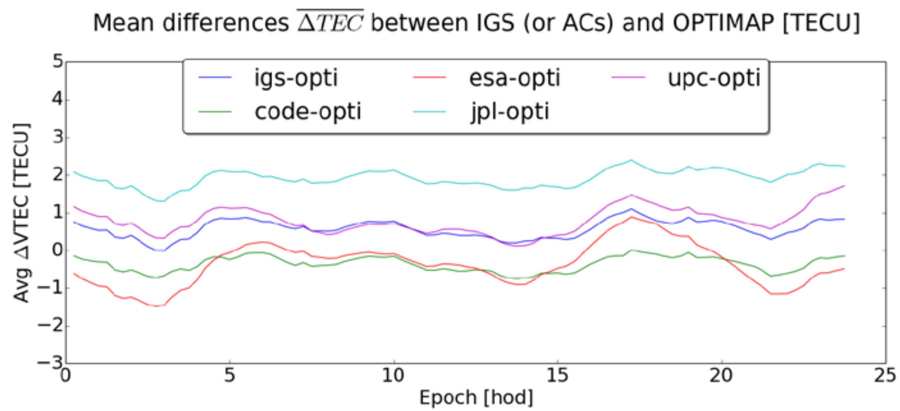
IGS Final - OPTIMAP

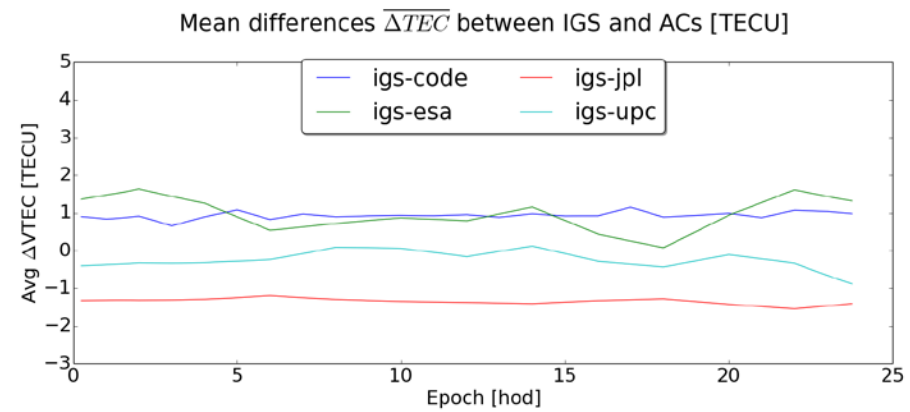


OPTIMAP GIM

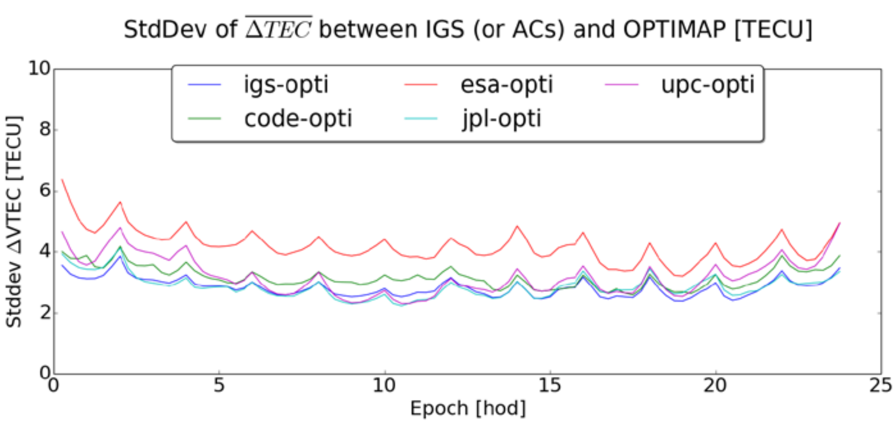
- Figures show VTEC maps for February 12, 2016 at 10:00h provided by OPTIMAP (right) and IGS (left). VTEC differences of IGS and OPTIMAP are depicted in the middle.

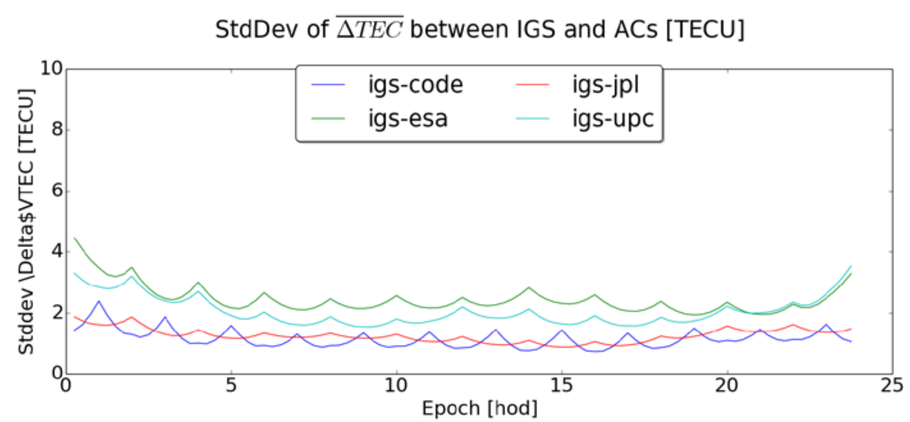
Initial Results





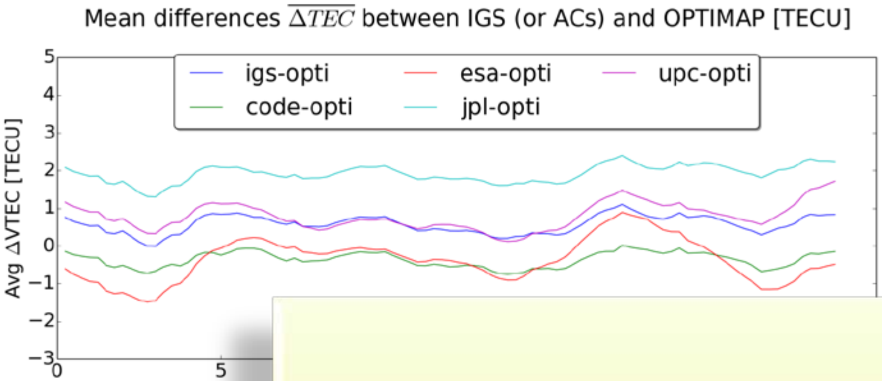
Global mean differences computed every 15 minutes on February 12, 2016 between the OPTIMAP product and the IGS /ACs (left) as well as the IGS and its ACs (right).

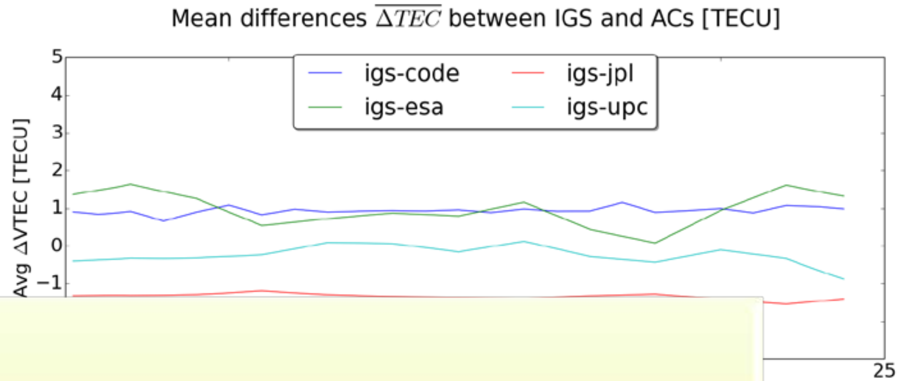




Standard deviations computed every 15 minutes for February 12, 2016 between the OPTIMAP product and the IGS /ACs (left) as well as the IGS and its ACs (right).

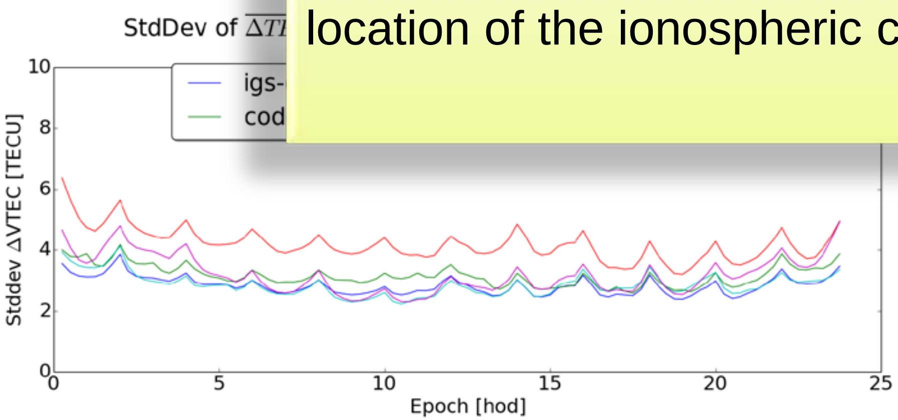
Initial Results

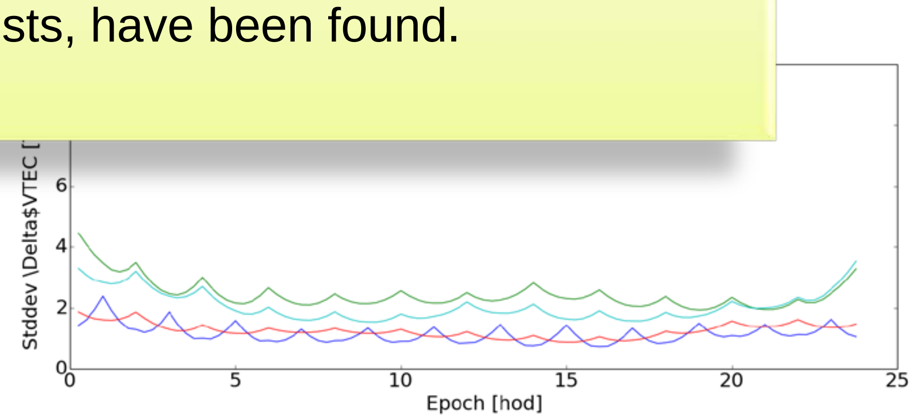




Global mean ... *en the OPTIMAP pro*...

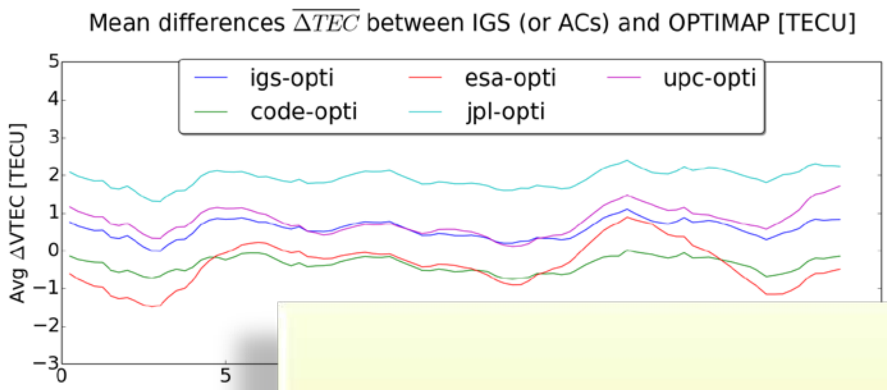
For February 12, 2016, mean differences between -1.5 and 2 TECU with standard deviations between 2 and 6 TECU w.r.t. VTEC maps of IGS and its ACs, mainly depending on the location of the ionospheric crests, have been found.

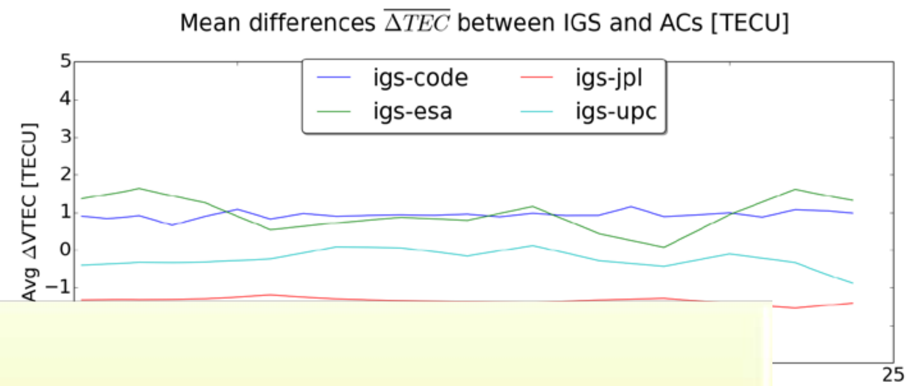




Standard deviations computed every 15 minutes for February 12, 2016 between the OPTIMAP product and the IGS /ACs (left) as well as the IGS and its ACs (right).

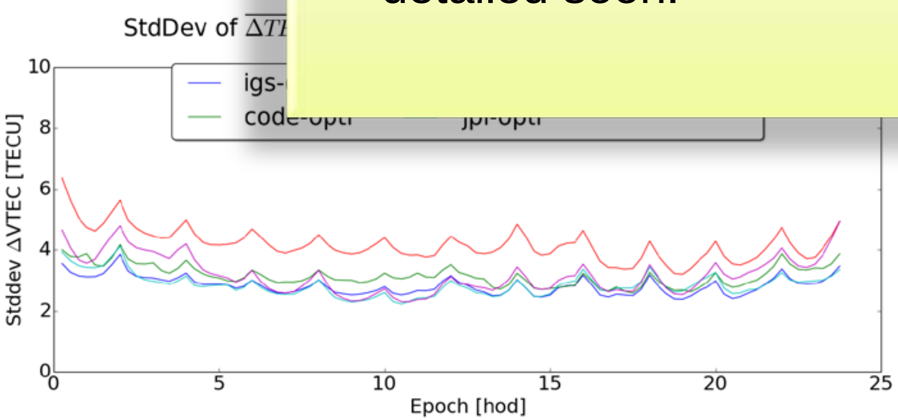
Initial Results

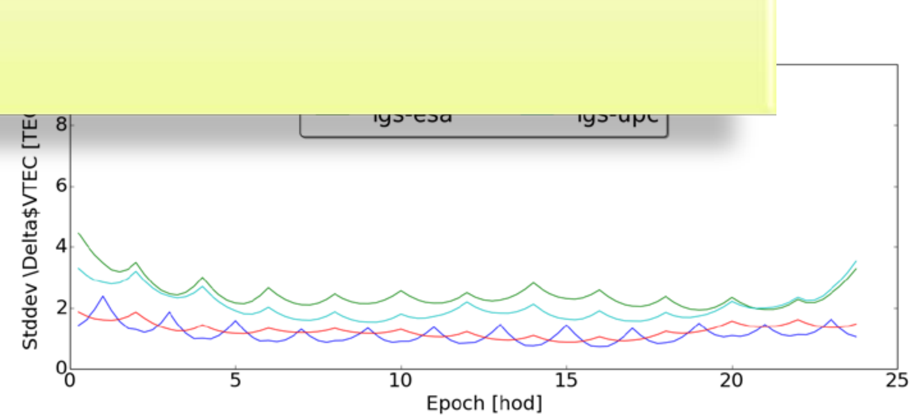




Global mean … *en the*
OPTIMAP pro …

Individual contribution of each of the observation techniques to the quality of estimated VTEC maps will be investigated in detailed soon.





Standard deviations computed every 15 minutes for February 12, 2016 between the OPTIMAP product and the IGS /ACs (left) as well as the IGS and its ACs (right).

Final Remarks

- All unknown parameters (B-spline coefficients, DCBs, offsets, etc.) are determined from a recursive parameter estimation, characterized by:
  - combination of different observation techniques
  - VTEC representation by B-splines
  - and Kalman filtering
- Near future considerations are
  - extending the VTEC modelling to an electron density modeling (2-D -> 3-D).
  - either analytic and/or stochastic incorporation of the Sun observations
  - combination of the global and regional modelling techniques for densification

Thank you very much for your consideration