Advanced algorithms for ionosphere modelling in GNSS applications within the AUDITOR project

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AUDITOR
ADVANCED MULTI-CONSTELLATION EGNSS
AUGMENTATION AND MONITORING NETWORK
AND ITS APPLICATION IN PRECISION AGRICULTURE

Introduction

- AUDITOR
  - is an acronym for “**Advanced Multi-Constellation EGNSS Augmentation and Monitoring Network and its Application in Precision Agriculture**”
  - is a project within the **Horizon 2020 programme** of the European Commission (EC),
  - was officially started in January 2016 with a running time of 2 years.
  - is a joint initiative of an **international consortium** of small and medium enterprises (SME) and universities under the leadership of a Spanish company.
- The main goal of the project is the implementation of a **novel precise positioning technique** – based on augmentation data – in a **customized GNSS receiver**.
- These new receivers will enable **cost-effective precision agriculture services** to farmers, especially those with small and medium-sized businesses in areas of Europe where **EGNOS coverage is poor**.
- Within the project four main concepts have to be developed
  - a **new receiver design** for precision farming,
  - the **processing of data** from continually operating GNSS network,
  - the **computation** and **delivery of the corrections** for the augmentation system and
  - **advanced algorithms** to improve the quality of the correction data (e.g. ionospheric corrections). (WP 4 of the work plan structure)

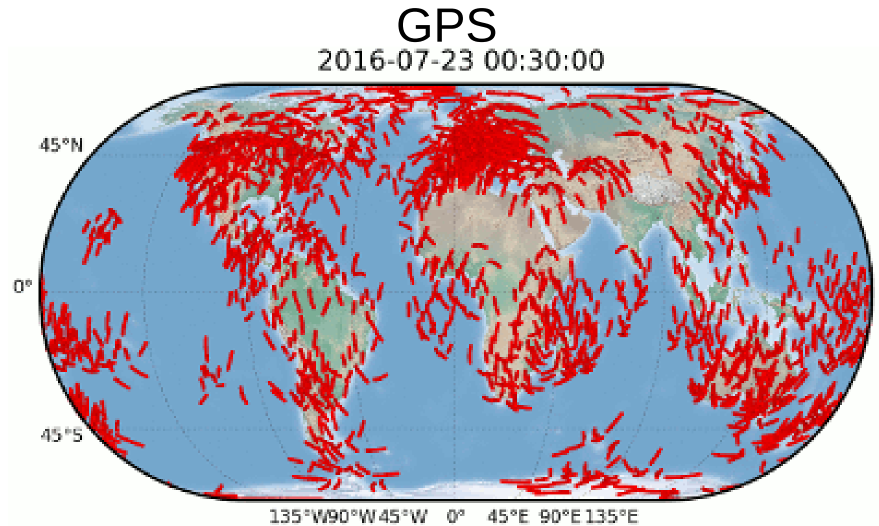
Introduction

- To reach this goal **sophisticated ionosphere models** have to be developed and implemented to increase the accuracy **in real-time** at the user side.
- The **scientific part** within the project has been performed mainly by DGFI-TUM and UPC, i.e. the involved universities.
- The main ambition of the project is to
  - **reduce the convergence time** of precise point positioning for multi-frequency receivers and to
  - **increase the accuracy** for single-frequency receivers.

Agricultural robots developed by the project partner DLO

Global and regional ionospheric modelling

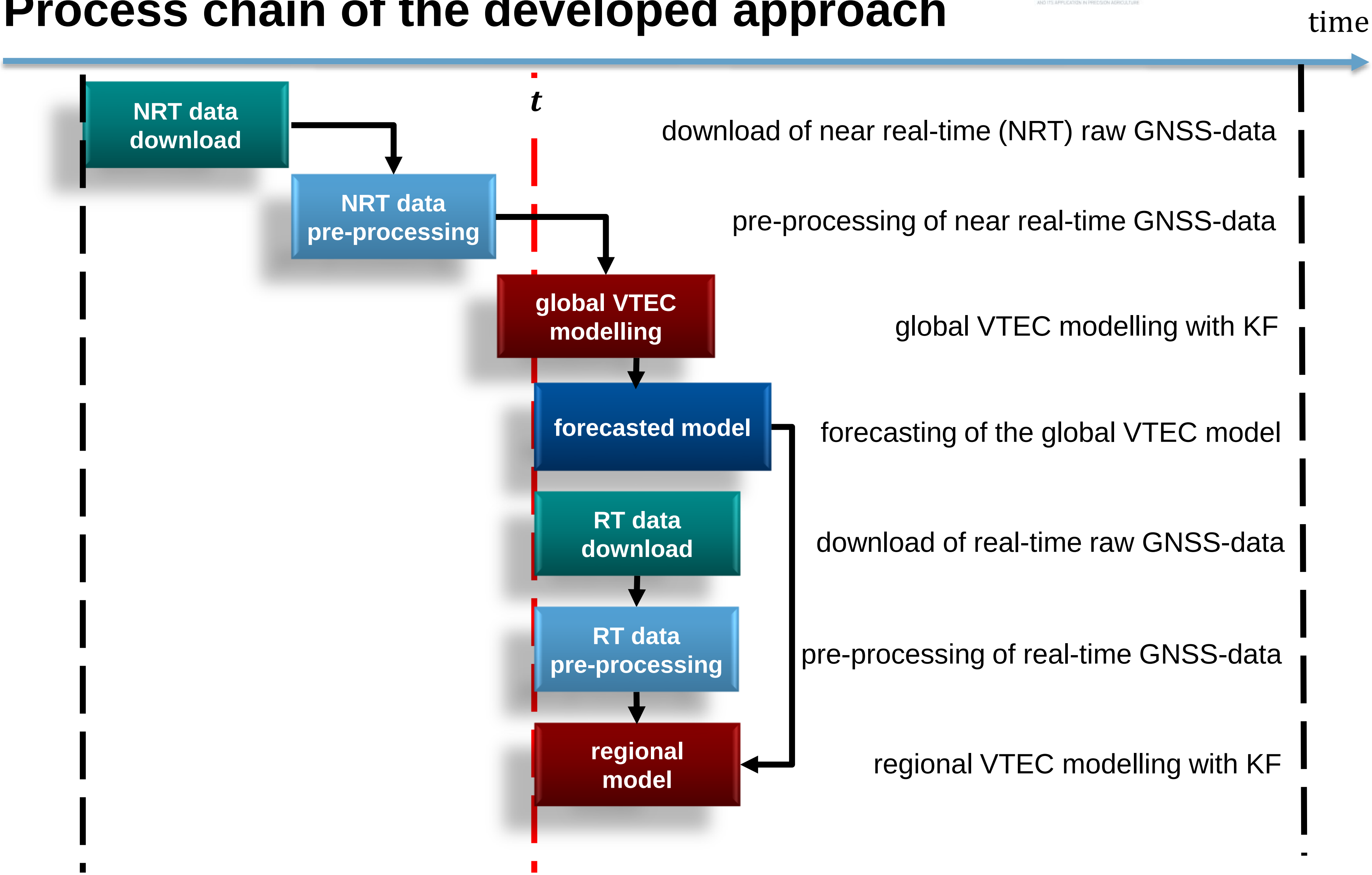
- One **goal** of the WP 4: **Advanced algorithms for GNSS** is to develop
  - global ionospheric **real-time products** with a **high-precision ionospheric information** for regions in Europe…
  - … based on an **data adaptive modelling approach** by means of appropriate B-spline series expansions.



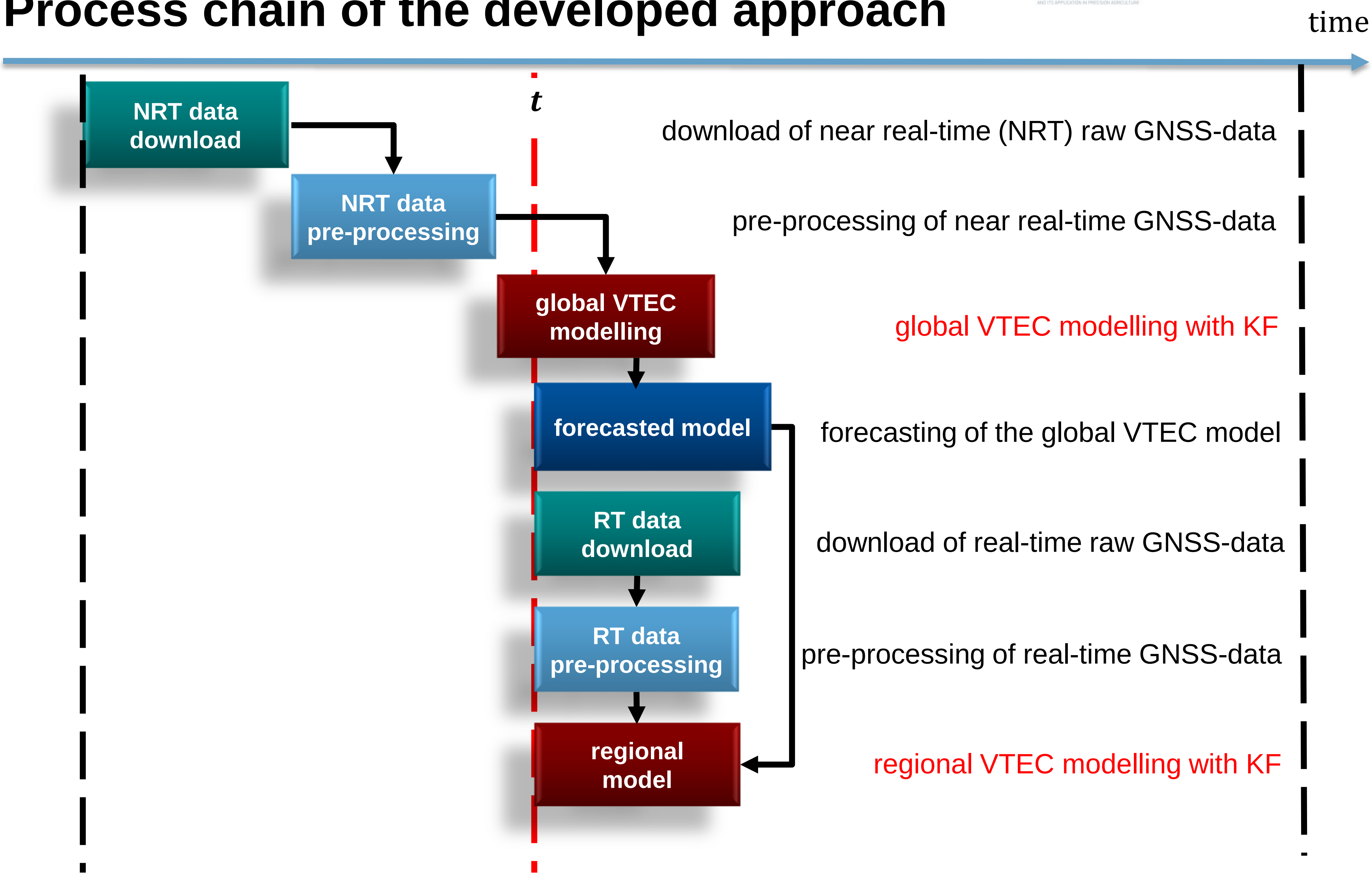
- Distribution of **ionospheric pierce points** (IPP) based on a batch of **hourly observation** on July 23, 2016.
- The terrestrial **GNSS observations** provide **high-resolution information** for specific continental regions, e.g., Europe or North America.
- In such areas a **global ionosphere model** for the vertical total electron content (VTEC) can be densified to a **regional ionospheric model**, according to

$$VTEC_{\mathrm{reg}}(\varphi,\lambda) = VTEC_{\mathrm{glob}}(\varphi,\lambda) + \Delta VTEC_{\mathrm{reg}}(\varphi,\lambda)$$

Process chain of the developed approach

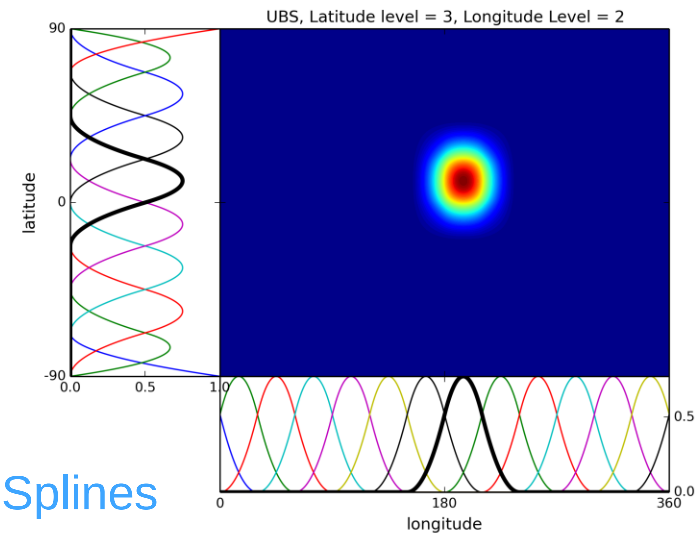


Process chain of the developed approach



Global B-spline modelling

- Usage of polynomial and trigonometric B-splines:



Polynomial B-splines

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

Trigonometric B-splines

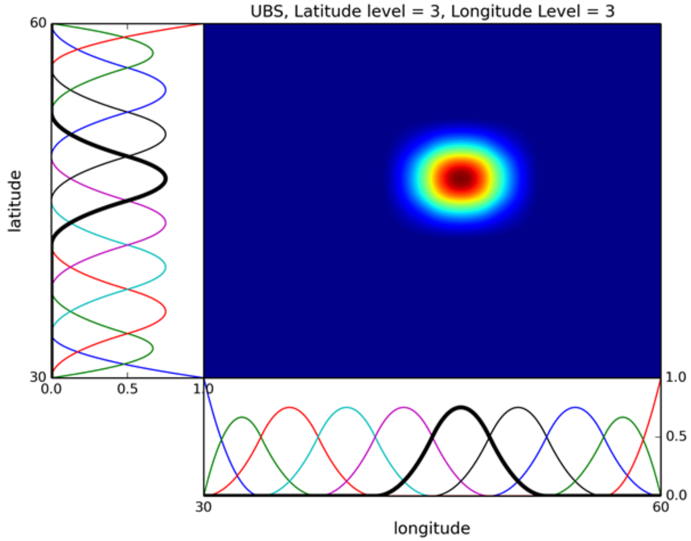
- $K_{J_1} = 2^{J_1} + 2$ defines the number of polynomial B-Splines
- $K_{J_2} = 3 \cdot 2^{J_2}$ defines the number of trigonometric B-Splines
- The B-spline levels J_1 and J_2 define the **spectral content** of the global representation.
- The values $J_1 = 4$ and $J_2 = 3$ provide a VTEC representation **comparable with the IGS products**, i.e. a spherical harmonic representation up to degree $n = 15$.
- The global model is set up in the **Geocentric Solar Magnetospheric (GSM)** coordinate system.
- ***References***: *Schmidt 2007, Dettmering et al. (2011), Schmidt et al. (2015),*

Regional B-spline modelling

- Usage of polynomial B-splines:

Polynomial B-splines

$$\Delta VTEC_{\text{reg}}(\varphi,\lambda) = \sum_{k_3=0}^{K_{J_3}-1} \sum_{k_4=0}^{K_{J_4}-1} d_{k_3,k_4}^{J_3,J_4} \, N_{J_3,k_3}^{2}(\varphi) \, N_{J_4,k_4}^{2}(\lambda)$$



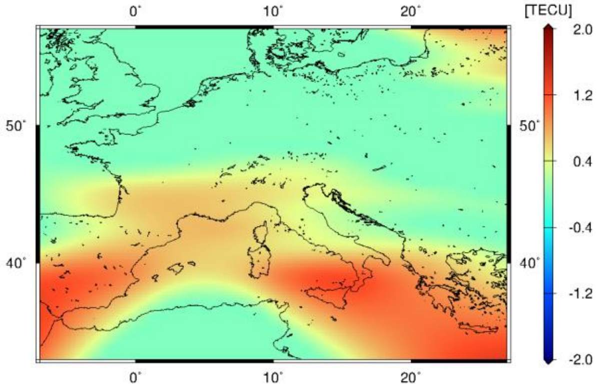
- The regional B-spline levels J_3 and J_4 define the number of 2-D basis functions in the area of investigation.

$$J_3 \le \log_2\left(\frac{\Phi}{\Delta\varphi} - 1\right) \qquad J_4 \le \log_2\left(\frac{\Lambda}{\Delta\lambda} - 1\right)$$

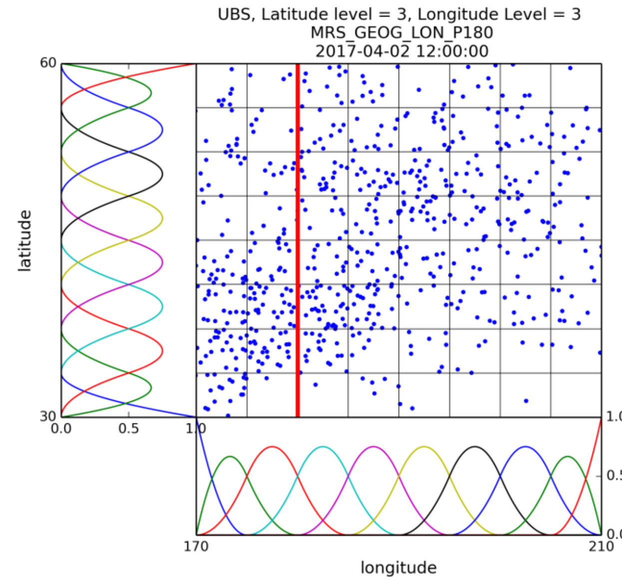
- From the empirical formulae above we chose for a region with size of $\Phi = 30°$ and $\Lambda = 40°$ in latitude and longitude with a mean sampling intervals of $\Delta\varphi = 4°$ and $\Delta\lambda = 6°$ of the IPPs the level values $J_3 = 3$ and $J_4 = 3$ result.
- It represents the finer signal structures (cf. spherical representation greater than degree $n = 30$)

Regional B-spline modelling

- Modelling of $\Delta VTEC_{\mathrm{reg}}$ with **uniform B-splines** (UBS)

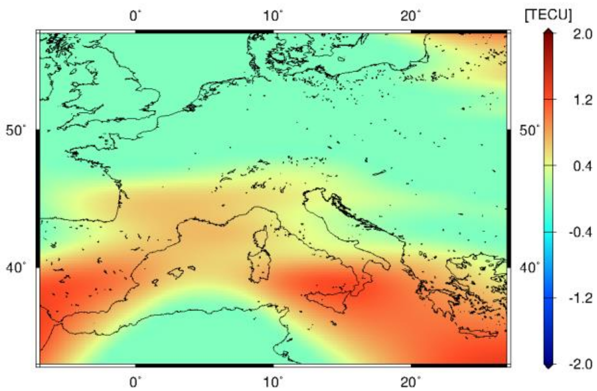


- The regional VTEC model is set up in the **Earth-fixed geographical coordinate system.**



Regional B-spline modelling

- **Adaptive** modelling of $\Delta VTEC_{\mathrm{reg}}$ with **Non-uniform Adapative B-Splines (NABS)**

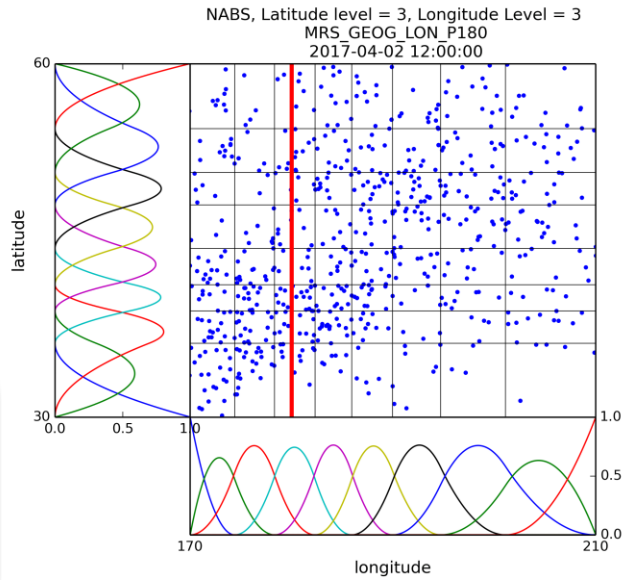


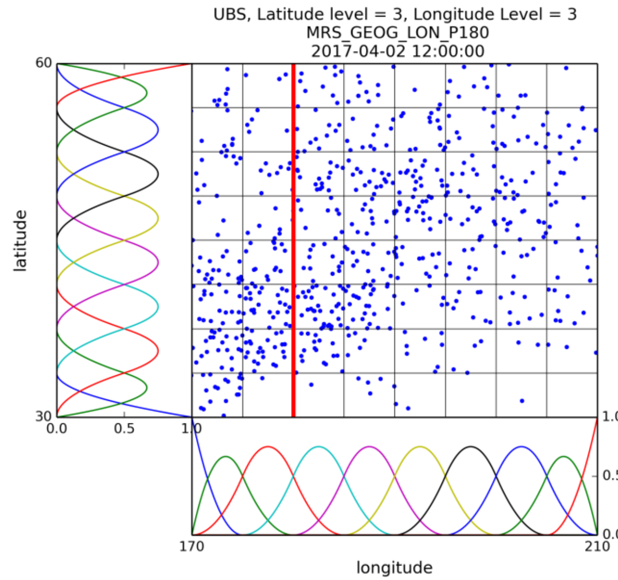
- The regional VTEC model is set up in the **Earth-fixed geographical coordinate system**.

- Due to the **inhomogeneous data distribution**, the NABS functions provide an **adaptive modelling**.

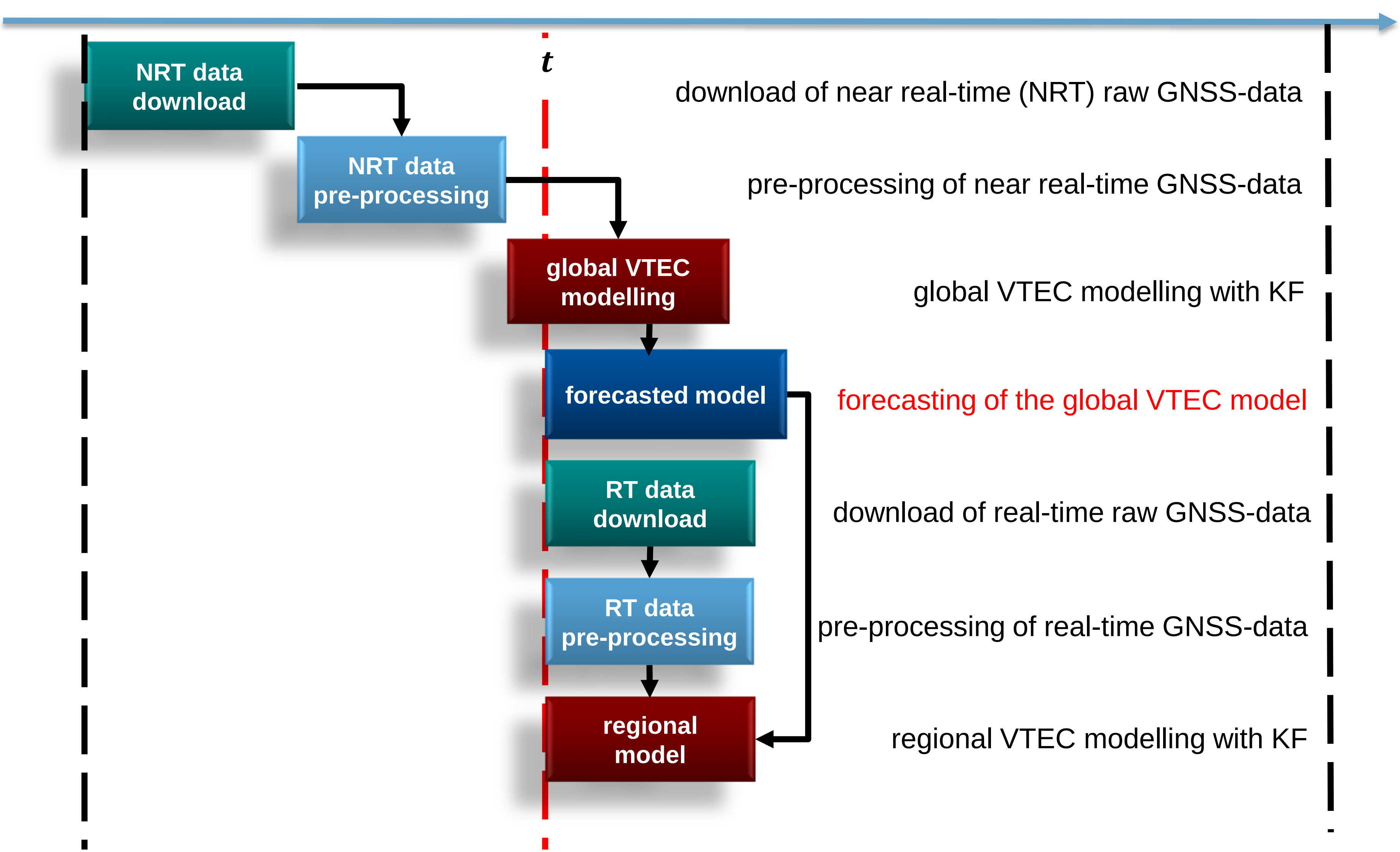
NABS represent the regions with a **higher data density** by a **larger number** of **basis functions** with a more **narrow spatial support.**

NABS represent the regions with **large data gaps** by a **less number** of **basis functions** with a **wider spatial support.**





Process chain of the developed approach



Preliminary forecasted global model

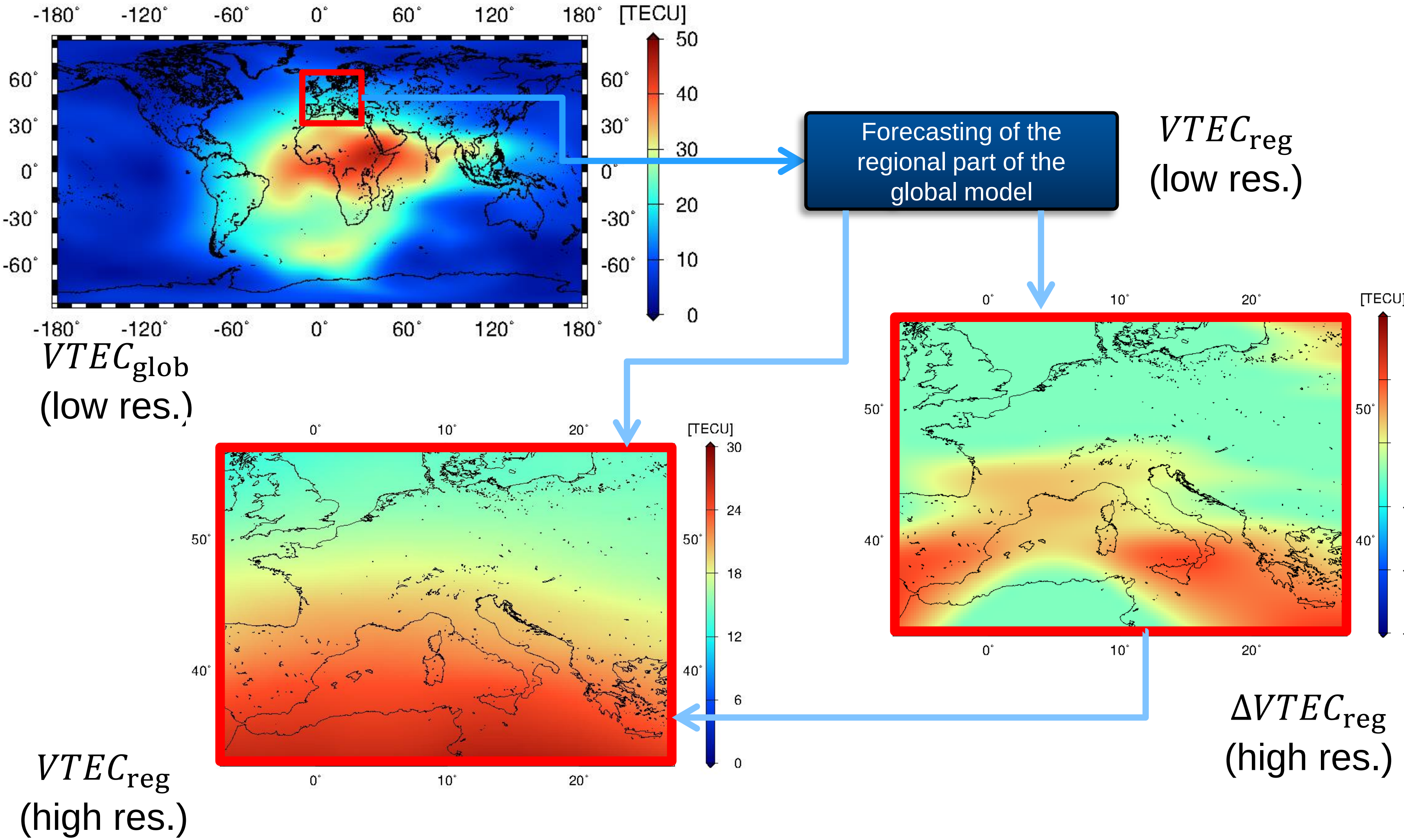
- An approach was developed to **forecas**t the VTEC values of the global model by introducing series expansions for the B-Spline coefficients $d_{k_1,k_2}^{J_1,J_2}$ for the time difference between RT and NRT of a maximum of 3 hours.
- The **series expansion** is set up as a sum of a **Fourier series** and a stochastic part, e.g. an **ARMA** model

$$d_{k_1,k_2}^{J_1,J_2}(t) = \left(a_0 + \sum_{i=1}^{n} \{a_i \cos(\omega_i t) + b_i \sin(\omega_i t)\} \right)_{k_1,k_2} + s_{k_1,k_2}(t)$$

- As **periods** $T_i = 2\pi/\omega_i$ we choose $T_1 = 1$ day, $T_2 = 0.5$ day, $T_3 = 0.33$ day, $T_4 = 0.25$ day and so on up to 15 min.
- The coefficients a_0, a_i and b_i for $i = 1, \cdots, n$ are estimated for each coefficient **independent** by evaluating its time series over the **five previous days**.

Preliminary forecast results:
Hoque et al.: Ionosphere monitoring and forecast activities within IAG working group „Ionosphere Prediction“, Poster Session G5.2,

Combination of global and regional model



Summary

- **Real-time ionosphere** modelling by means of a **densification** approach has been developed and can be applied for precision agriculture on autonomous driving robots.
- The approach consists of a
  - **global forecasted model** which represents the **low-frequency part**, i.e. the **coarser signal structures** as the basis and the
  - **regional real-time B-spline model for areas of investigation** which represents the **higher-frequency part**, i.e. the **finer structures** of the **signal**.
- In order to set up an optimal **compromise** between the **UBS** and the **NABS** as basis functions we chose
  - the **UBS** for the **global part** and
  - the **NABS** for the **regional densification area**.
- With the proposed **Barcelona Ionospheric Mapping** (BIM) function the estimated STEC value corrects the GNSS measurement which can then be used, e.g., for **precision farming**.