Use of a modified NeQuick2 for the evaluation of different 3D Ionospheric algorithms

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- Scenarios for the simulations
- Models used for the simulations
- Results on simulations
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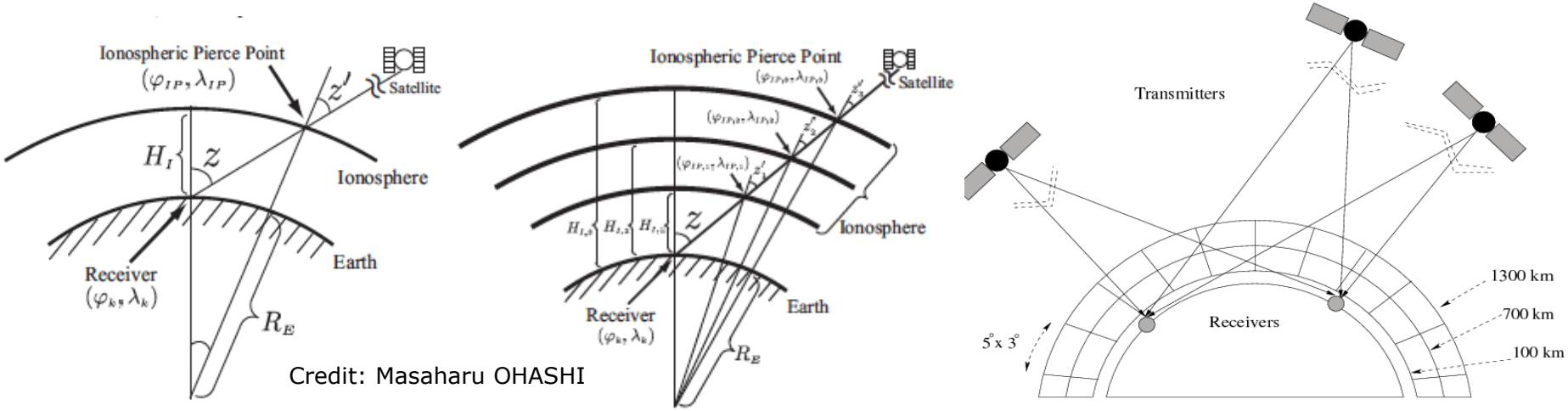
Introduction

- For extracting the ionospheric information from GNSS it is necessary to model the ionosphere to be able to split the biases form the TEC.

- In general, one can use the 2D (much faster and less complex) or 3D (slower and more complex).

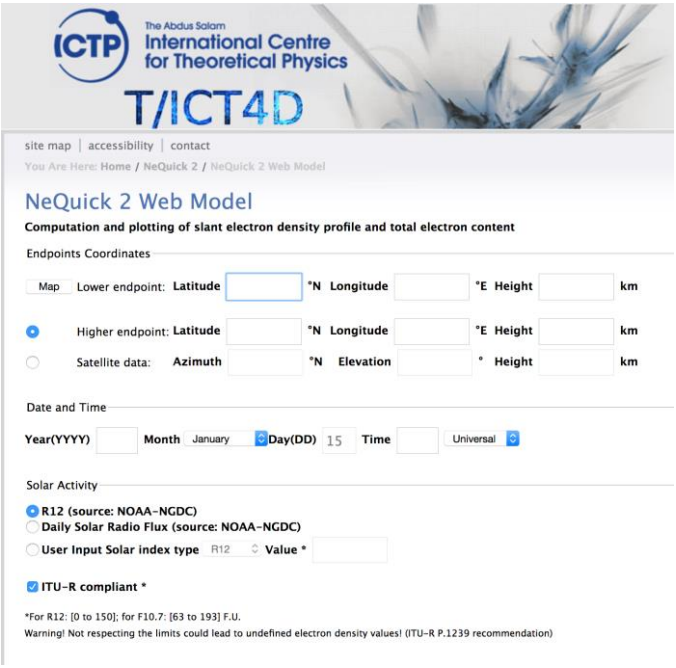
- The inverse problem to compute the TEC is not well conditioned. Thus, a tool to check whether the algorithm will perform as expected in a controlled environment is a must.



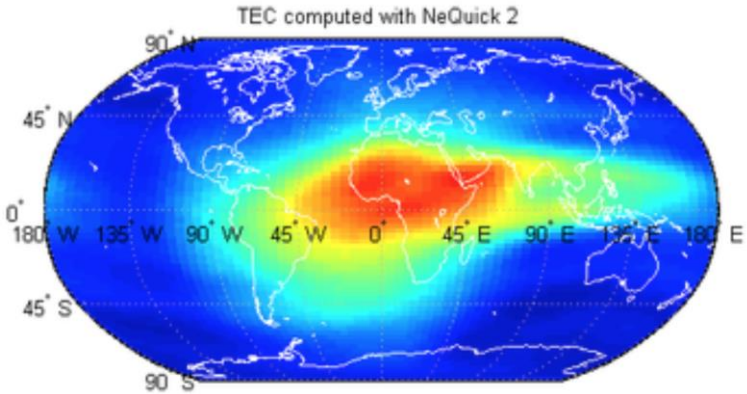
Credit: Masaharu OHASHI

NeQuick 2

- NeQuick 2 is the latest version of the ionospheric electron density model developed at The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy, and at the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria.
- It is a quick-run empirical model particularly designed for trans-ionospheric propagation applications, conceived to reproduce the median behavior of the ionosphere ("climate").



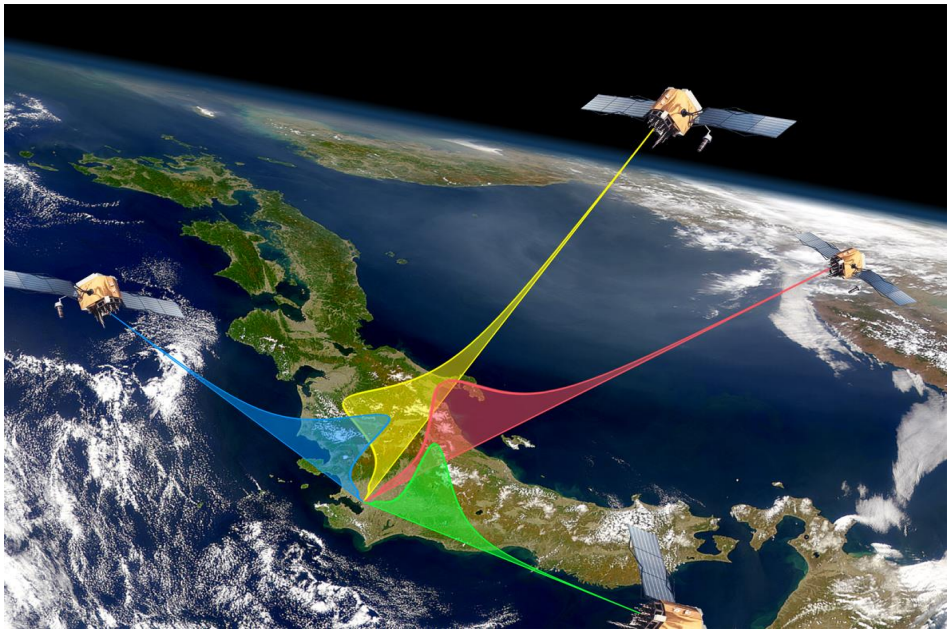
- NeQuick 2, has been adopted by the ITU-R Recommendation P.531-12/13 of 2013-2016 as a procedure for estimating TEC.



NeQuick 2 description

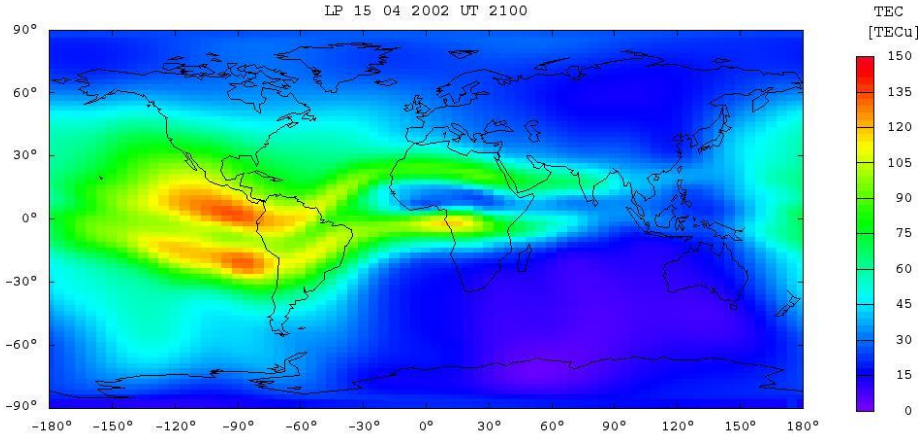
- The model profile formulation includes 6 semi-Epstein layers with modeled thickness parameters and is based on anchor points defined by foE, foF1, foF2 and M(3000)F2 values.
- These values can be modeled (e.g. ITU-R coefficients for foF2, M(3000)F2) or experimentally derived.
- NeQuick inputs are: position, time and solar flux; the output is the electron concentration at the given location and time.

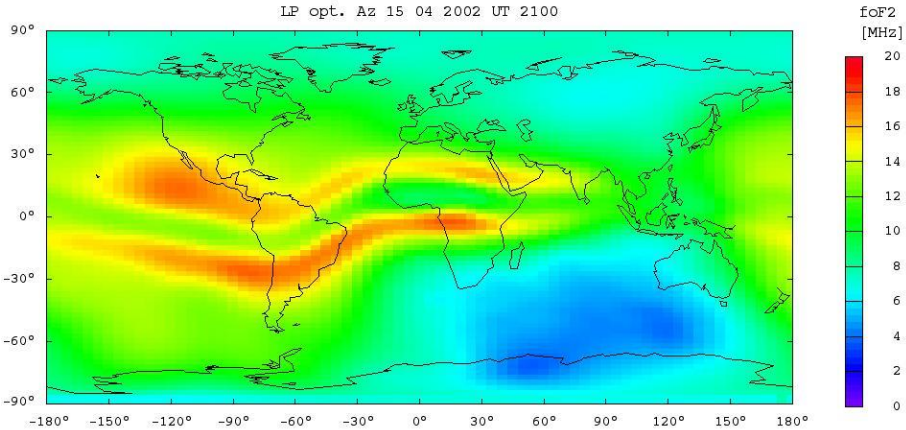
- NeQuick package includes routines to evaluate the electron density along any "ground-to-satellite" ray-path and the corresponding Total Electron Content (TEC) by numerical integration.



Data ingestion into NeQuick 2

- To provide the 3-D "weather-like" descriptions of the ionosphere electron density, different data ingestion techniques have been implemented using:
    - ground/space-based GNSS-derived TEC &/or
    - ionosonde measured peak parameters values
- In the case of VTEC map ingestion, for each grid point, a local and instantaneous effective F10.7 (symbol Az) can be defined as the F10.7 input value that minimizes the difference between an "experimental" and the corresponding modeled vertical TEC.
- Using an Az grid as an input for NeQuick, a 3D representation of the electron density of the ionosphere all over the World can be computed.

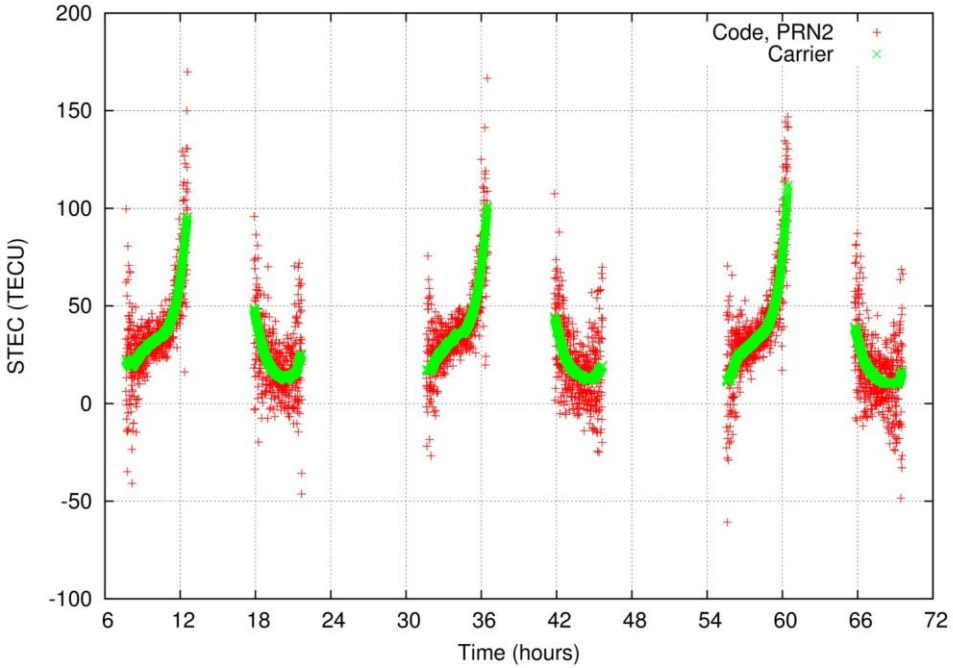




Modified NeQuick 2

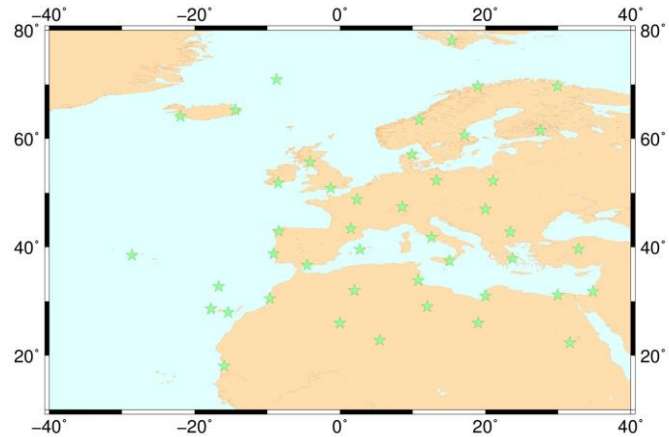
- In the present work the modified NeQuick model (= with data ingestion capabilities) has been used to:
  - ingest vTEC maps
    - => to obtain global Az grids => 3-D electron density values, which reproduce exactly to the given vTEC maps
  - compute sTEC values (by numerical integration) for selected receivers on the ground, consistently with the given vTEC maps
  - compute vTEC values for predefined grid points (to be used as reference values)
- Note 1: when a sTEC is computed with the modified NeQuick, the relevant Az values are varied along the given ground-to-satellite ray-path to ensure self-consistency in terms of electron density at any point in space.
- Note 2: in the modified NeQuick a “climatological” (= not affected by the ingestion procedure) hmF2 description is implemented to avoid possible "artificial" structures in the reconstructed hmF2.
- Note 3: the consistency between sTEC and vTEC (obtained through numerical integration of the electron density as retrieved from the vTEC map ingestion) is a key point for the assessment of the TEC calibration models proposed in the following.

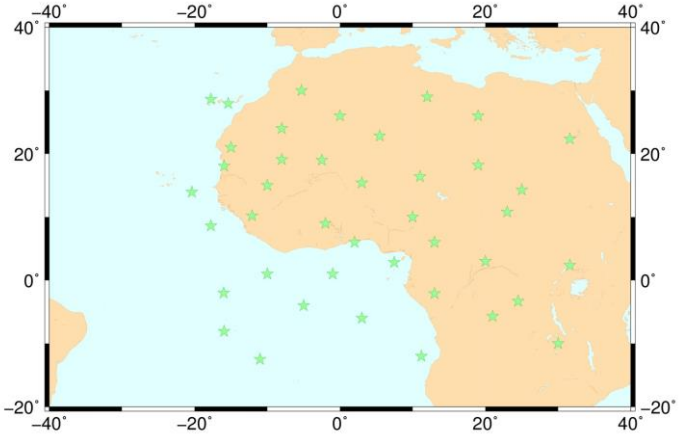
Scenarios for the simulations



- $L = (1.0 + 10.0*e^{-Elev/15.0})\ mm_{L1}$
- $P = 0.3 * (1.0 + 10.0*e^{-Elev/15.0})\ m_{L1}$

- The biases and IFBs are set to 0. There is the potential to study the influence of fixed double differences or introduce different multipath models for the receivers.





Models used for the simulations

The models used are:

1. Voxel (with exact length; 60 km – 740 km – 1420 km)
2. Multi-Layer (300 km and 1700 km)
3. Spherical Harmonic Multi-Layer (300 km and 1700 km)
4. Spherical Harmonic Single-Layer (400 km)

- Grid of 3° by 3° Local Time, Latitude; Spherical harmonics of degree 15.
- Maps every 300 seconds as baseline (viability of using 720 seconds, which is 3° to avoid interpolation). All parameters are updated in a Kalman filter at the same sampling.
- Equivalence between process noise (Q) for Multi-layer and Voxel as (TECU/√h):
    - $Q_{Voxel} = Q_{Multi} * 10^{16} / 4*10^{5}$; since the voxel height is $4*10^{5}$.
    - Upper layer has a Q divided by a factor of 2.
- IFB from Satellites and Receivers treated as Random Walk (Higher for the Receiver with a factor of 90).
- Weight of the observation fully in line with the simulated noise.

Results on simulations. Mid latitude

Voxel (Q_{multi})	4e-1	4e-2	4e-3	4e-4	4e-5
RMS bias	0.71	0.45	0.61	0.76	0.78
RMS IFB Rec	0.46	0.21	0.31	0.45	0.46
RMS IFB Sat	0.57	0.46	0.52	0.57	0.57

Multilayer 0.105 m_{LI}=1 TECU	4e-1	4e-2	4e-3	4e-4	4e-5
RMS bias	2.84	2.76	3.24	3.39	3.41
RMS IFB Rec	0.73	0.51	0.51	0.65	0.66
RMS IFB Sat	2.64	2.61	2.86	2.95	2.97

Results on simulations. Mid latitude

Sph Single	4e+1	4e0	4e-1	4e-2	4e-3
RMS bias	3.35	3.33	3.21	3.10	3.36
RMS IFB Rec	0.57	0.51	0.50	0.45	0.81
RMS IFB Sat	0.41	0.40	0.43	0.44	0.54

Sph Multi 0.105 m_{LI}=1 TECU	4e+1	4e0	4e-1	4e-2	4e-3
RMS bias	6.68	5.14	4.29	4.34	4.53
RMS IFB Rec	5.67	3.49	1.67	1.67	1.57
RMS IFB Sat	1.76	2.12	2.1	2.05	2.21

Results on simulations. Mid latitude

- Biases and IFB for Multi-layer and spherical harmonics (**in the current implementation**) seem to suffer from a convergence with respect the Voxel model. If the data is filtered with different sigma the results are the following.

Multilayer (4e-3)	**0.03**	**0.05**	**0.1**	**1**
RMS bias	0.71 *(97.9%)*	1.02 *(98.2%)*	1.51 *(98.5%)*	3.20 *(99.7%)*
RMS IFB Rec	0.00 *(0%)*	0.09 *(0.6%)*	0.51 *(94%)*	0.51 *(100%)*
RMS IFB Sat	0.21 *(21%)*	0.25 *(52%)*	0.52 *(91%)*	2.72 *(99%)*

Sph Multi (4e-2)	**0.03**	**0.05**	**0.1**	**1**
RMS bias	1.20 *(96%)*	1.71 *(98%)*	2.29 *(99%)*	4.19 *(100%)*
RMS IFB Rec	0.00 *(0%)*	0.00 *(0%)*	1.66 *(94%)*	1.67 *(100%)*
RMS IFB Sat	0.61 *(26.3%)*	0.84 *(54%)*	1.93 *(98%)*	2.05 *(100%)*

Results on simulations. Mid latitude

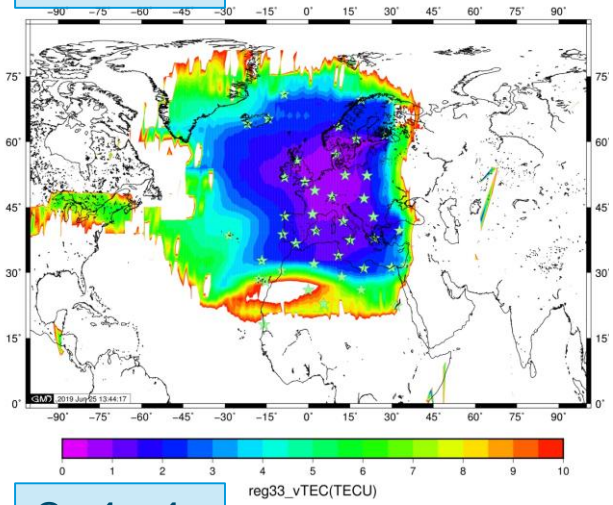
- Two stations are responsible of the *non convergence* of the values of the Bias and IFB Rec. If they are removed the results are consistent with the other models.

Being a simulation allows to identify outliers!!!
The Why comes later…

Sph Multi (4e-2)	**0.03**	**0.05**	**0.1**	**1**
RMS bias	0.84 *(99.0%)*	*1.02 (99.4%)*	1.42 *(99.7%)*	2.88 *(100%)*
RMS IFB Rec	0.00 *(0%)*	0.00 *(0%)*	0.64 *(94%)*	0.65 *(100%)*
RMS IFB Sat	0.61 *(26.3%)*	0.84 *(54%)*	1.93 *(98%)*	2.05 *(100%)*

Results on simulations. Mid latitude (vTEC)

Q=4e-1



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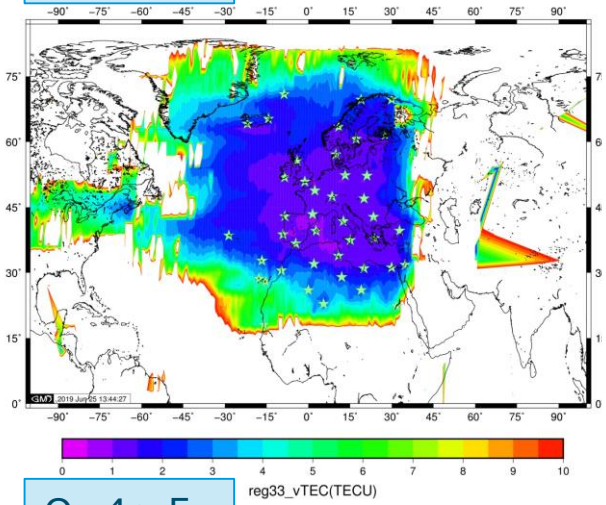

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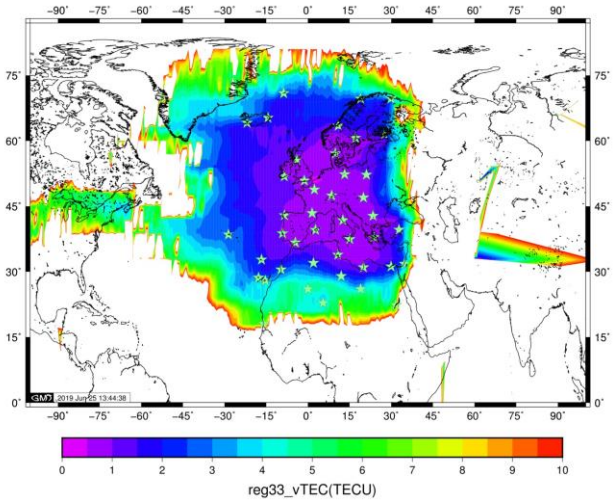

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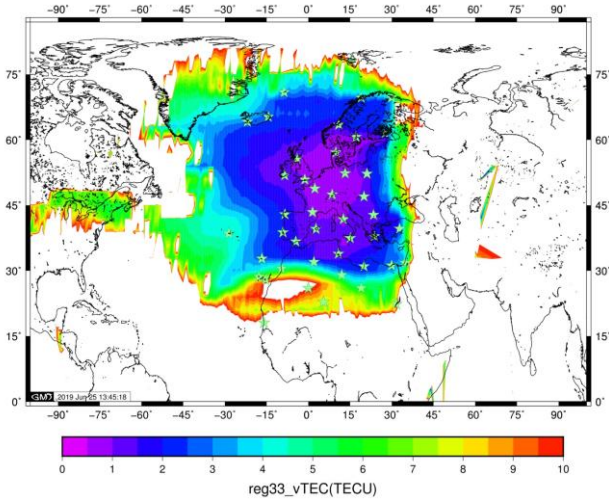

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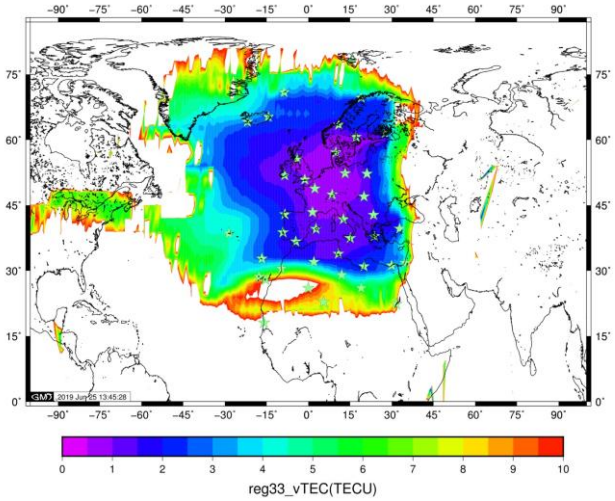

Voxel

Results on simulations. Mid latitude (vTEC)

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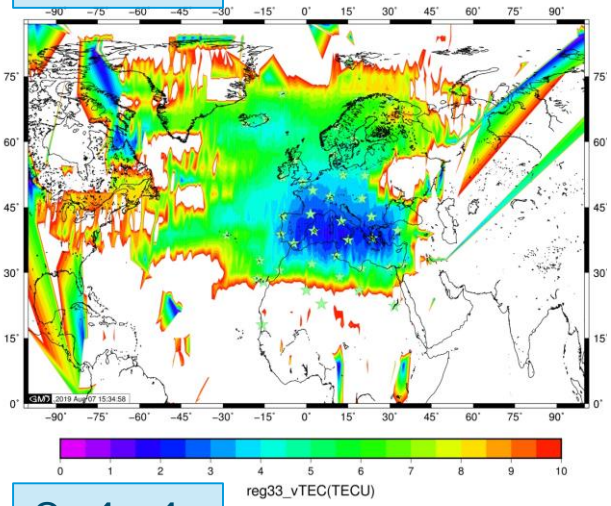

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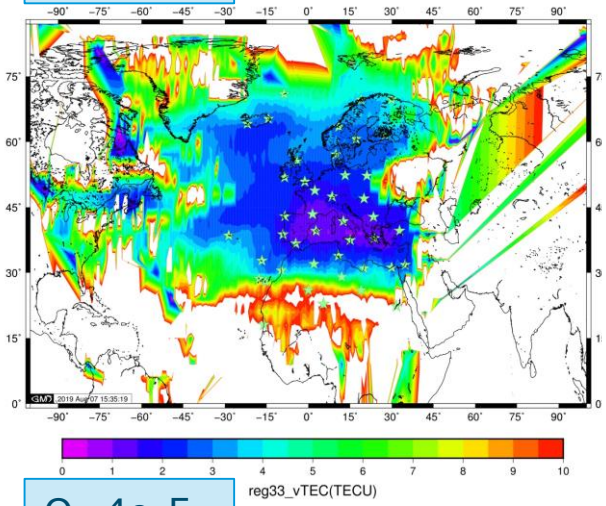

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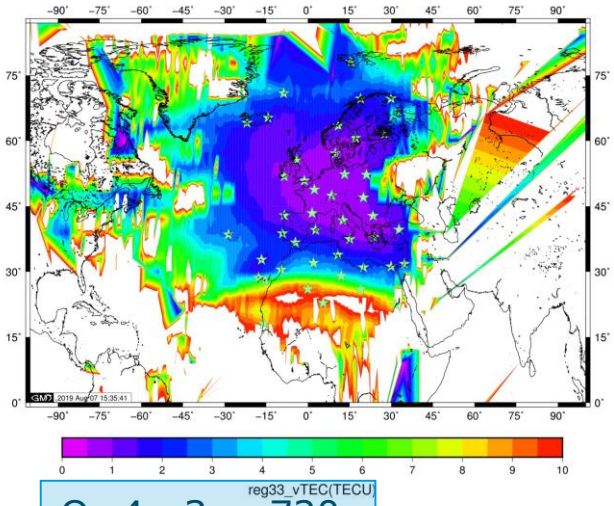

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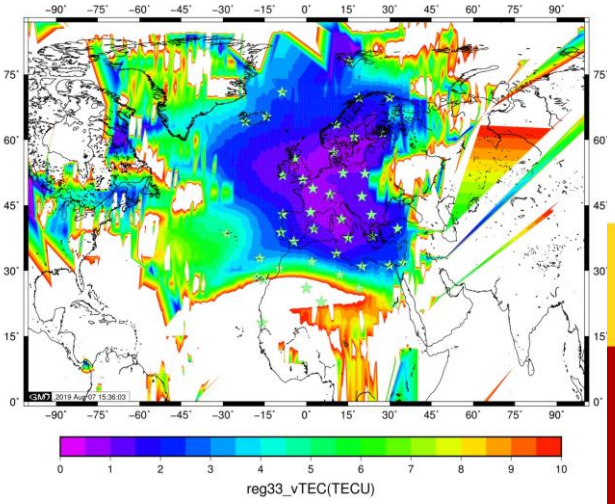

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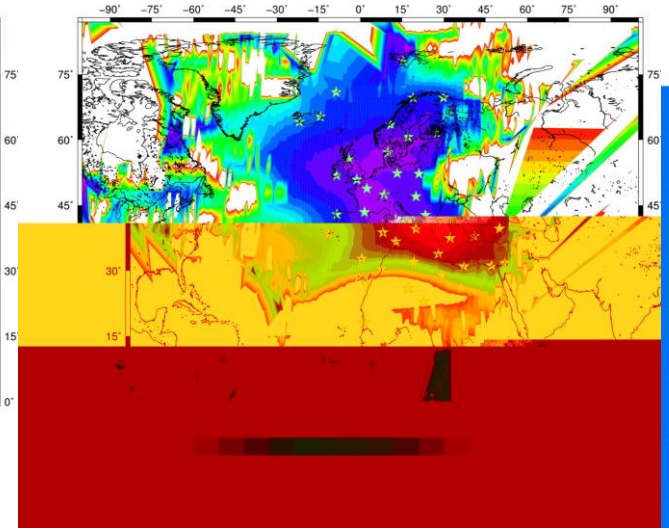

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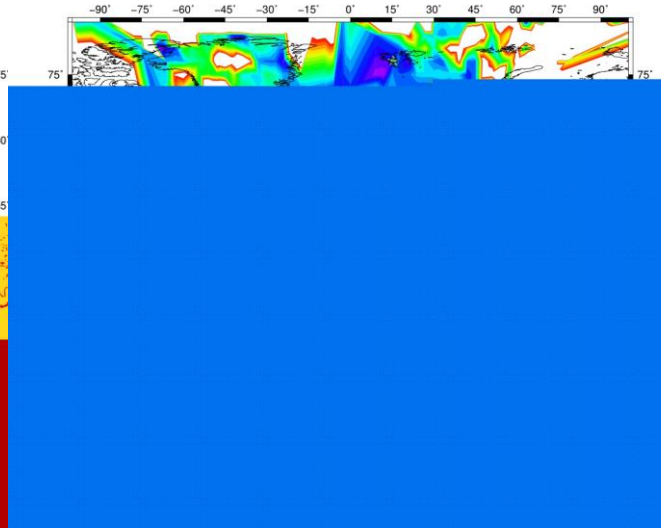
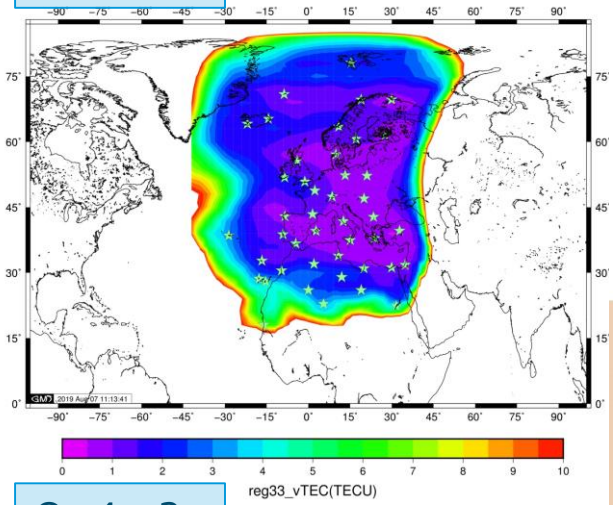


Results on simulations. Mid latitude (vTEC)

Q=4e+1



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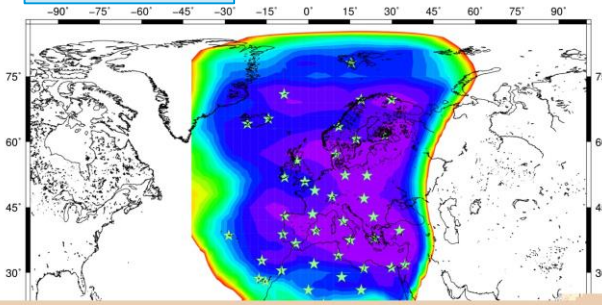

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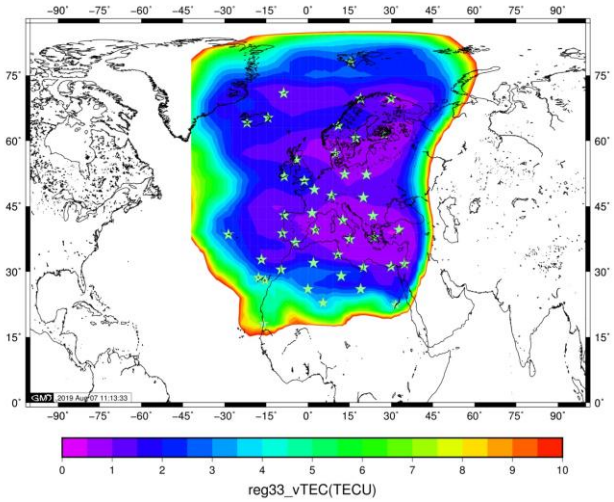

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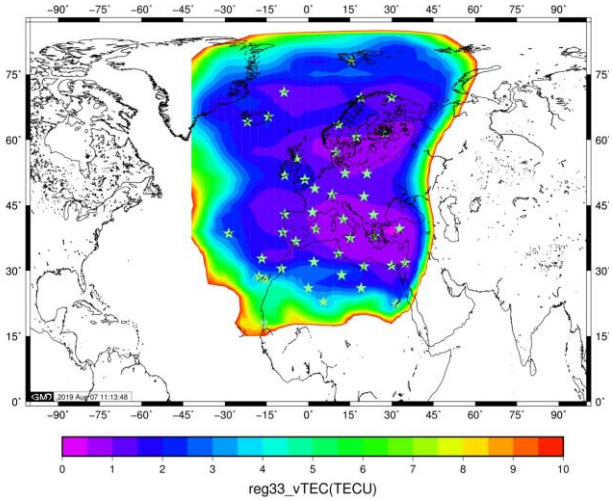

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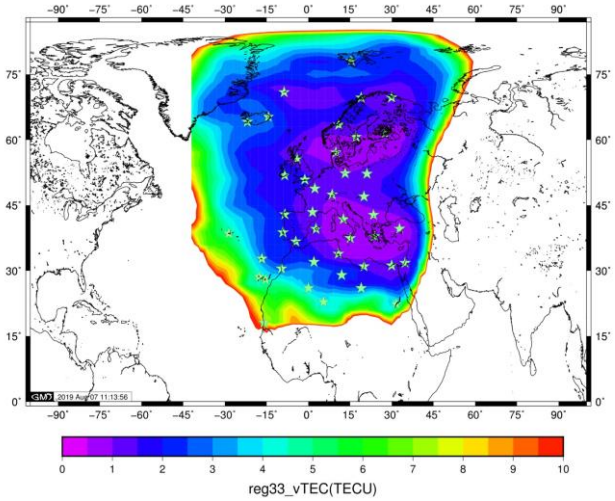
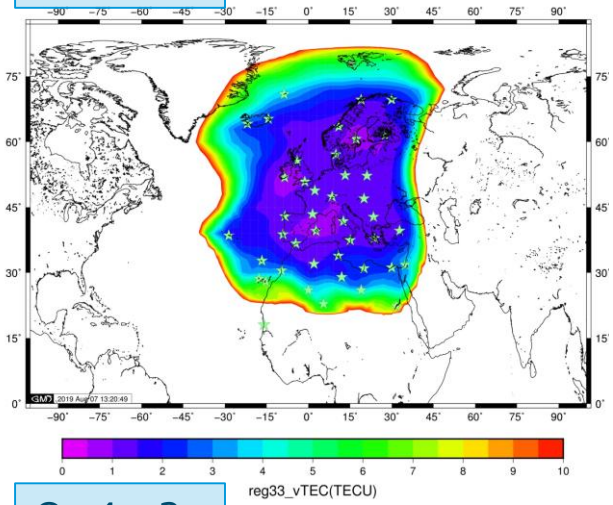


Spherical Single

Results on simulations. Mid latitude (vTEC)

Q=4e+1



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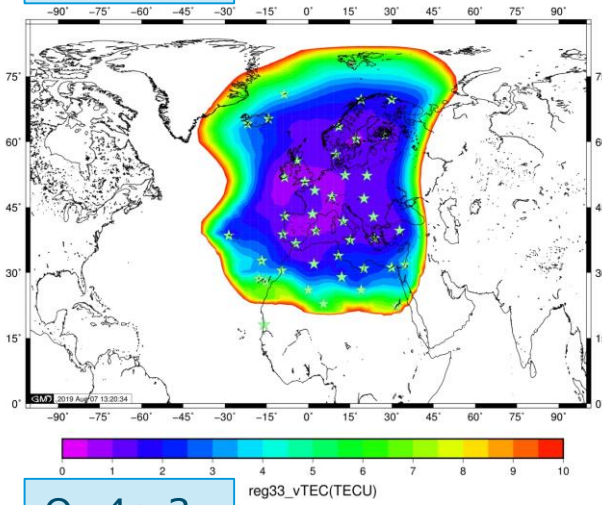

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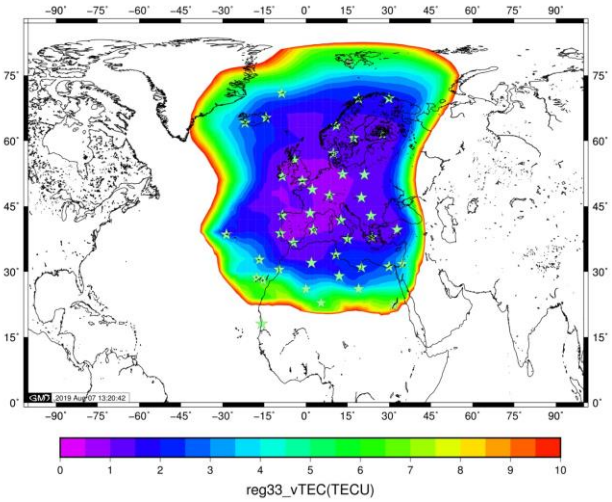

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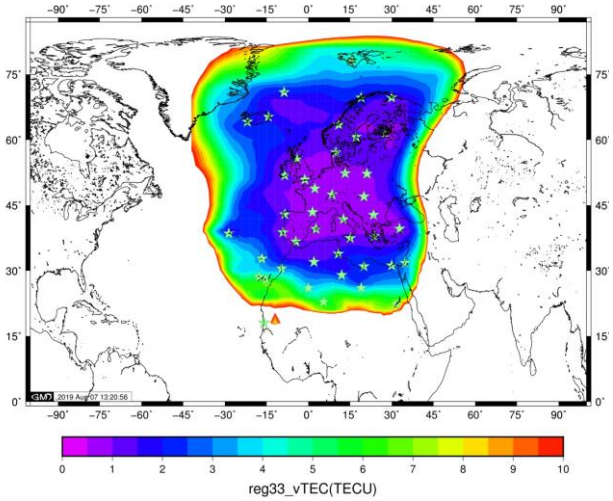

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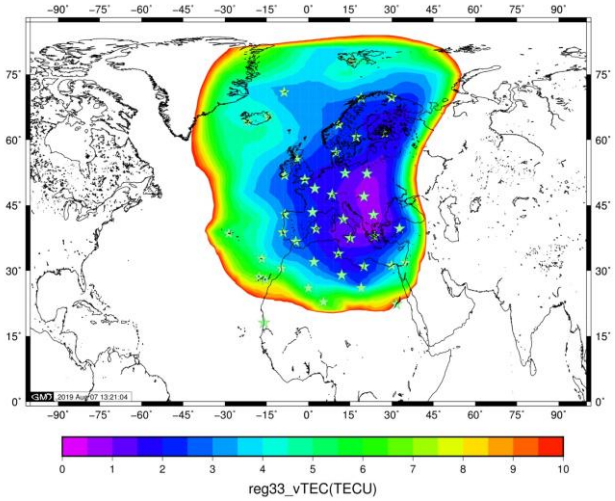
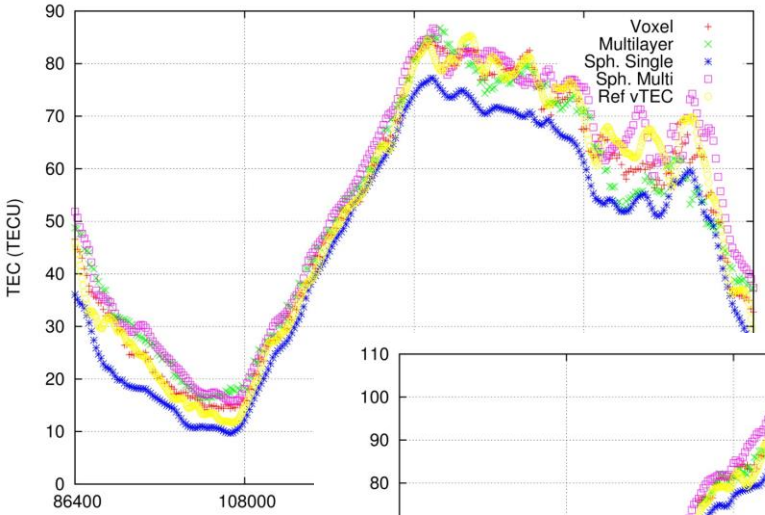
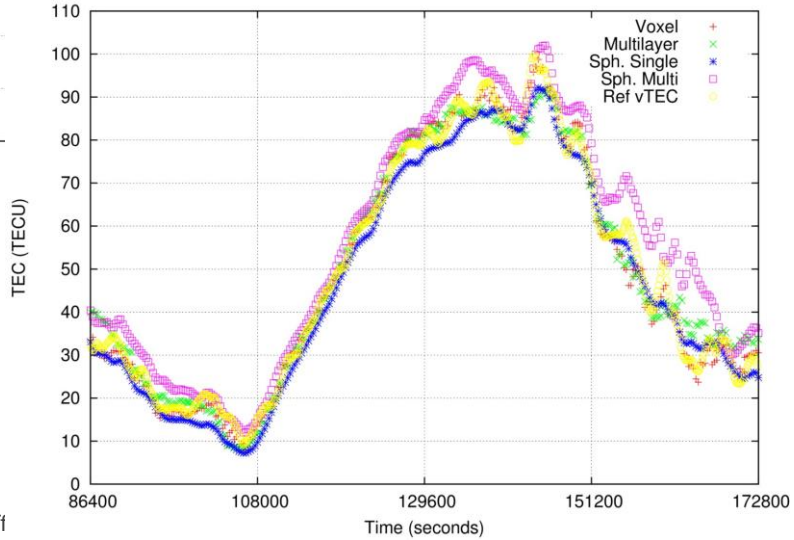


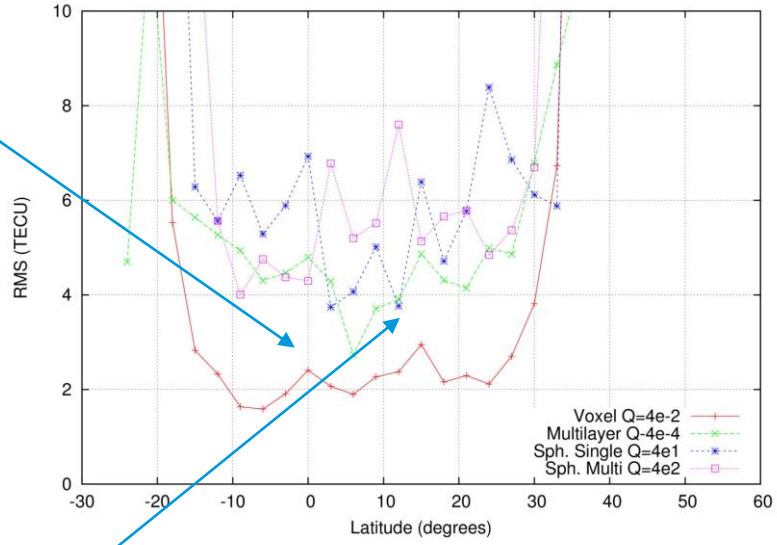
Spherical Multi

Results on simulations. Low latitude

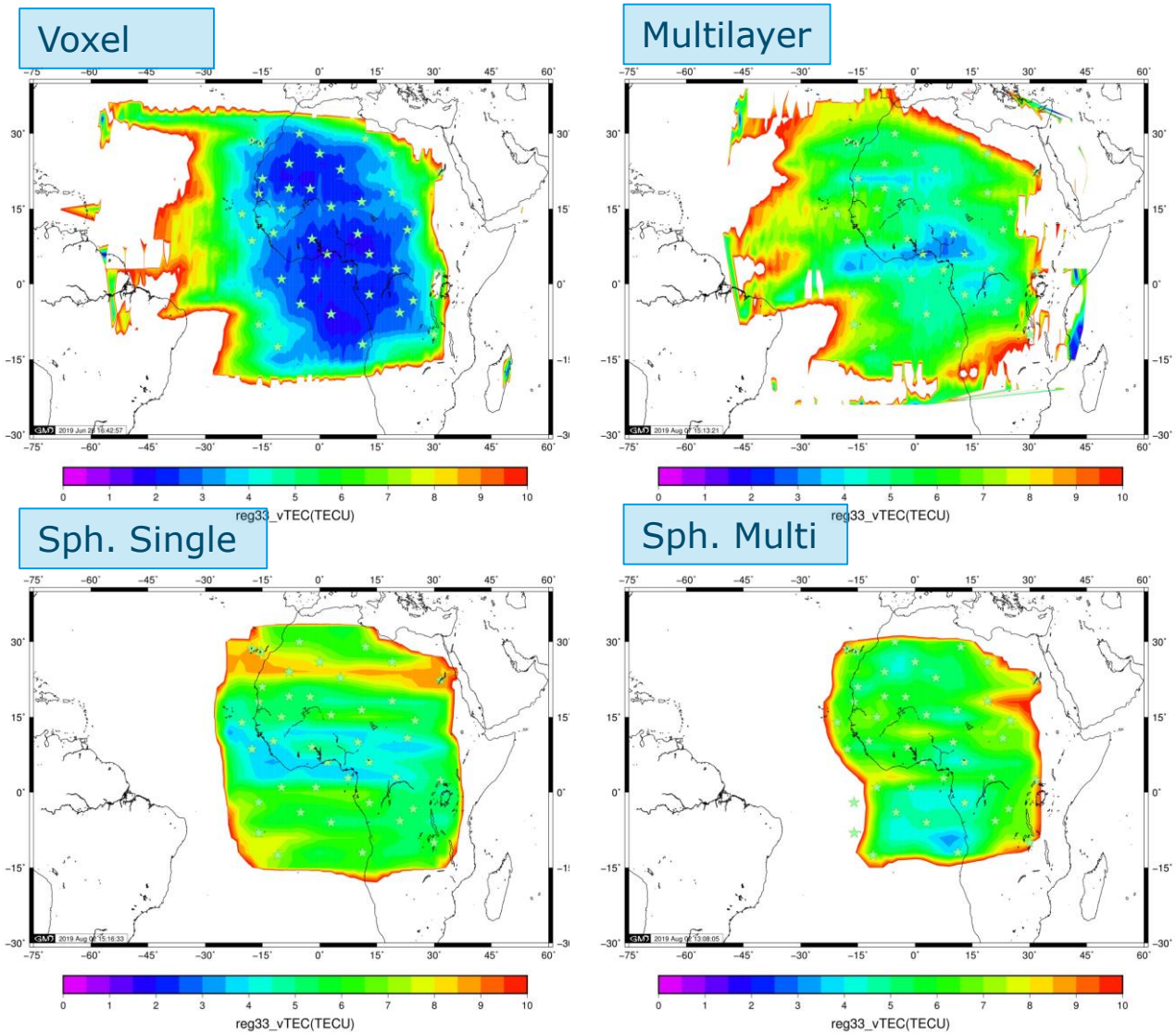
0.105 m_{LI}=1 TECU	Voxel	Multi	Sph.Sing	Sph.Multi
RMS bias	0.57	4.48	1.37	3.32
RMS IFB Rec	0.30	0.54	0.62	0.59
RMS IFB Sat	0.21	0.67	0.29	1.05







Results on simulations. Low latitude (vTEC)



- For this simulation the Voxel model outperforms the other models.
- The best RMS of the Voxel is between 2-4 TECU for this region, as opposed to the 3-7 of the rest.
- Additional checks should be made on the 3D other models, since they *should* be equivalent.

With only data from mid latitudes one could think that everything was ok!

Actual data example. Navigation equations

The basic GNSS observable for absolute navigation for dual frequency the code an phase:

$$P_1^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j + \tilde{\alpha}_1\left(STEC^j + DCB_r - DCB^j\right) + \varepsilon_{P_1}^j$$
$$L_1^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j - \tilde{\alpha}_1\left(STEC^j + DCB_r - DCB^j\right) + B_1^j + \lambda_1\omega + \varepsilon_{L_1}^j$$
$$P_2^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j + \tilde{\alpha}_2\left(STEC^j + DCB_r - DCB^j\right) + \varepsilon_{P_2}^j$$
$$L_2^j = \rho^j + c\left(\delta t - \delta t^j\right) + T^j - \tilde{\alpha}_2\left(STEC^j + DCB_r - DCB^j\right) + B_2^j + \lambda_2\omega + \varepsilon_{L_2}^j$$
$$STEC_{cor}^j = STEC^j + \varepsilon_{ion}^j$$
$$DCB_{cor}^j = DCB^j + \varepsilon_{DCB}^j$$

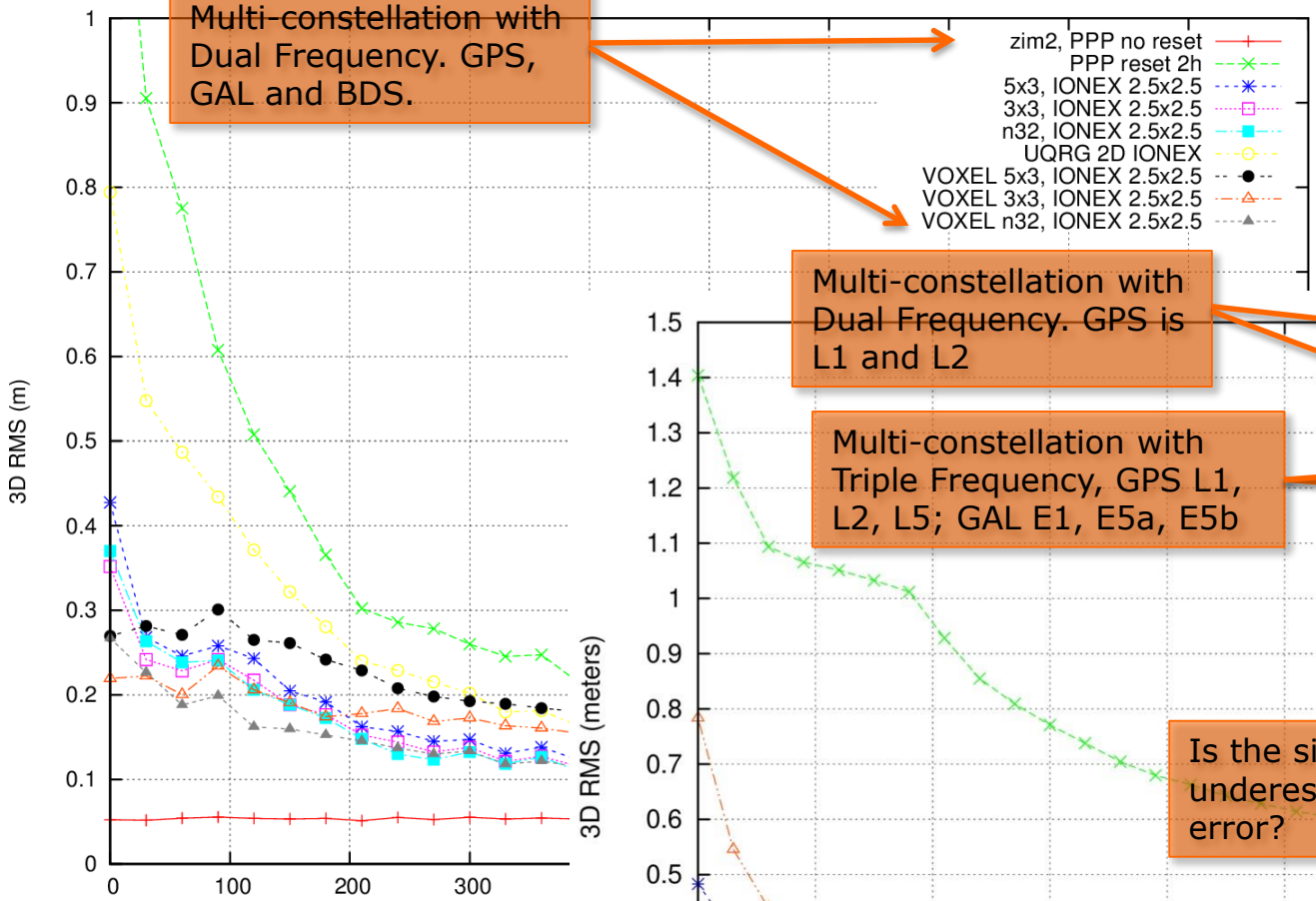
The equations are connected via the Ionosphere delay and Hardware biases. With equivalent weights this is the same as doing the "iono free" but the number of unknowns is increased. However, if the ionosphere model is ***precise enough*** and ***well weighted*** the convergence time decreases since the information is well received by the navigation filter and the ambiguities preserve their integer nature.

(From: R. Orus-Perez, M. Hernandez-Pajares, A. Garcia-Rigo, M. Garcia-Fernandez, P. Wielgosz "Testing Ionospheric Models for Precise Positioning". URSI 2018)

Actual data example. Mid latitude

Multi-constellation with Dual Frequency. GPS, GAL and BDS.

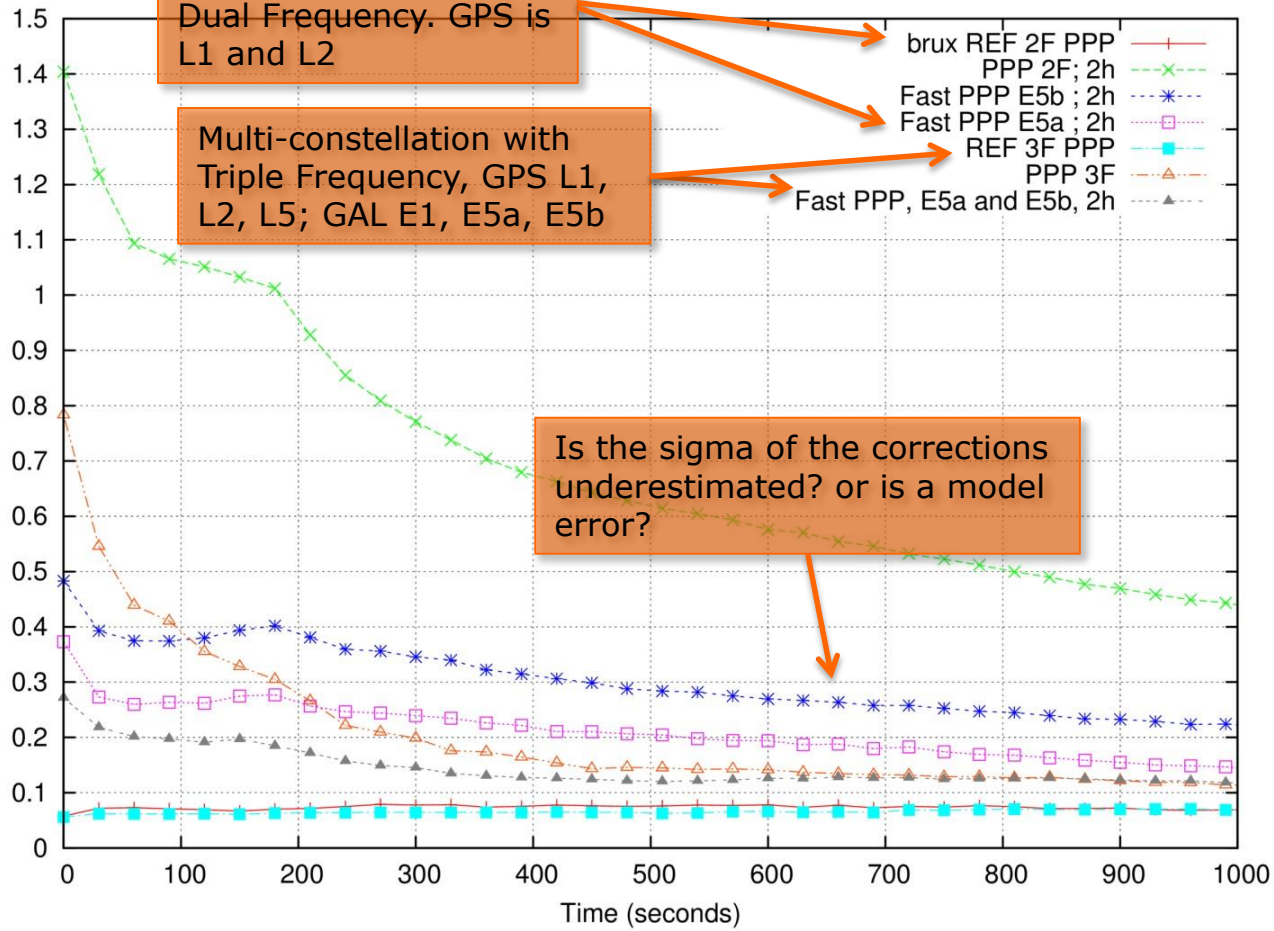
Using Optimized parameters.



Multi-constellation with Dual Frequency. GPS is L1 and L2

Multi-constellation with Triple Frequency, GPS L1, L2, L5; GAL E1, E5a, E5b

Is the sigma of the corrections underestimated? or is a model error?



Conclusions

- The Modified NeQuick 2 shows that is very useful for ionospheric algorithm development. It allows to check all the parameters involved in the calculation of TEC. It also allows to get an idea on how the algorithms will fail and it allows for the troubleshooting of problems.
- **From simulated data:**
    - For middle latitudes the 2D models behave as good as the 3D models. The RMS in the well sounded areas is below 1 TECU. Biases range from 2 to 5 TECU.
    - For Low latitudes, the Voxel model outperforms all the rest of the models. Indeed, more checking with the NeQuick2 has to be done to determine whether the error is real or a an algorithm limitation. In the current implementation. The Voxel can estimate the VTEC in the well sounded area with an RMS around 2 TECU. Biases range from 2 to 6 TECU.
- **From actual data:**
    - The 3D models (Voxel and Muktilayer) can be used for Fast PPP-like technique allowing better convergence.

- Next steps:
    - To test the effect of different multipath for the stations (Weight in the Kalman?)
    - To test the use of fixed ambiguities. Optimal number needed.
    - To calibrate the parameters for getting meaningful Sigma.

Thank you for your attention!