MULTI-GNSS IONOSPHERE MODELING WITH THIN PLATE SPLINES INTERPOLATION

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UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

European Commission

POLITECHNIKA GDAŃSKA

IAG Commission 4 Positioning and Applications Symposium
Wroclaw, Poland

OUTLINE

1. Basics in GNSS-TEC estimation
2. Short review of exiting global models
3. Regional ionosphere modeling at UWM in Olsztyn, Poland
4. Comparison to well established models

FUNDAMENTAL OBSERVATION EQUATIONS

$$L1_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k - \boldsymbol{\Delta I_i^k} - \lambda_1 N1_i^k + c(b_{L1}^k + b_{L1.i}) + \varepsilon$$

$$P1_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k + \boldsymbol{\Delta I_i^k} + c(b_1^k + b_{1.i}) + \varepsilon$$

where:

$L1_i^k$	– the carrier phase observations on L1 frequency.
$P1_i^k$	– the P-code observations on L1 frequency.
q_i^k	– the geometric distance between receiver *i* and satellite *k*.
c	– the speed of light.
$\Delta t_i . \Delta t^k$	– offsets of the receiver (*i*) and satellite (*k*) clocks.
ΔT_i^k	– delay of the signal due to the troposphere.
ΔI_i^k	**– delay of the signal due to the ionosphere.**
$b_1^k . b_{L1}^k$	– the satellite hardware delay.
$b_{1.i} . b_{L1.i}$	– the receiver hardware delay.
$N1_i^k$	– the initial carrier phase ambiguity.
λ_1	– the wavelength.
ε	– indicates a random error.

Geometry-Free Linear Combination (P4)

$$P1_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k + \boldsymbol{\Delta I_i^k} + c(b_1^k + b_{1.i}) + \varepsilon$$

$$P2_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k + \xi\boldsymbol{\Delta I_i^k} + c(b_2^k + b_{2.i}) + \varepsilon$$

$$\xi = \frac{f_1^2}{f_2^2} \approx 1.647; \qquad \xi_4 = 1 - \xi = \approx -0.647;$$

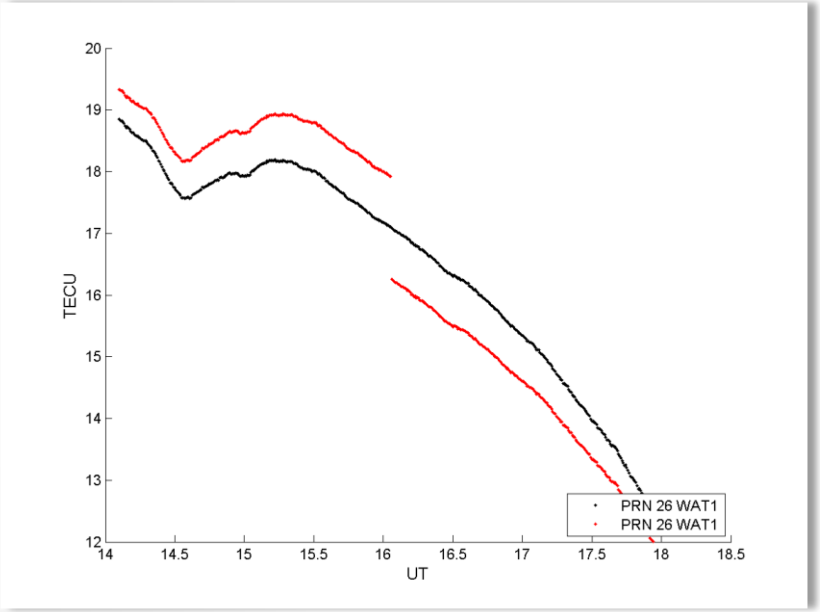
$$\boldsymbol{P4_i^k} = P1_i^k - P2_i^k = +\xi_4 \Delta \mathrm{I}_i^k + \mathrm{c}(DCB_{P1P2}^k + DCB_{P1P2i}).$$

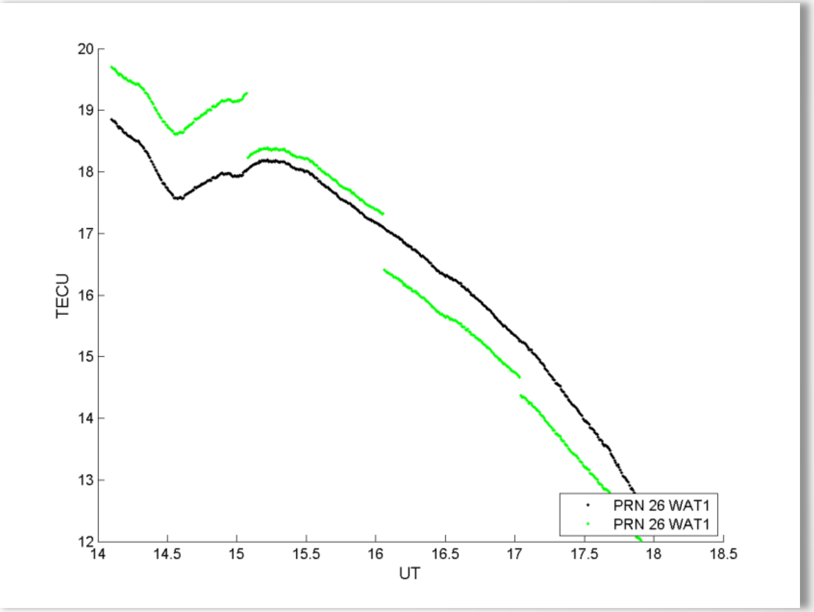
where: $DCB_{P1P2}^k = b_1^k - b_2^k$. $DCB_{P1P2i} = b_{1.i} - b_{2.i}$.

$$\boldsymbol{\Delta I_i^k} = \frac{\boldsymbol{P4_i^k} - \mathrm{c}(\boldsymbol{DCB_{P1P2}^k} + \boldsymbol{DCB_{P1P2i}})}{\xi_4} \qquad \boldsymbol{\Delta I_i^k} = -\frac{\mathbf{40.3}}{\boldsymbol{f^2}}\mathbf{TEC}$$

❑ DISPERSION OF TEC CALCULATED FROM SMOOTHED PSEUDORANGE DATA

- ✓ **Clear *vTEC* dependence on the smoothed arc length**





20 MARCH 2012

GEOMETRY-FREE LINEAR COMBINATION (L4) OF CARRIER PHASE DATA

$$L1_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k - \boldsymbol{\Delta I_i^k} - \lambda_1 N1_i^k + c(b_{L1}^k + b_{L1.i}) + \varepsilon$$

$$L2_i^k = q_i^k + c(\Delta t_i - \Delta t^k) + \Delta T_i^k - \boldsymbol{\xi\Delta I_i^k} - \lambda_2 N2_i^k + c(b_{L2}^k + b_{L2.i}) + \varepsilon$$

$$\xi = \frac{f_1^2}{f_2^2} \approx 1.647; \qquad \xi_4 = 1 - \xi.$$

$$\boldsymbol{L4_i^k} = L1_i^k - L2_i^k = -\xi_4 \Delta \mathrm{I}_\mathrm{i}^\mathrm{k} + \mathrm{B}_{\mathrm{i.4}}^\mathrm{k}.$$

$$where: \quad B_{i.4}^k = \lambda_1 N_{i.1}^k - \lambda_2 N_{i.2}^k - (b_{L1}^k - b_{L2}^k) - (b_{L1.i} - b_{L2.i})$$

$$\boldsymbol{\Delta I_i^k = \frac{L4_i^k - B_{i.4}^k}{-\xi_4}}$$

Carrier phase bias:
constant for continuous data arc

AVAILABLE PRODUCTS

- International GNSS Service **(IGS)** Global Ionosphere Maps (GIMs), 2.5x5.0 deg @ 2 hours, combinations of GIMs provided by ACs, carried out at UWM in Olsztyn:
  - **CODE** (SH TEC modeling, DD_L4, also available @1 hour)
  - **ESA** (SH TEC modeling, P4, also available @1 hour)
  - **JPL** (three shell model, GAIM, also available @15-minutes)
  - **UPC** (two layer tomography, splines TEC modeling)
  - **NRCan** (SH TEC modeling)
- **WHU** (SH TEC modeling)
- UPCs **UQRG** (tomography, kriging, @15 minutes)

AVAILABLE PRODUCTS

- **Prof. M. Hernandez-Pajares et al. validated these products against TEC derived from altimeter data (2002-2015) in his presentation at recent IGS Workshop in Sydney (see: Hernandez-Pajares et al. 2016 „Comparing performances of seven different global VTEC ionospheric models in the IGS context")**

- **MHP also compared reference sTEC variation during four selected days of 2015 at ~50 globally distributed stations (not used in models' production)**

UPC Ion-SAT validation results

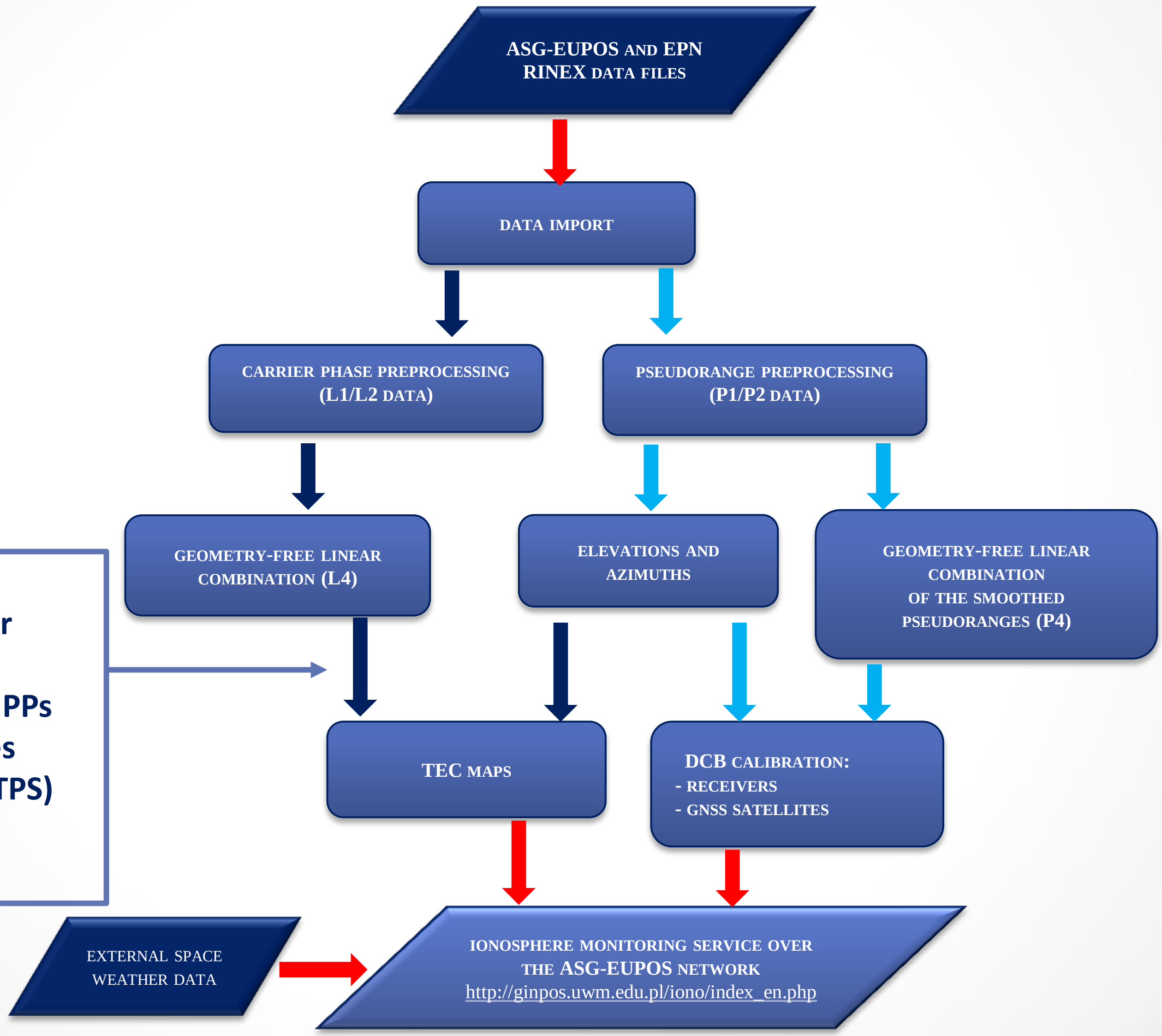
AC/GIM	Altim-GIM std in TECU	Altim-GIM rel. err. %	dSTEC rel. err. %
IGSG	3.9	19.9	28.9
CODG	4.3	22.0	27.8
ESAG	5.3	26.6	33.0
JPLG	4.1	21.2	31.0
UPCG	3.9	19.7	26.9
EMRG*	4.8	26.2	33.6
WHUG*	4.6	24.8	30.7
UQRG	3.6	17.8	20.5

Hernandez-Pajares et al. 2016

Global GIMs – summary:

- low temporal and spatial resolutions
- relatively low accuracy, mostly due to:
  - smoothing effect of SH
  - often usage of carrier phase-smoothed pseudoranges
  - simple SLM mapping function

UWM-RT1 IONOSPHERE MODEL



Three-step procedure:

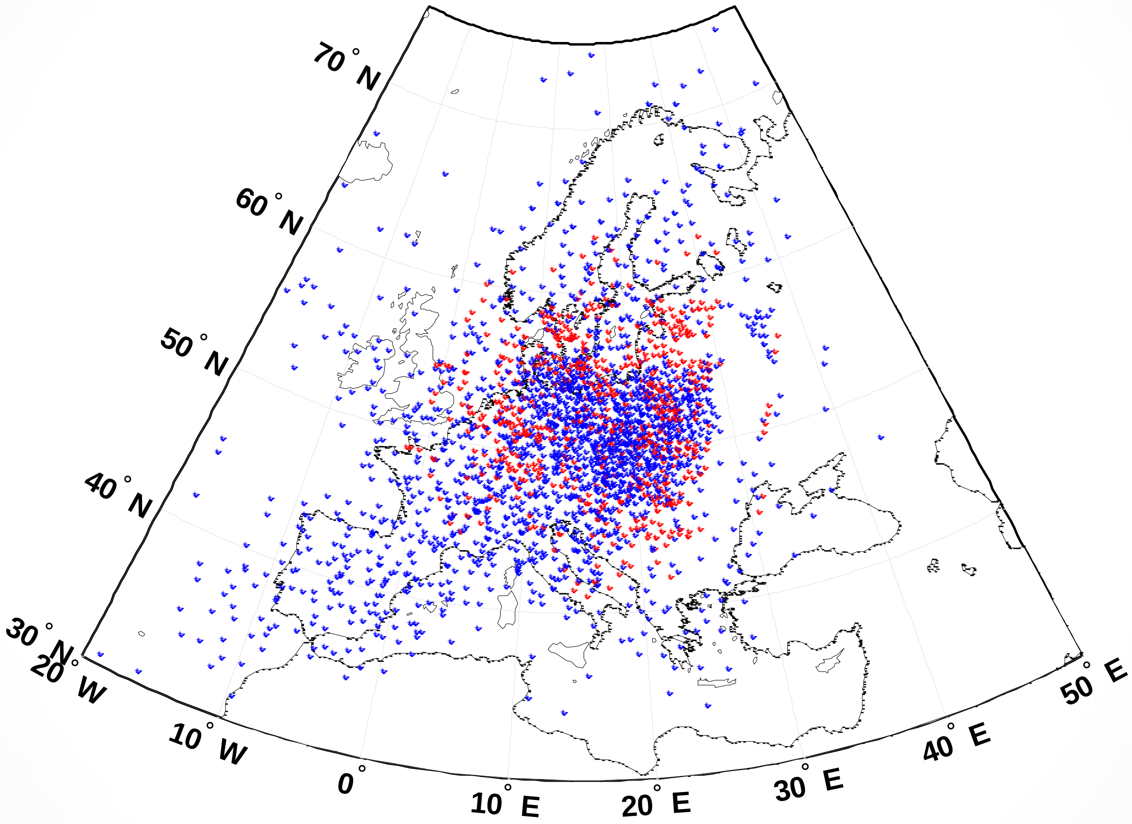
1) Estimation of carrier phase bias
2) TEC calculations at IPPs using L4 observables
3) Thin Plate Splines (TPS) TEC interpolation

UWM-RT1 IONOSPHERE MODEL

OBSERVATIONAL DATA:

- L1&L2 carrier phase data from:
  - ✓ 50 GNSS stations of Polish *ASG-EUPOS* network.
  - ✓ >200 GNSS stations of *EPN* (EUREF Permanent Network).
- dual-frequency carrier phase and pseudorange GPS + GLONASS data.
- sampling interval: 60/120 seconds.
- elevation cut-off: 30°.

UWM-RT1 IONOSPHERE MODEL



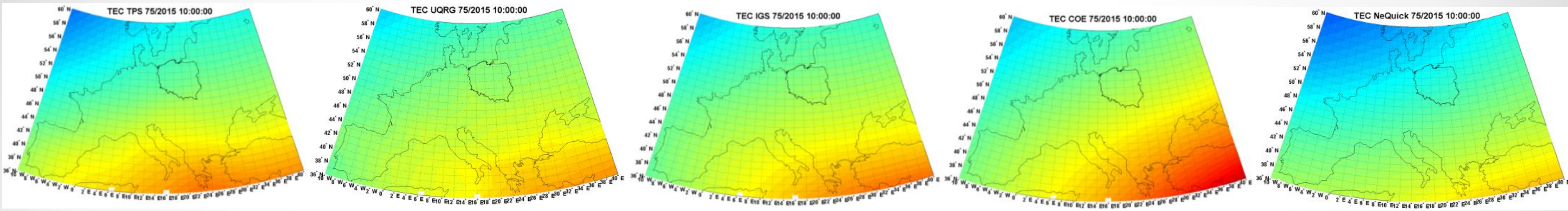
Example IPP locations (GPS+GLONASS)

Test period: 14-20.03.2015 (DoY 73-79, 2015)

TEC maps during quiet day (75/2015)

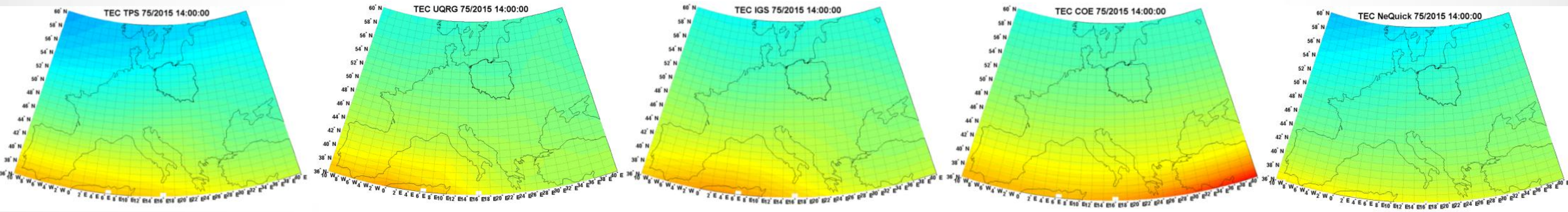
75/2015 10:00:00

UWM –rt1 | UQRG | IGS | CODE | NeQuick



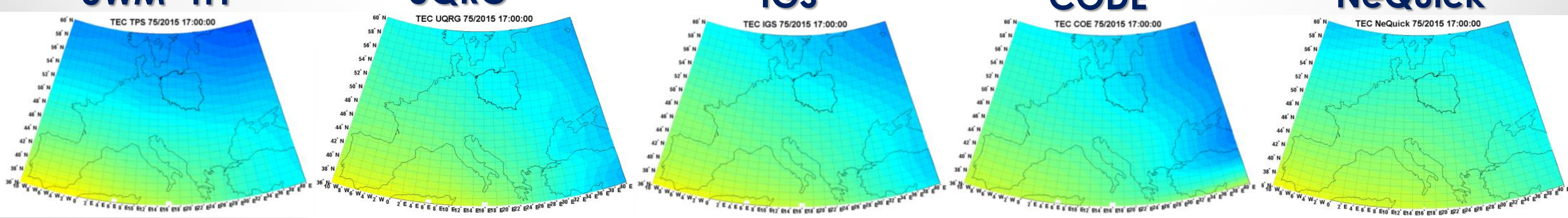
75/2015 14:00:00

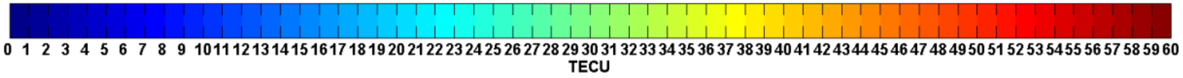
UWM –rt1 | UQRG | IGS | CODE | NeQuick



75/2015 17:00:00

UWM –rt1 | UQRG | IGS | CODE | NeQuick

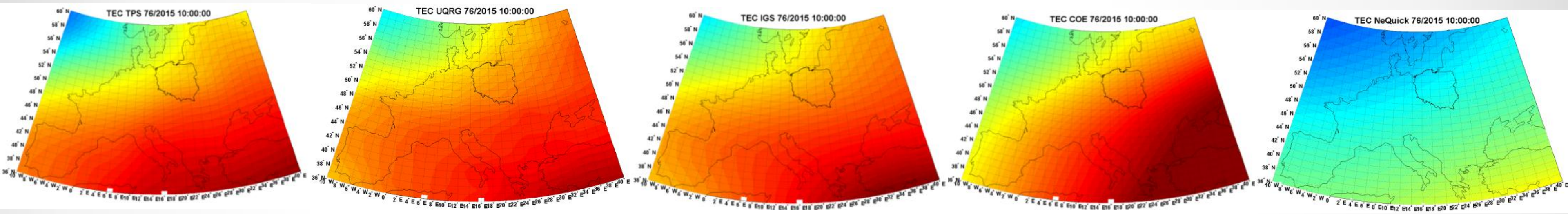




TEC maps during stormy day (76/2015)

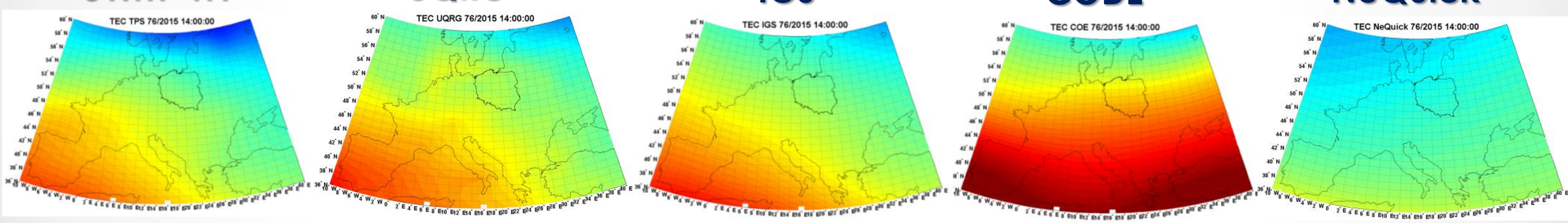
76/2015 10:00:00

UWM –rt1 | **UQRG** | **IGS** | **CODE** | **NeQuick**



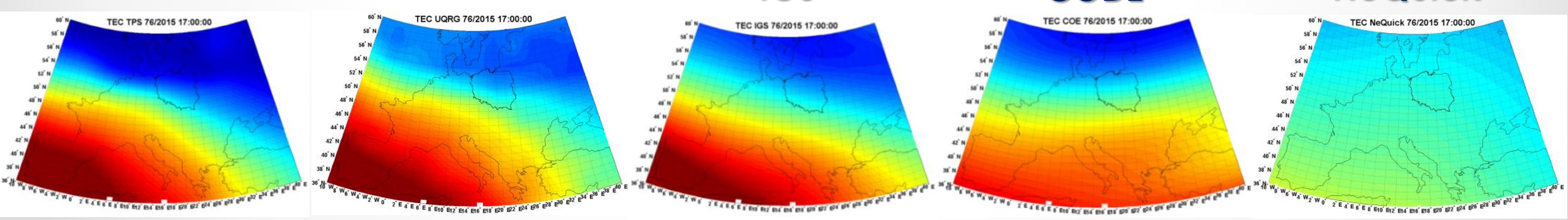
76/2015 14:00:00

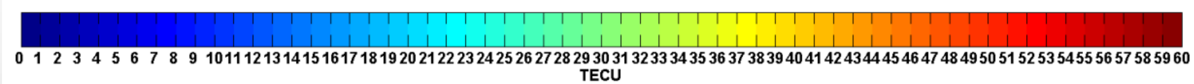
UWM –rt1 | **UQRG** | **IGS** | **CODE** | **NeQuick**



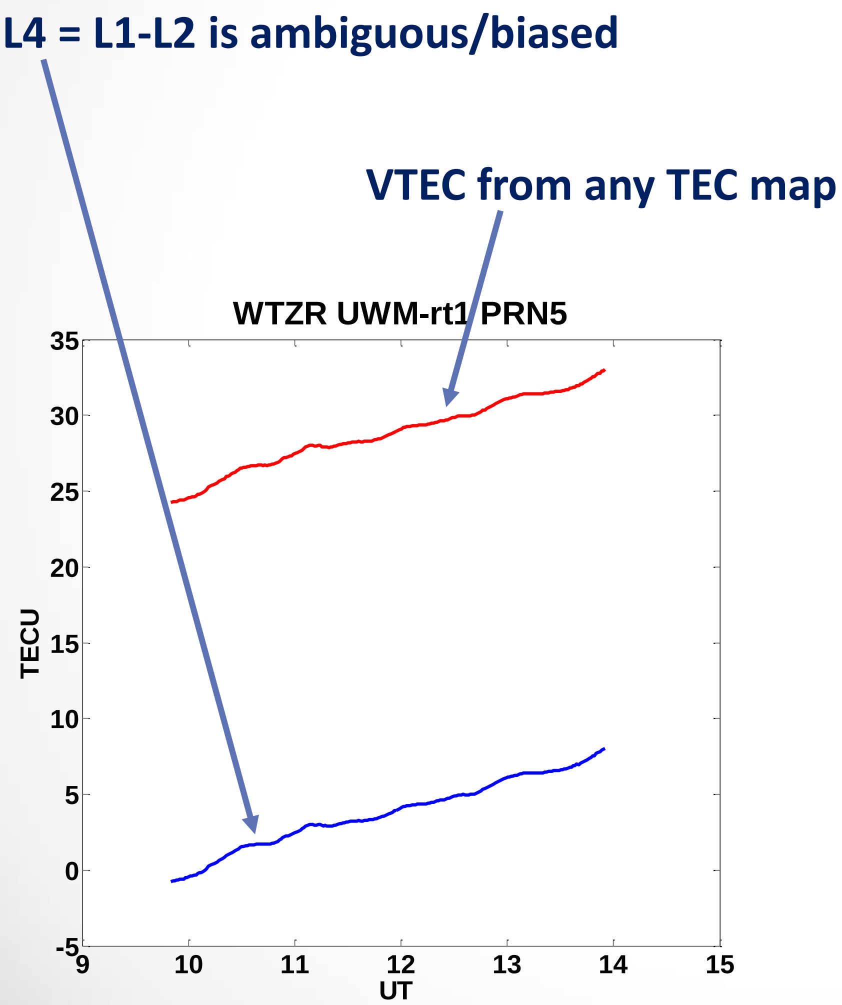
76/2015 17:00:00

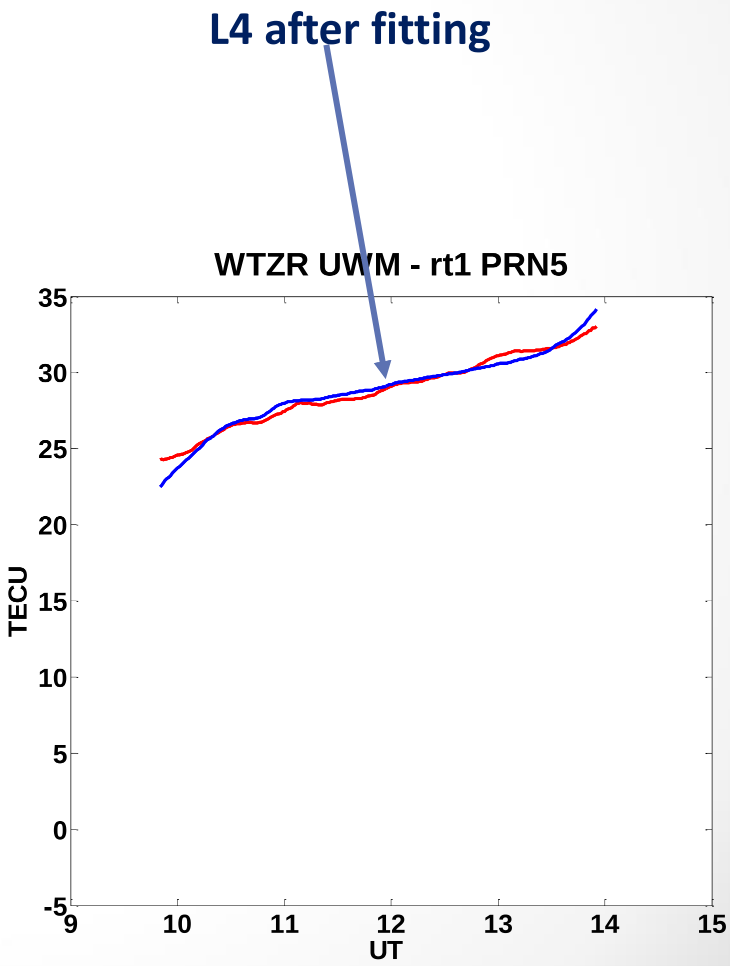
UWM –rt1 | **UQRG** | **IGS** | **CODE** | **NeQuick**





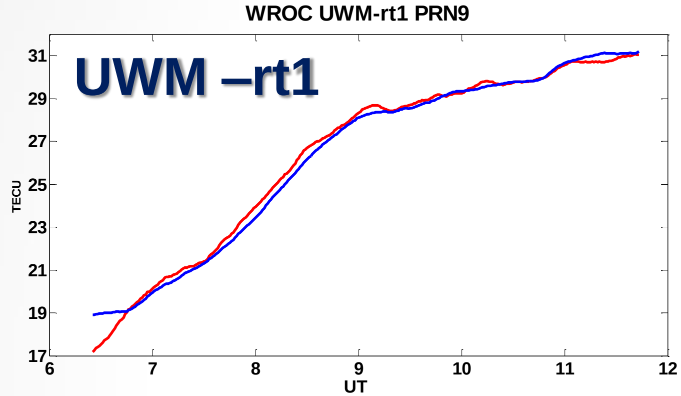
VTEC Validation:
- post-fit residual analysis

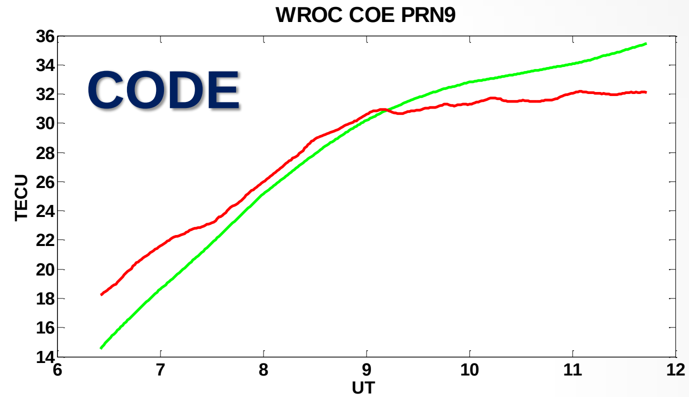


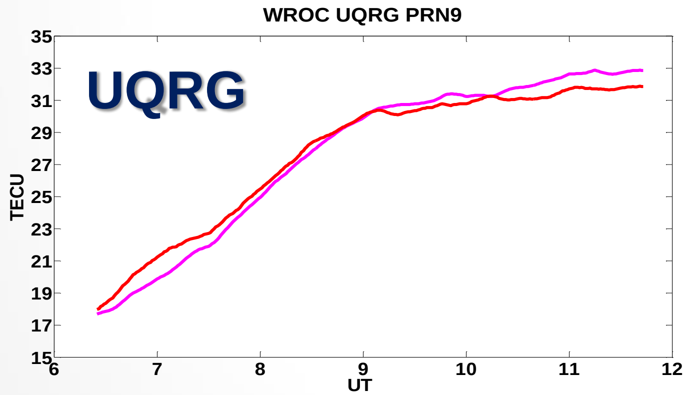


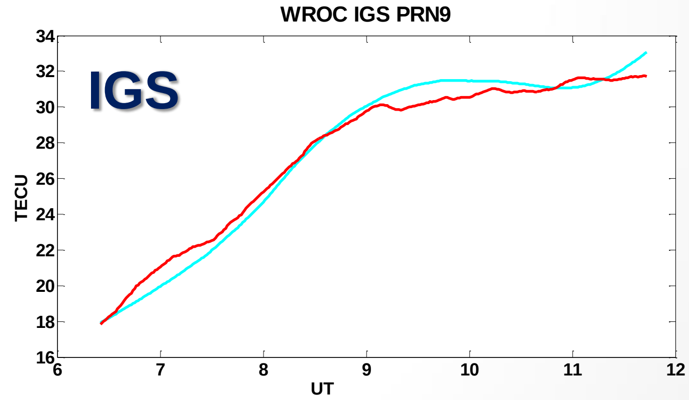
QUIET DAY

WROC 75/2015



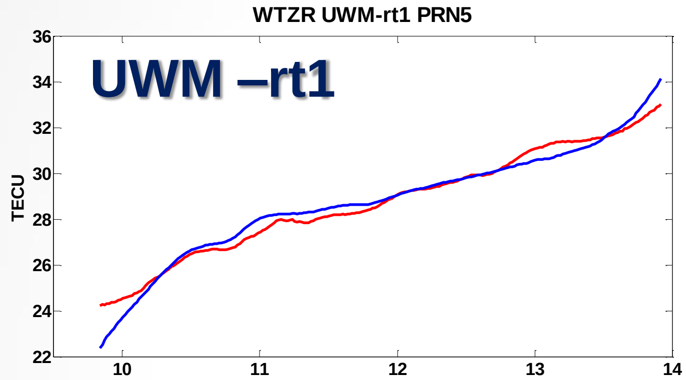


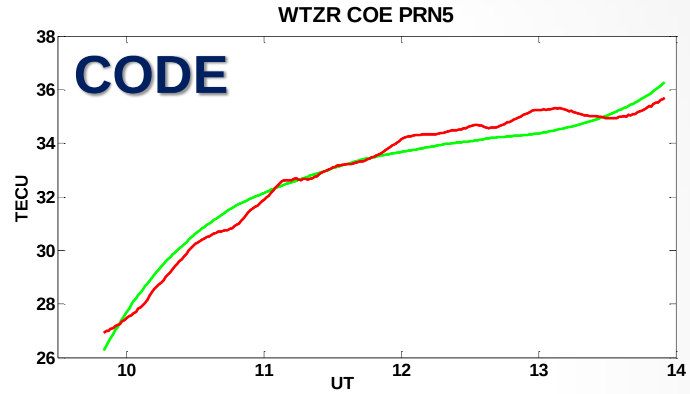


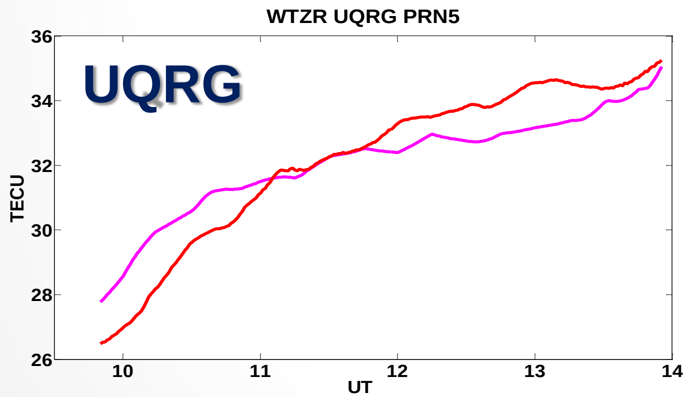


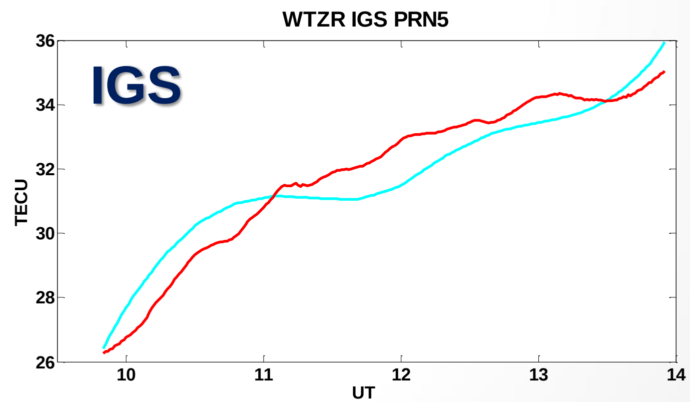
QUIET DAY

WTZR 75/2015



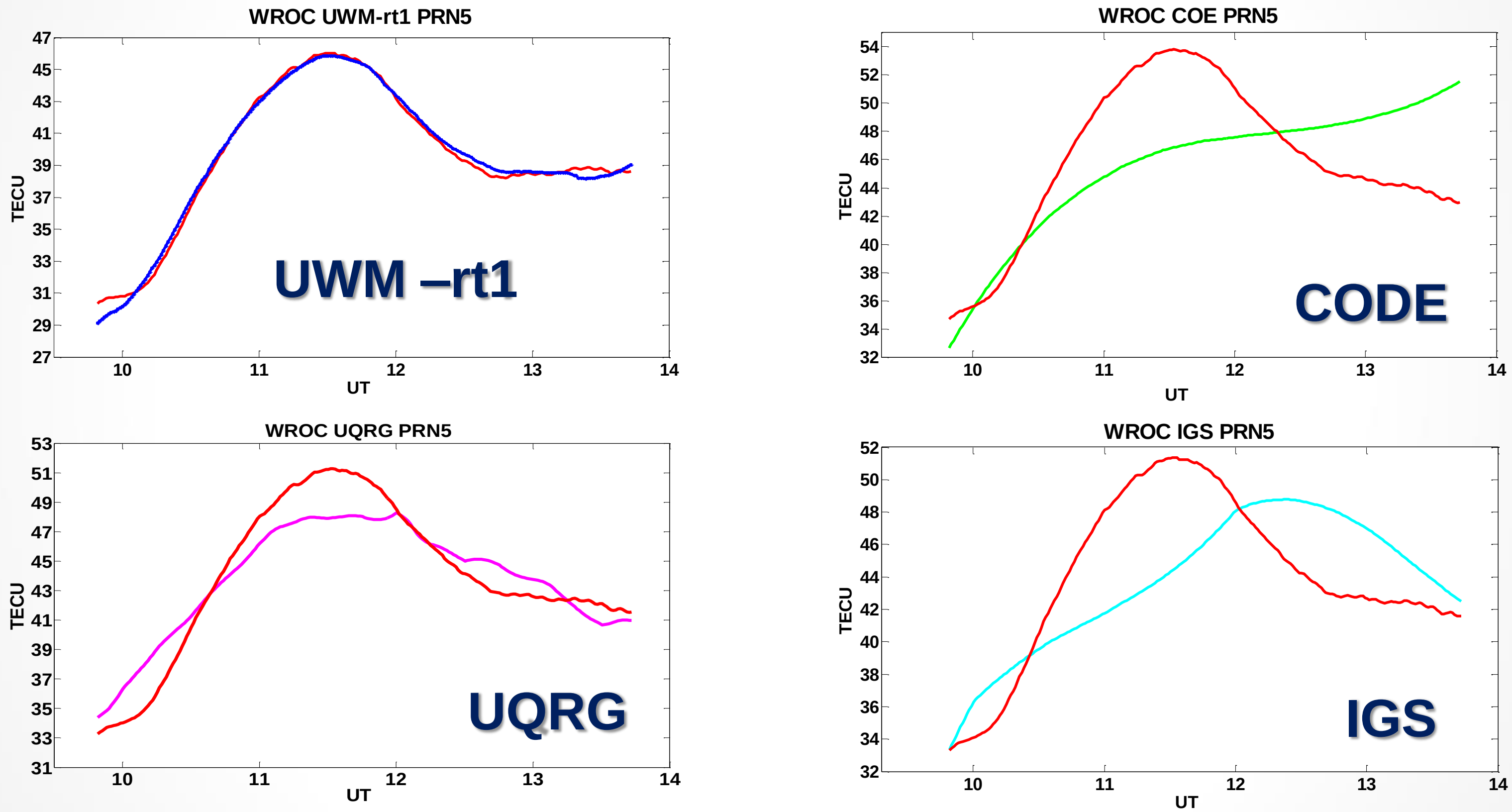






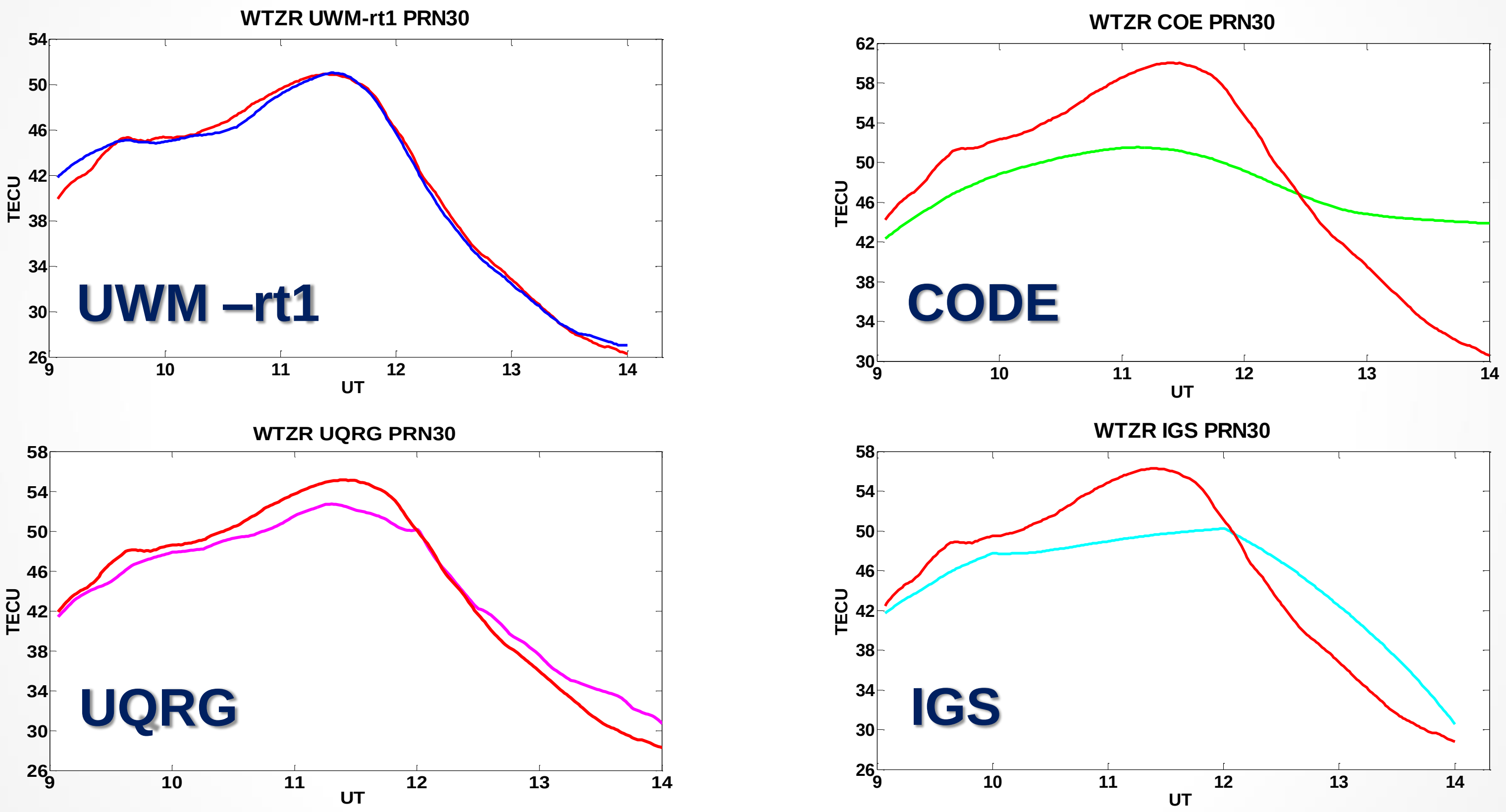
STORMY DAY

WROC 76/2015



STORMY DAY

WTZR 76/2015



RMS of post fit residuals for the analyzed TEC maps (vTEC) [TECU]

DOY	UWM – rt1	UQRG	IGS	CODE	NeQuick
73	*0,48*	0,86	0,77	1,66	1,89
74	*0,49*	0,85	0,76	1,87	1,57
75	*0,53*	0,92	0,82	1,41	1,32
76	*0,65*	1,28	1,63	2,47	4,48
77	*0,24*	0,55	0,75	1,33	2,07
78	*0,23*	0,61	0,77	1,80	2,17
79	*0,19*	0,56	0,81	1,18	1,47

RMS of post fit residuals for the analyzed TEC maps (sTEC) [TECU]

DOY	UWM – rt1	UQRG	IGS	CODE	NeQuick
73	*0,84*	1,28	1,15	2,65	2,92
74	*0,87*	1,27	1,14	2,98	2,49
75	*0,97*	1,38	1,22	2,23	2,04
76	*1,09*	1,93	2,37	3,88	7,18
77	*0,39*	0,84	1,11	2,12	3,23
78	*0,38*	0,92	1,18	2,91	3,42
79	*0,33*	0,84	1,16	1,88	2,27

The overall RMS based on all days, stations and satellite arcs (vTEC) [TECU]

UWM – rt1	UQRG	IGS	CODE	NeQuick
0,42	0,83	0,91	1,70	2,17

The overall RMS based on all days, stations and satellite arcs (sTEC) [TECU]

UWM – rt1	UQRG	IGS	CODE	NeQuick
0,73	1,24	1,35	2,70	3,44

NEXT STEPS:

- ❑ Application of ionosphere mapping factors (GFZ)
  - Should allow for including data down to 10-15 degs.
  - This in turn may extend the range of the model
  - and also may reduce the number of stations
- ❑ Validation in PPP (WUELS and GFZ)

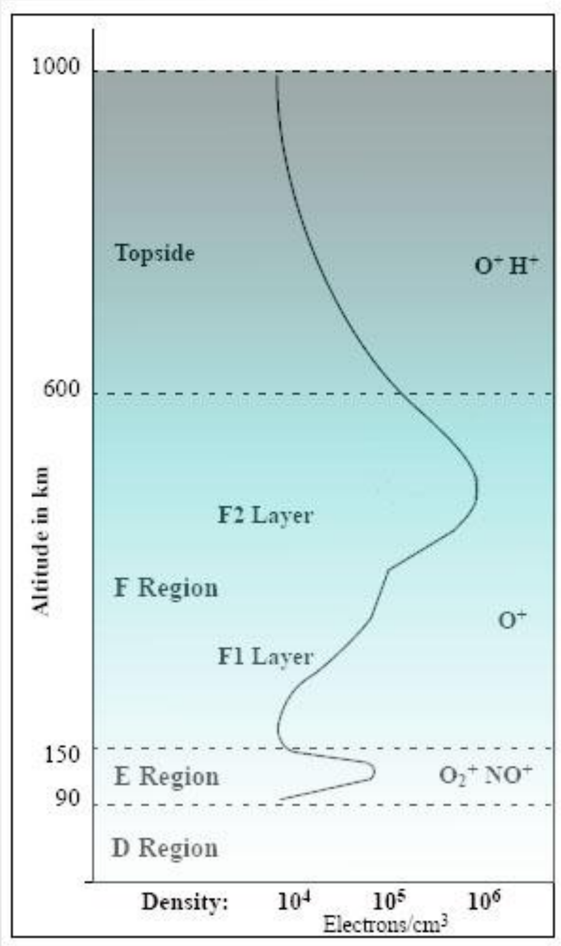
FUTURE:

- ❑ Providing Global model
- ❑ Real-time application
- ❑ 3D modeling

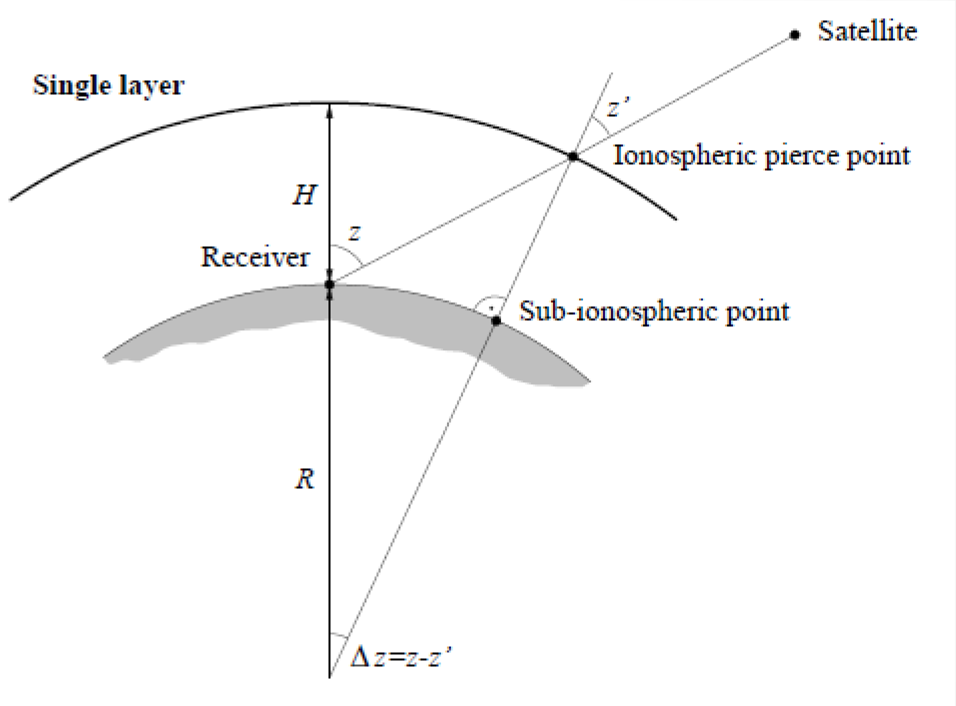
Thank you for your attention!

Backup slides

Single Layer Model *(SLM)*



http://grupposole.astrofili.org/



where:

z – the satellite's zenith distance at the receiver's location.

z' – the satellite's zenith distance at the ionospheric pierce point.

R – the mean earth radius.

H – the height of the single layer.