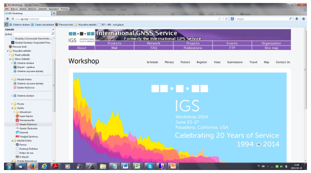
Space Radio Diagnostics Research Centre (SRRC/UWM)
IGS Ionospheric Working Group

GPS/TEC Ionosphere diagnostics and IGS services



Andrzej Krankowski

University of Warmia and Mazury in Olsztyn,
Space Radio Diagnostics Research Centre (SRRC/UWM)

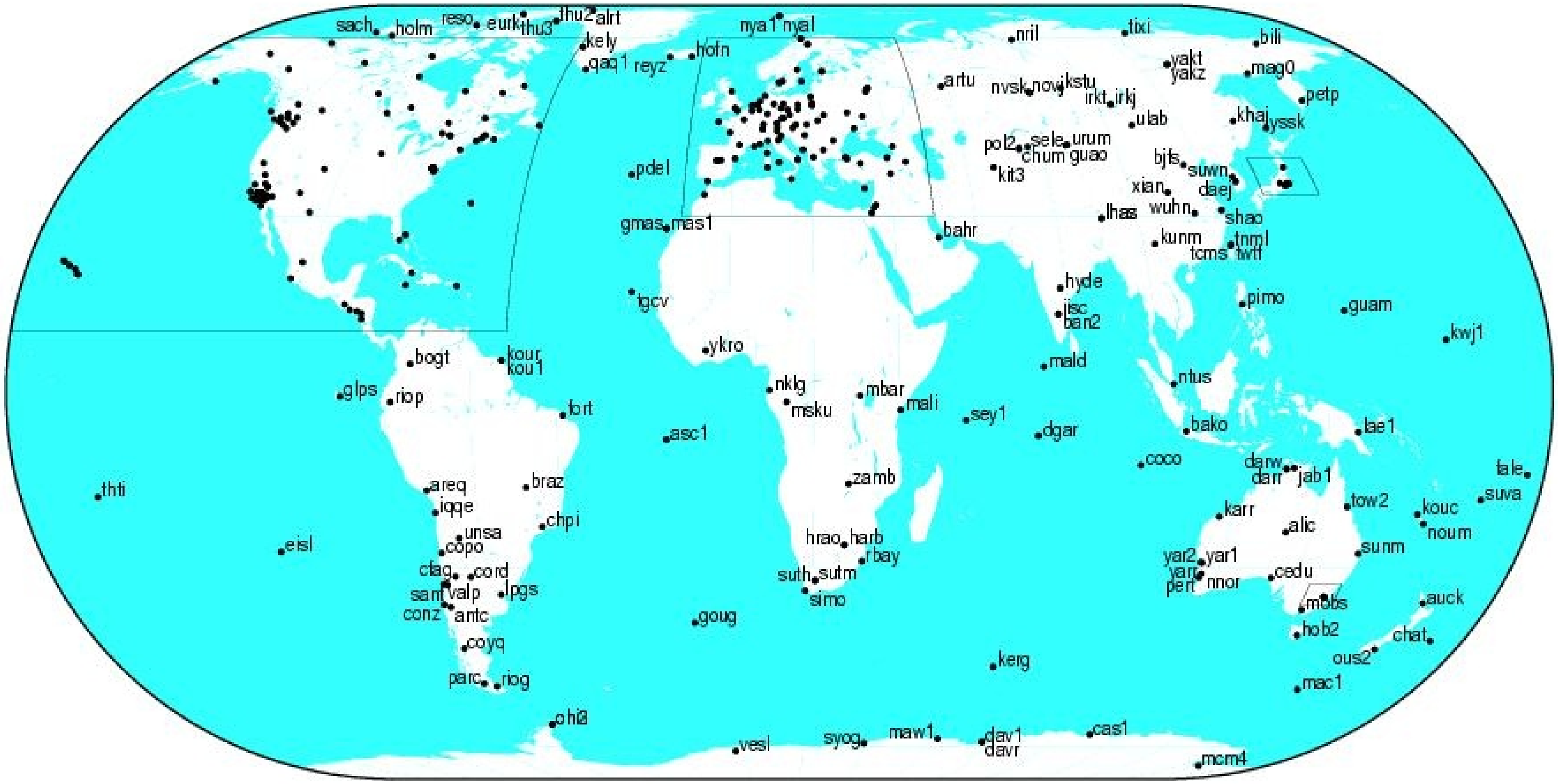
Manuel Hernández-Pajares

UPC-IonSAT res. group

Outline

- Introduction
- IGS IONO WG activities
  - Current performance of IGS global TEC maps
- Recommendations after IGS 2014 Workshop
  - TEC fluctuation maps using ROTI over Northern Hemisphere
- Agenda of IONO splinter meeting of IGS 2016
  - New IGS Ionosphere Associate Analysis Centers (IAACs)
  - Brief summary of new and existing VTEC GIMs performance
  - Real-time IRI in cooperation with IGS
  - Cooperation with International LOFAR Telescope (ILT)
  - The new IONEX 1.1 format
- Recommendations after IGS 2016 Workshop
- Conclusions

International GNSS Service - IGS



IGS directly manages ~400 permanent GNSS stations observing 4-12 satellites at 30 s rate: more than 250,000 STEC observations/hour worldwide, but there is lack of stations at some areas (e.g., over the oceans)

Space Radio Diagnostics Research Centre (SRRC/UWM)
IGS Ionospheric Working Group

IGS IONO WG activities

The IGS Ionosphere Working group started its activities in June 1998 with the main goal of a routinely producing IGS Global TEC maps.

This is being done now with a latency of 11 days (final product) and with a latency of less than 24 hours (rapid product).

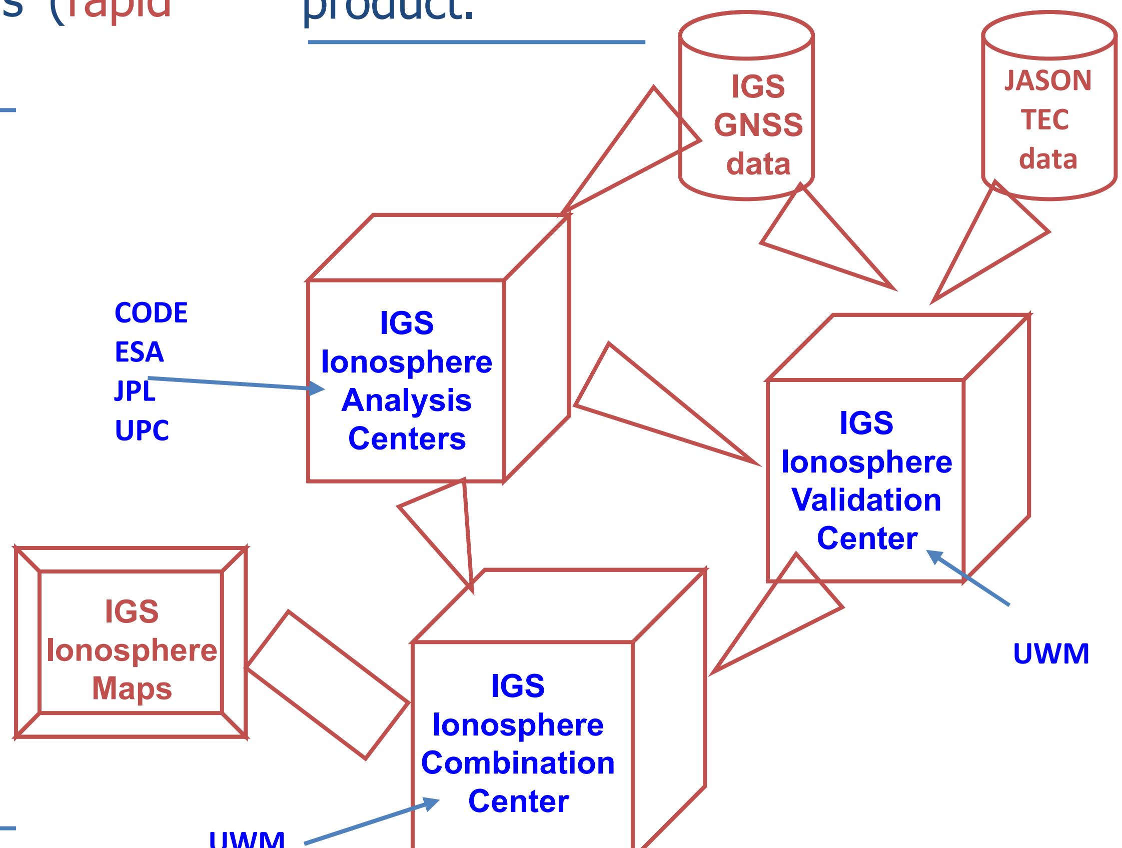
This has been done under the direct responsibility of the Iono-WG chairmans:

1. Dr Joachim Feltens, ESA 1998–2002,

2. Prof.. Manuel Hernández-Pajares, UPC, 2002–2007

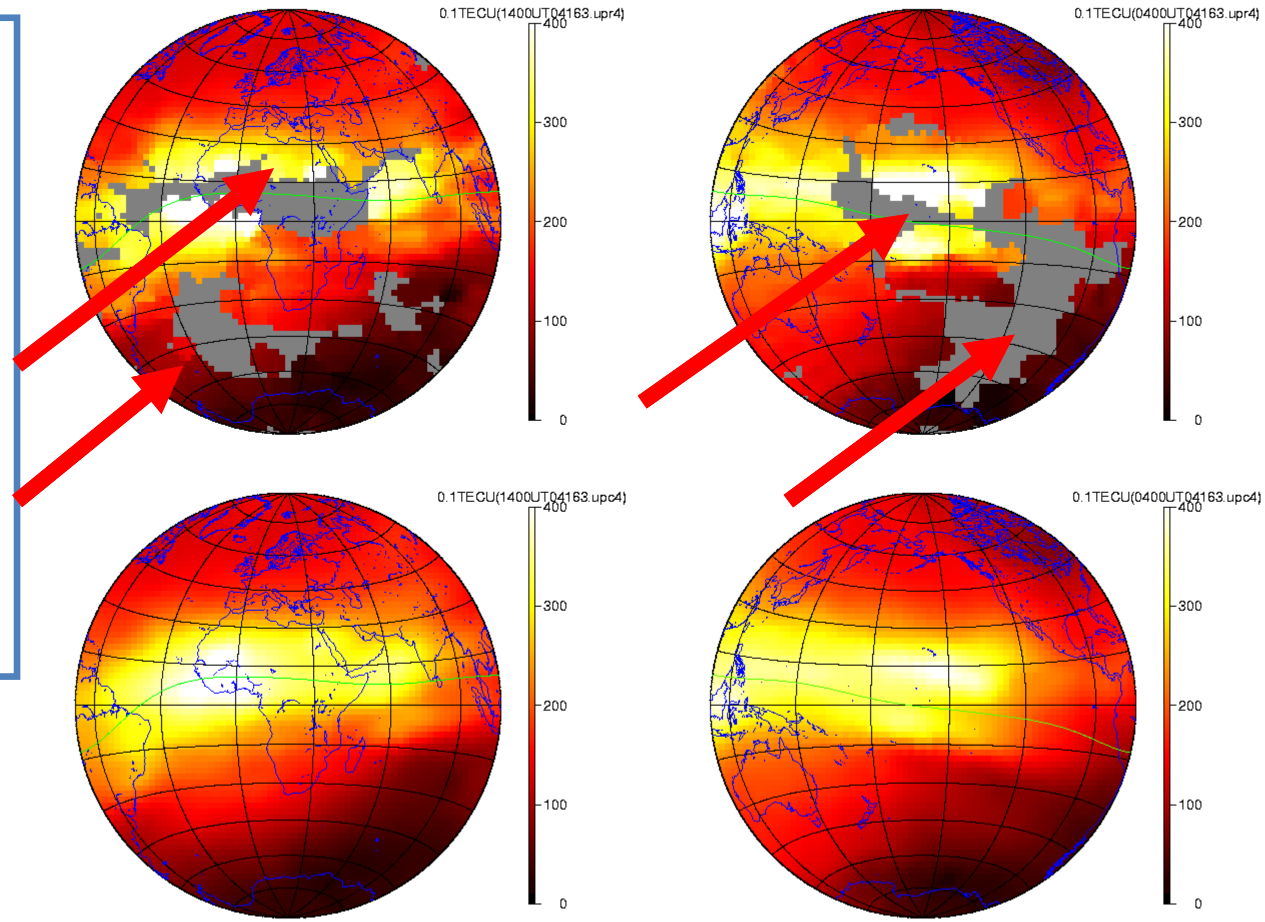
3. Prof. Andrzej Krankowski, UWM, 2008-

The IGS ionosphere product is a result of the combination of TEC maps derived by different Analysis Centers by using weights computed by Validation Center, in order to get a more accurate product.



Determining VTEC in a global network: main problem: lack of data - South and Oceans

It can be seen that the typical "holes" appearing at the first stage of the global maps computation (each 2 hours). This requires an optimum spatial-temporal interpolation technique to cover all the Ionosphere.



Lack of data over the equatorial Africa and Atlantic, and in part over equatorial and southern Pacific, hamper the detection of the equatorial anomalies (June 13, 2004).

The IONEX format body

The **IONEX** (IONosphere inter EXchange) format allows to store the VTEC and its error estimates in a grid format.

```
     1                                                            START OF TEC MAP
  2004     4    27     0     0     0                              EPOCH OF CURRENT MAP
    87.5-180.0 180.0   5.0 450.0                                  LAT/LON1/LON2/DLON/H
  123  123  123  124  125  125  126  126  126  126  126  126  125  125  125  128
  125  125  125  126  126  125  124  124  124  124  124  123  123  122  122  121
  120  120  119  118  118  118  118  118  117  117  116  116  115  114  114  113
  113  113  114  114  114  114  115  115  115  116  116  117  117  118  119  120
  120  121  121  122  123  123  123  123  123
    85.0-180.0 180.0   5.0 450.0                                  LAT/LON1/LON2/DLON/H
   29  129  130  131  132  132  133  133  134  134  134  134  134  134  134  136
   35  136  130  129  129  129  128  128  128  127  126  124  123  122  121  120
   19  118  117  117  117  117  116  116  115  115  114  113  112  111  110  109
   09  110  109  109  109  110  111  111  112  112  113  113  115  116  117  118
   20  122  123  125  126  127  128  129  129

   -87.5-180.0 180.0   5.0 450.0                                  LAT/LON1/LON2/DLON/H
   87   88   88   90   90   91   92   93   93   94   94   95   94   93   91   89
   87   86   85   84   83   82   81   81   80   80   79   78   78   78   77   77
   76   76   76   75   75   76   77   77   76   79   79   79   80   81   82   83
   83   84   85   85   85   85   85   85   85   86   87   87   87   88   88   87
   87   87   87   88   87   87   87   87   87
     1                                                            END OF TEC MAP
     2                                                            START OF TEC MAP
...
...
    13                                                            END OF TEC MAP
     1                                                            START OF RMS MAP
  2004     4    27     0     0     0                              EPOCH OF CURRENT MAP
    87.5-180.0 180.0   5.0 450.0                                  LAT/LON1/LON2/DLON/H
    7    7    7    7    7    7    7    7    7    7    8    8    9    9    9    6
    8    8    8    6    6    7    7    7    7    6    6    6    6    6    6    6
    6    6    7    7    7    6    7    6    6    7    7    7    7    8    8    9
   10    9    8    8    8    8    7    7    8    8    8    8    7    7    7    7
    7    6    6    7    6    7    6    6    7
...
```

Example of IGS Final GIM: 2010-141 DOY

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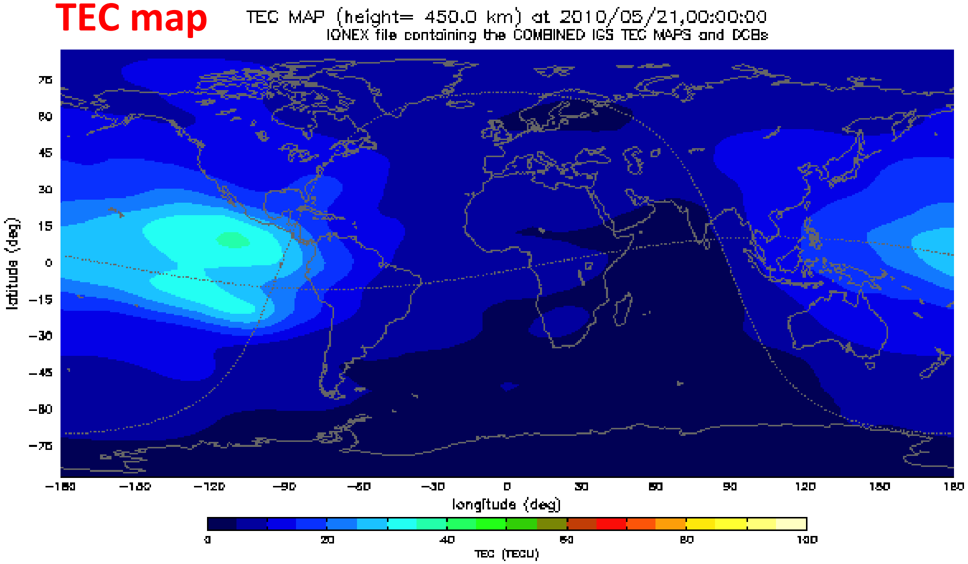
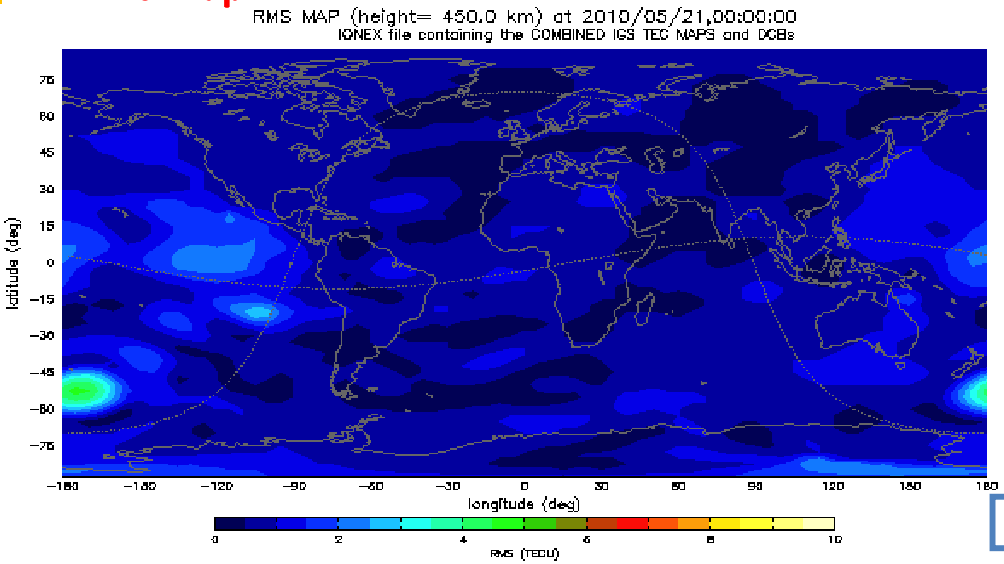
TEC map



4 Analysis Centers (CODE, ESA, JPL, and UPC) and a Validation Center (UPC) have been providing maps (at 2 hours x 5 deg. x 2.5 deg in UT x Lon. x Lat.), weights and external (altimetry-derived) TEC data.

RMS map



From such maps and weights the Combination Center (at first ESA, then UPC, and since 2008 - UWM) has produced the IGS TEC maps in IONEX format.

Units: TECU

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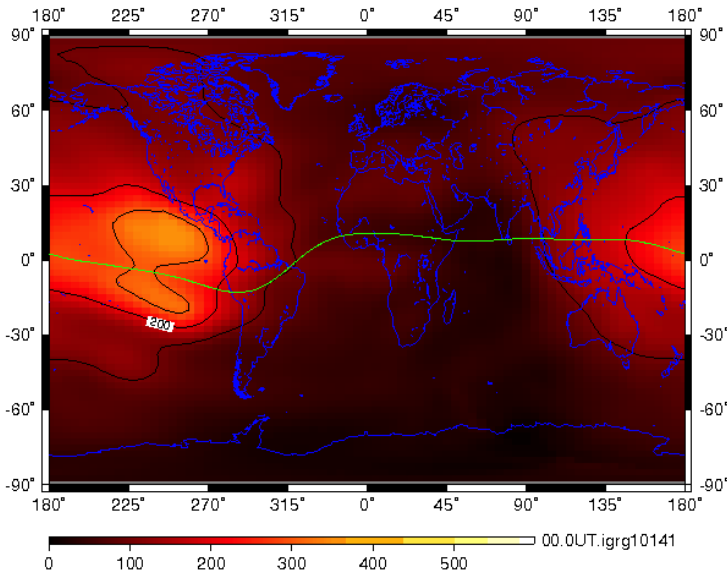
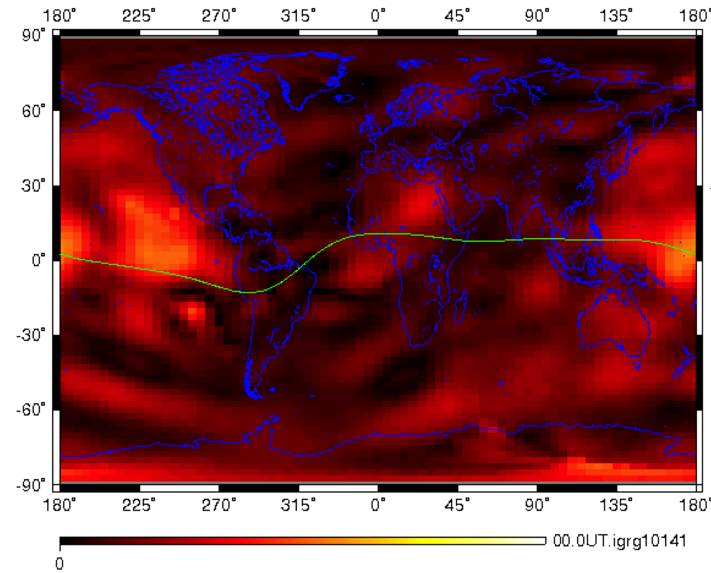
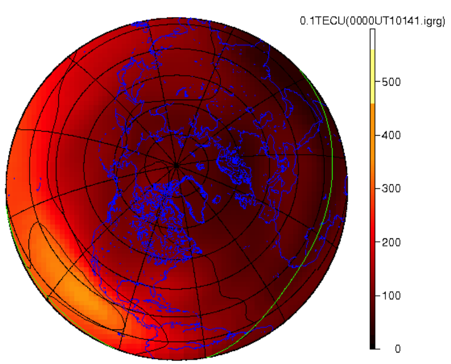
Example of IGS RAPID GIM: 2010-141 DOY

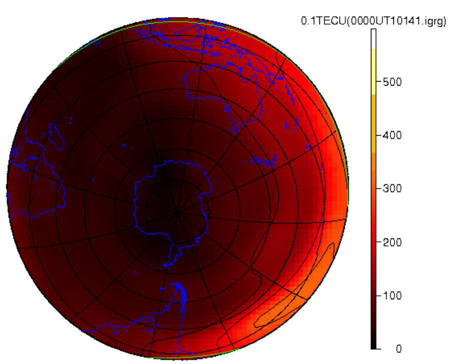
TEC maps

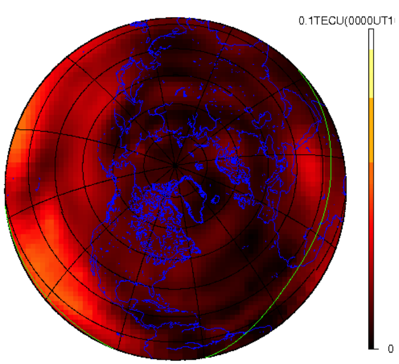


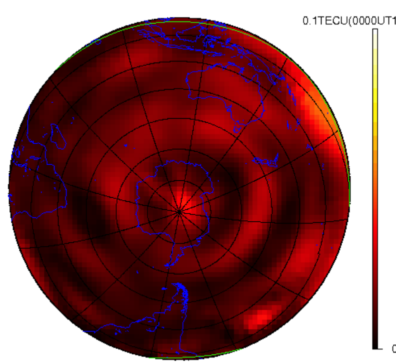
RMS maps









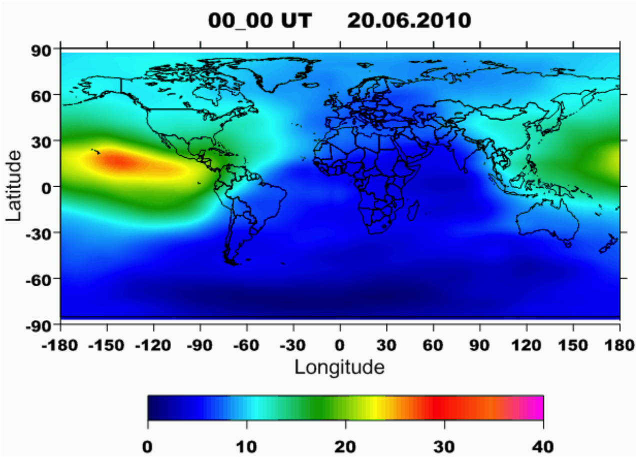


Units: 0.1 TECUs

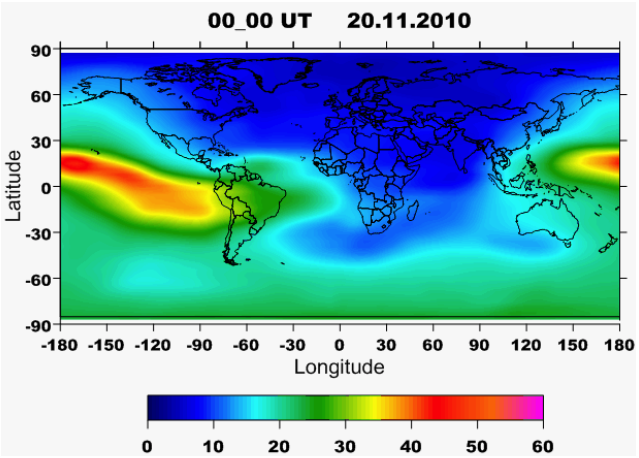
Example of IGS PREDICTED GIM

IGS Predicted GIM

June 20, 2010

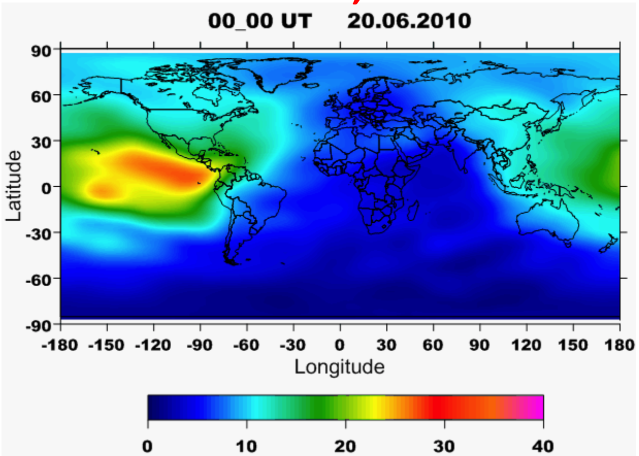


November 20, 2010

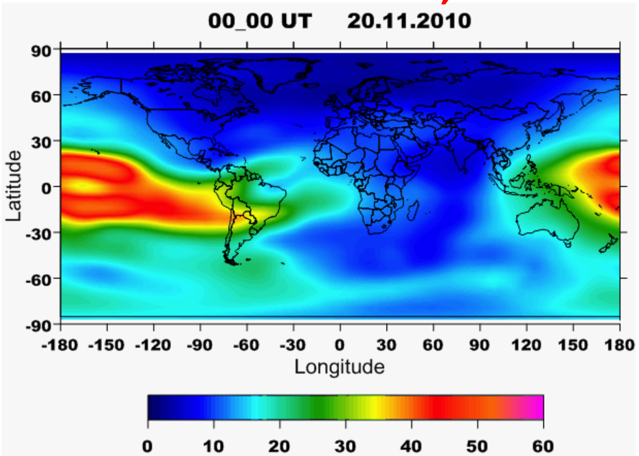


IGS Final GIM

June 20, 2010



November 20, 2010



IGS 2014 Workshop in Pasadena

Recommendations:

Starting a new potential official product – TEC fluctuation maps using ROTI over Northern Hemisphere to monitor the dynamic of oval irregularities

Cooperation with IRI COSPAR group for improving IRI TEC.

Announcements:

Natural Resources Canada (NRCan) is resuming the activities on global VTEC modelling. After a performance evaluation period, NRCan can become again an IAAC.

The Institute of Geodesy and Geophysics (IGG), Chinese Academy of Sciences, Wuhan, China (Yunbin Yuan, beginning 2015) is computing on routinely basis global VTEC maps, and it can become a new IAAC after a performance evaluation period.

Monitoring of the TEC fluctuations using GNSS data

High latitude TEC fluctuations

For fast detecting phase fluctuation occurrence the rate of TEC (dTEC/dt) is more preferred (Wanninger, 1993):

ROT = 9.52 A 1016 el/m A (Φi - Φk)

Φki - differential carrier phase sample with 30 sec interval

Δt = tk – t i= 1 min.

As a measure of ionospheric activity we used also the Rate of TEC Index (ROTI) based on standard deviation of ROT (for 5 minut intervals)(Pi et all, 1997):

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}$$

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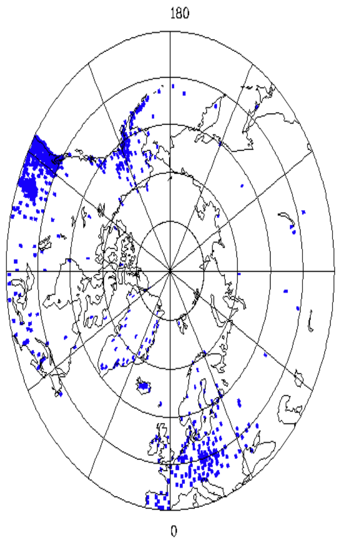
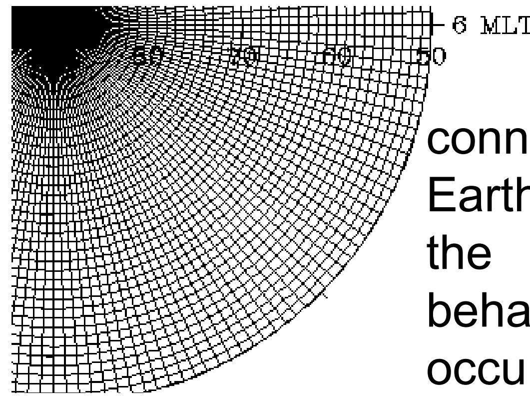
TEC fluctuation service for creating ROTI maps

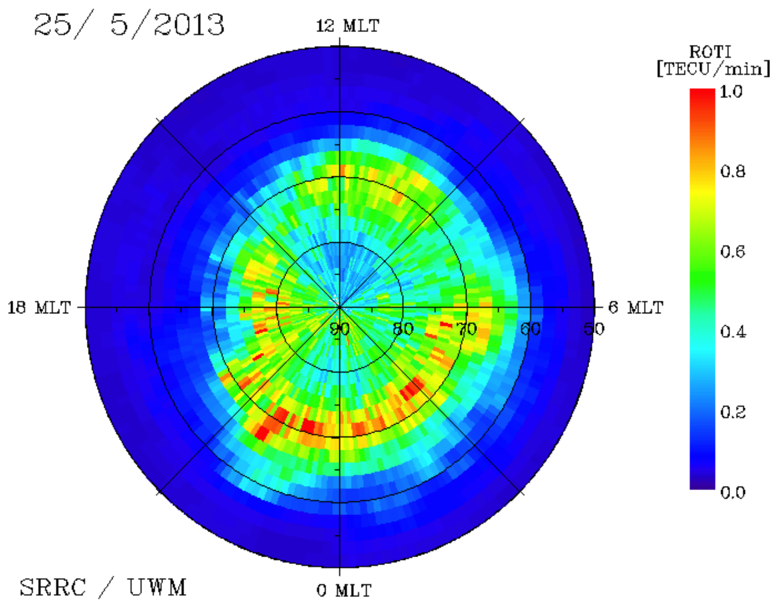
SPACE RADIO-DIAGNOSTICS RESEARCH CENTRE (SRRC/UWM)
IGS IONOSPHERE WORKING GROUP



The locations of the stations in the North Hemisphere used for ROTI map construction



Due to strong connections between the Earth's magnetic field and the ionosphere, the behavior of the fluctuation occurrence is represented as a function of the magnetic local time (MLT) and of the corrected magnetic latitude. The grid of ROTI maps in polar coordinates with cell size 2 degree (magnetic local time) and 2 degree (geomagnetic latitude).



Each map, as a daily map, demonstrates ROTI variation with geomagnetic local time (00-24 MLT).

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In the updated version more than 700 permanent stations (from IGS, UNAVCO and EUREF databases) have been involved into processing for the ionosphere fluctuation service. Such number of stations provides enough data for representation a detailed structure of the ionospheric irregularities pattern.

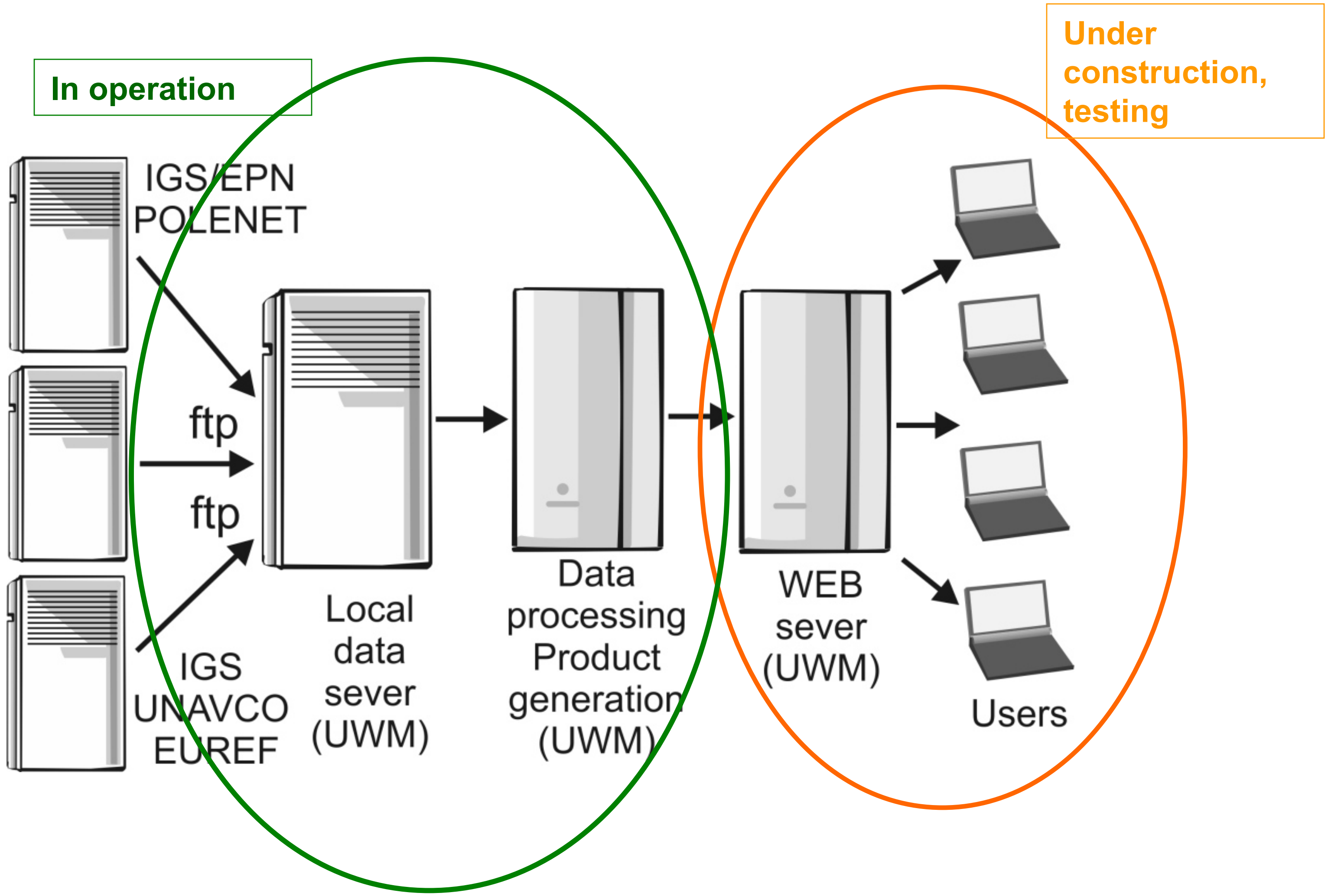
The proposed format to store the ROTI values

For ROTI data storing it is proposed simple ASCII format based on grid 2 x 2 degree - geomagnetic latitude from 89o to 51o with step 2 and corresponded to magnetic local time (00-24 MLT) polar coordinates from 0 to 360.

	89	87	85	83	81	79	77	75	73	71	69	67	65	63	61	59	57	55	53	51
1	0.2959	0.4422	0.465	0.311	0.3678	0.4486	0.3578	0.3835	0.4148	0.3314	0.3425	0.126	0.0913	0.032	0.0351	0.0331	0.036	0.0372	0.0382	0.0336
3	0.2927	0.4224	0.3924	0.3731	0.4034	0.4608	0.3389	0.4352	0.4048	0.2986	0.248	0.1268	0.1171	0.0378	0.0352	0.0335	0.0346	0.0343	0.0396	0.0335
5	0.2792	0.394	0.3942	0.4697	0.3284	0.4379	0.3944	0.465	0.3843	0.2807	0.2481	0.1496	0.1099	0.0438	0.0323	0.0327	0.0355	0.0367	0.0374	0.0336
7	0.2609	0.4365	0.3266	0.3829	0.4267	0.5317	0.4661	0.4689	0.3635	0.3103	0.2117	0.1402	0.0725	0.0444	0.0335	0.0344	0.0363	0.0382	0.0357	0.034
9	0.4455	0.4226	0.3477	0.4237	0.4313	0.5694	0.5135	0.3641	0.4155	0.2923	0.2217	0.1319	0.0794	0.0449	0.0369	0.0335	0.0385	0.0396	0.0383	0.0358
11	0.5008	0.4245	0.4262	0.3578	0.3814	0.5214	0.5073	0.3896	0.3925	0.3136	0.2374	0.1492	0.08	0.0393	0.0322	0.033	0.0367	0.0411	0.0384	0.0389
13	0.3294	0.3593	0.4965	0.3778	0.4072	0.7487	0.5215	0.3219	0.3607	0.3442	0.2959	0.1609	0.0808	0.0463	0.0344	0.0292	0.0343	0.0422	0.0377	0.038
15	0.3004	0.3847	0.4443	0.3325	0.3606	0.6081	0.3513	0.3715	0.368	0.307	0.2705	0.1739	0.068	0.0364	0.0365	0.0293	0.0342	0.0416	0.0397	0.0401
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
345	0.3648	0.6725	0.3646	0.4227	0.4633	0.4701	0.568	0.433	0.3694	0.3681	0.2091	0.1214	0.0726	0.0373	0.0385	0.0391	0.0347	0.0342	0.0352	0.0336
347	0.3667	0.4735	0.3784	0.3845	0.5204	0.5891	0.5423	0.434	0.4858	0.3508	0.2132	0.1101	0.0882	0.0437	0.0373	0.0412	0.0361	0.0345	0.0343	0.0345
349	0.3688	0.5449	0.4021	0.3499	0.5294	0.6081	0.578	0.4124	0.4193	0.3378	0.2235	0.1295	0.0939	0.0418	0.0367	0.0369	0.0379	0.0346	0.0334	0.036
351	0.4049	0.5729	0.4159	0.3901	0.4119	0.5135	0.4602	0.4285	0.4767	0.3112	0.2217	0.1312	0.0837	0.0399	0.0355	0.034	0.0536	0.035	0.0328	0.0325
353	0.3524	0.389	0.4495	0.3115	0.5101	0.5135	0.4072	0.4766	0.5348	0.282	0.2186	0.1162	0.0782	0.0412	0.0342	0.0314	0.0545	0.0372	0.0326	0.0339
355	0.297	0.3992	0.3368	0.3606	0.5323	0.4776	0.367	0.4452	0.5001	0.336	0.282	0.1088	0.0834	0.0404	0.0327	0.0321	0.0391	0.0441	0.0323	0.0352
357	0.2614	0.4348	0.31	0.4465	0.3972	0.4235	0.3796	0.3958	0.44	0.3829	0.3155	0.1115	0.0709	0.0361	0.033	0.0318	0.0408	0.0397	0.0382	0.0367
359	0.2838	0.3851	0.3392	0.4338	0.4432	0.3893	0.323	0.3949	0.4581	0.3688	0.3274	0.147	0.0744	0.0332	0.0331	0.0338	0.0365	0.0378	0.0377	0.0364

The sample of ROTI-ex format body

TEC fluctuation service for creating ROTI maps



The TEC fluctuation service operation diagram and status

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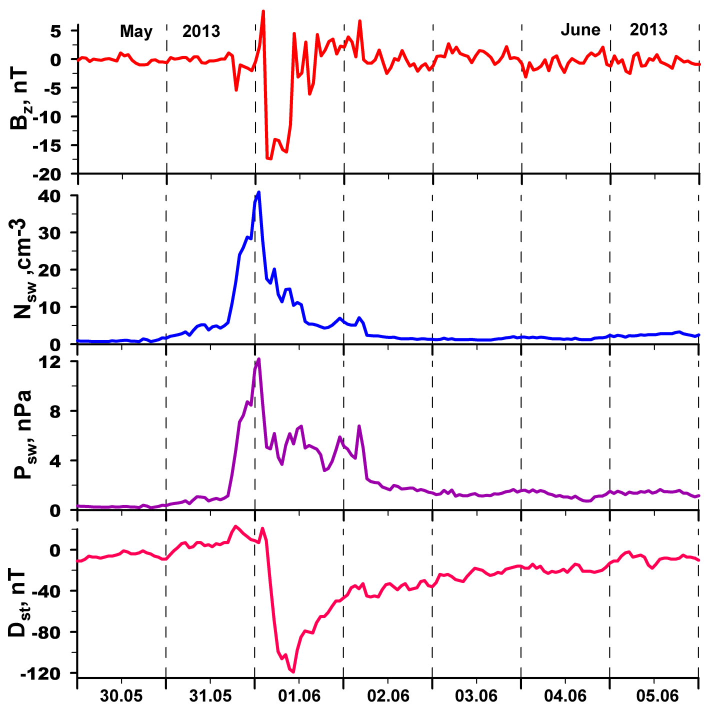
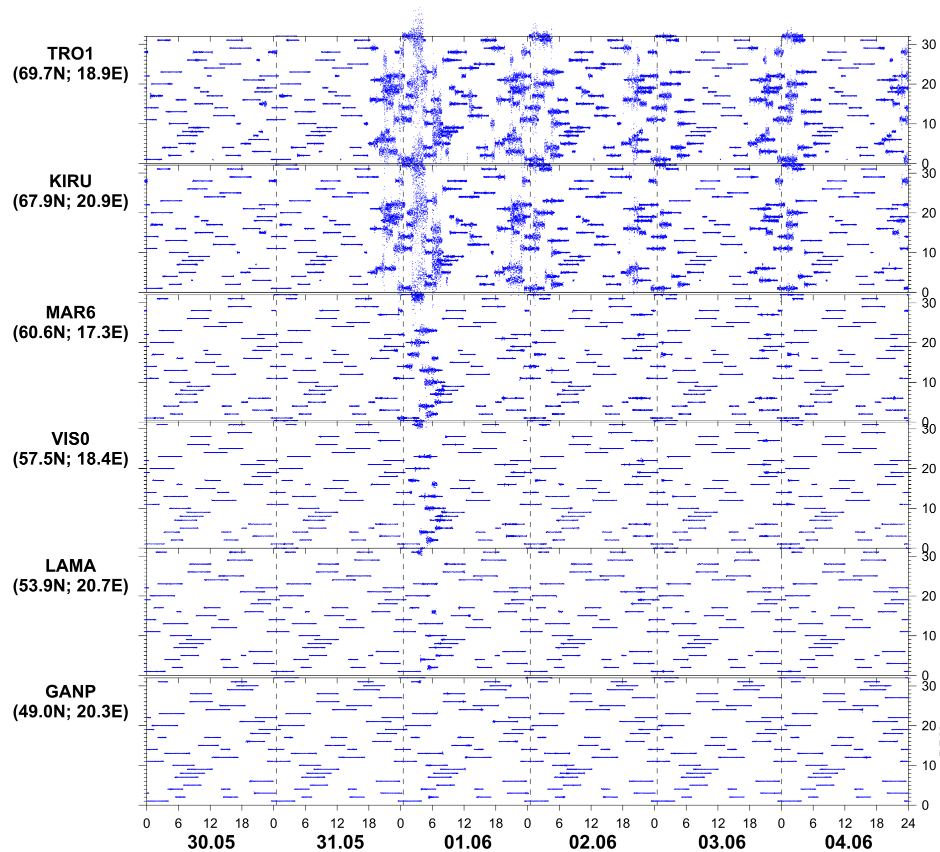
SPACE RADIO-DIAGNOSTICS RESEARCH CENTRE (SRRC/UWM)
IGS IONOSPHERE WORKING GROUP

Variability of ROT values over chain of selected European GNSS stations Geomagnetic storm 30 May – 5 June 2013.



The interplanetary geomagnetic field Bz component, density and pressure of solar wind and Dst index variations for 30 May – 5 June 2013.



Variability of ROT values over chain of selected European GNSS stations (30 May – 4 June 2013). Right vertical axis shows the number of satellite (PRN).

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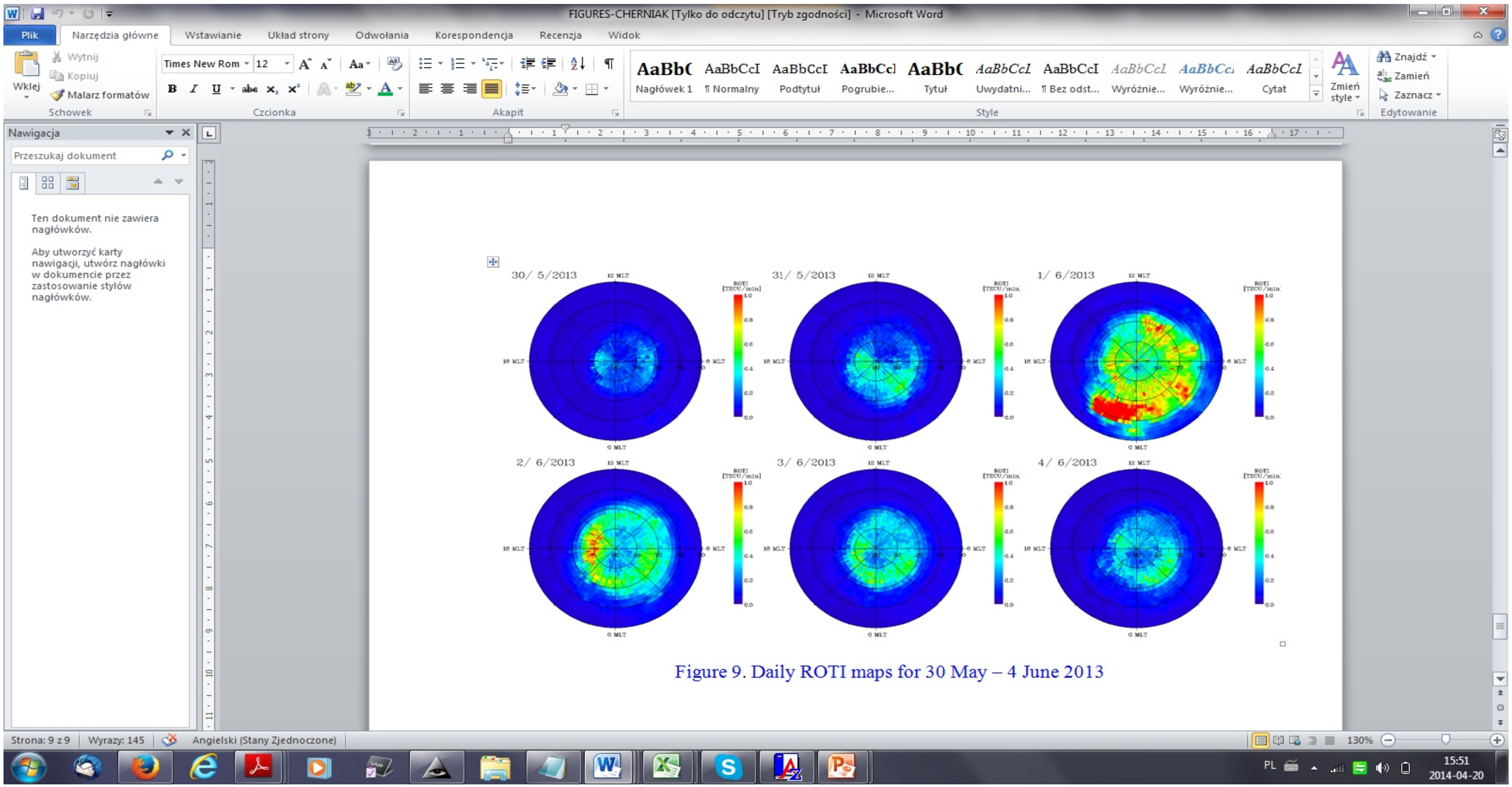
IGS IONOSPHERE WORKING GROUP

ROTI maps

Geomagnetic storm 30 May – 5 June 2013.



Evolutions of the daily ROTI maps for 30 May – 4 June 2013

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ROTI publications

Cherniak Iu., Krankowski A., Zakharenkova I.E, 2014b, *Observation of the ionospheric irregularities over the Northern Hemisphere: Methodology and Service*, **Radio Science** 49, pp. 653-662, 2014, DOI: 10.1002/2014RS005433.

Cherniak Iu., Zakharenkova I.E., Krankowski A., 2014c, *The approaches for the ionosphere irregularities modeling on the base of ROTI mapping*, **Earth, Planets and Space (EPS)** 66:165, 2014, doi:10.1186/s40623-014-0165-z

Cherniak Iu., Zakharenkova I.E., *2015a, Dependence of the high-latitude plasma irregularities on the auroral activity indices: A case study of 17 March 2015 geomagnetic storm*, **Earth, Planets and Space**, 2015, 67:151 doi:10.1186/s40623-015-0316-x

Cherniak Iu., Zakharenkova I.E., Redmon R.J. 2015, *Dynamics of the high-latitude ionospheric irregularities during the March 17, 2015 St. Patrick's Day storm: Ground-based GPS measurements*, **Space Weather**, Vol. 13, Issue 9, 585–597, doi:10.1002/2015SW001237

Recommendations of IGS 2016 Workshop

- To accept CAS-IGG, NRCan and WHU as new Ionospheric Analysis Centers, contributing to the IGS combined VTEC GIMs.
- The IONEX format shall be updated in order to accommodate contributions using multiple constellations and adequately describe the associated resulting differential code biases.
- Cooperation with IRI COSPAR group for potential improvement of both IRI and IGS TEC.
- Cooperation with International LOFAR Telescope (ILT) for potential synergies.

Comparing performances of seven different global VTEC ionospheric models in the IGS context

IGS WS, Feb. 8-12, 2016, Sydney, Australia

Manuel Hernandez-Pajares(1), David Roma-Dollase(1,10), Andrzej Krankowski(2), Reza Ghoddousi-Fard(3), Yunbin Yuan(4), Zishen Li(5), Hongping Zhang(6), Chuang Shi(6), Joachim Feltens(7), Attila Komjathy(8), Panagiotis Vergados(8), Stefan C. Schaer(9), Alberto Garcia-Rigo(1), Jose M. Gómez-Cama(10)

(1)UPC-IonSAT, Spain, (2) UWM, Poland, (3)NRCan, Canada, (4) CAS-IGG, China, (5)CAS-AOE, China, (6) WHU, China, (7) ESOC/ESA, Germany, (8) JPL/NASA, USA, (9) CODE, Switzerland, (10)UB-D.Electronics, Spain

1) Seven different ionospheric modelling techniques and/or software to be assessed

- **CODE**: (expansion in terms of Spherical Harmonics)
- **ESA/ESOC**: TEC maps are still computed with a single-layer approach, taking sTEC observables derived from dual-frequency GPS & GLONASS data (TEC is modelled by spherical harmonics in combination with a daily DCBs fitting).
- **JPL**: Global daily TEC maps with 15-minute temporal and ≥ 5x5 spatial resolution. Three-shell model ionosphere with slabs centered at: 250, 450, and 800 km from 200 globally distributed stations and Kalman-filter approach.
- **UPC**: Global voxel-defined 2-layer tomographic model solved with Kalman filter and splines (UPCG@2h) and kriging (UQRG@15m) interpolation to common grid of 5ºx2.5º in LONxLAT.
- **CAS**: The global and local ionospheric TEC is modeled by SH and GTS functions and then are integrated to generate the global map based on DADS (Different Areas for Different Stations) approach.
- **EMRG**: Canadian Geodetic Survey of Natural Resources Canada (NRCan) has resumed since April 2015 the generation of VTEC GIMs (single-layer + grid + Spherical Harmonics).
- **WHU**: The University of Wuhan is using an expansion in terms of Spherical Harmonics

GIM TEC Derivation

Jet Propulsion Laboratory
California Institute of Technology

TEC Observation
Equa n

TEC Retrieval: GIM Fundamentals

Providing GIMs JPLG (2h–final)

- Global daily TEC maps with 15-minute temporal and ≥ 5x5 spatial resolution
- Three-shell model ionosphere with slabs centered at: 250, 450, and 800 km
- GIM uses observations from 200 globally distributed stations (*zeta* function)
- A Kalman-filter approach is used to estimate the basis functions and biases

$$TEC = M_1(h_1, E_1) \sum_i C_{1i} B_{1i}(\lambda_1, \phi_1) + M_2(h_2, E_2) \sum_i C_{2i} B_{2i}(\lambda_2, \phi_2) +$$

$$M_3(h_3, E_3) \sum_i C_{3i} B_{3i}(\lambda_3, \phi_3) + \underbrace{b_{s,GPS} + b_{r,GPS} + b_{r,GLONASS_f}(GLONASS_f)}, \quad (1)$$

Basis functions
(functions of lat/lon)

Ground-based receiver differential code biases
GPS and GLONASS satellite biases

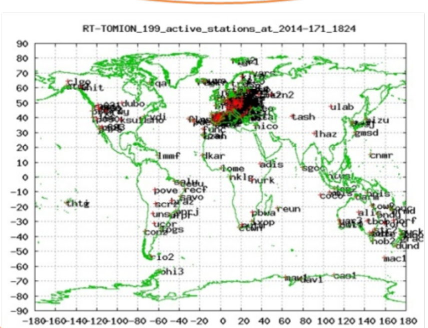
Baseline: Global tomographic UPC-IonSAT runs since 1998.5

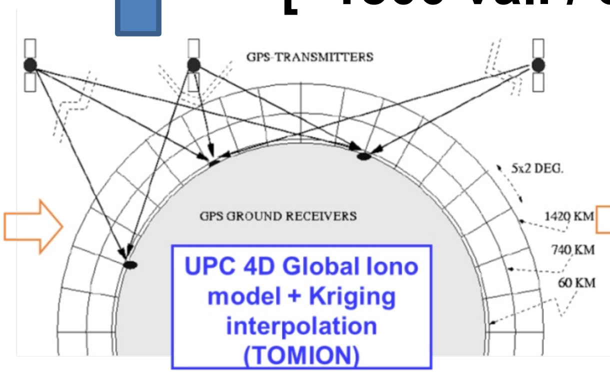
Providing GIMs UPCG (2h-final w tomo-splines) and UQRG (15min-rapid w. tomo-kriging) to this study

From each obs. we get one STEC value: V=S/M=(Li-Bi)/M. [~1500 val. / 30 s]

Interpol. by Splines (UPCG)

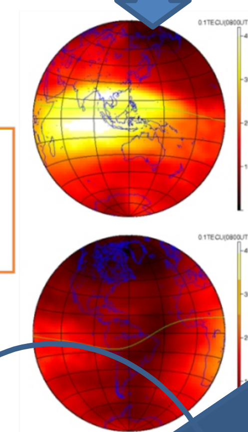
RT IGS ground GPS data (70 to 195 worldwide receivers)





$$L_I = S + B_I \simeq \sum_{i=1}^{n} N_{e,i} \Delta l_i + B_I$$

UPC global VTEC maps



Kriging Interpolation

New VTEC maps (UQRG)

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Layout summarizing the global VTEC computation from ground GP data by means of the UPC TOMION software, including the mai tomographic model equation[*]

[*](data: ionospheric combination of carrier phases LI, and length intersection wi each voxel, Δli; unknowns: its ambiguity BI, the STEC, S, which includes the mean electron density within each given voxel, Ne,i).

(see for instance Hernandez-Pajares, M., Juan, M. and Sanz, J., 1999. *New approaches in global ionospheric determination using ground GPS data*. Journal of Atmospheric and Solar-Terrestrial Physics 61, pp. 1237–1247.).

CAS: New Approach for generating GIM with high accuracy

The global and local ionospheric TEC is modeled by SH and GTS functions and then are integrated to generate the global map based on DADS (Different Areas for Different Stations) approach.

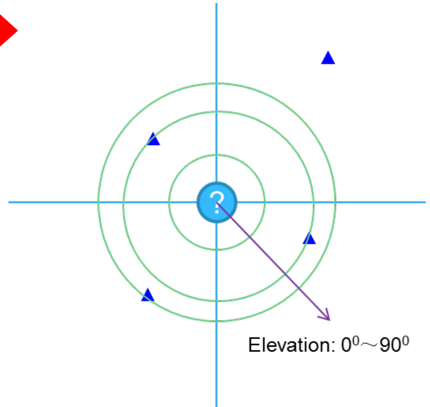
$$E_i = \begin{cases} VTEC_{g,i} & M = 0 \\ \dfrac{\sum_{m=1}^{M} P_m \cdot VTEC_{z,i,m}}{\sum_{m=1}^{M} P_m} & M \neq 0 \end{cases}$$

$$P_m = \frac{1}{\sigma_{0,m}^2 \cdot \left[\cos^2\left(elev_{i,m}\right) + 1\right]}$$

Spherical Harmonic Function + Trigonometric Series Function

$$VTEC(\phi, \lambda) = \sum_{n=0}^{n_{d\max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\varphi) \cdot \left(\tilde{A}_{nm}\cos(m\lambda) + \tilde{B}_{nm}\sin(m\lambda)\right)$$

$$\begin{cases} \mathrm{TEC}(\varphi, \lambda, z) = \mathrm{VTEC}(\varphi, \lambda) \cdot M(z) \\ \mathrm{VTEC}(\varphi, \lambda) = \sum_{n=0}^{n_{\max}} \sum_{m=0}^{m_{\max}} \left\{E_{nm}(\varphi - \varphi_0)^n \lambda^m\right\} \\ \quad + \sum_{k=1}^{k_{\max}} \left\{C_k \cos(k\lambda) + S_k \sin(k\lambda)\right\} \\ \lambda = \frac{2\pi(t-14)}{T}, (T = 24h) \end{cases}$$



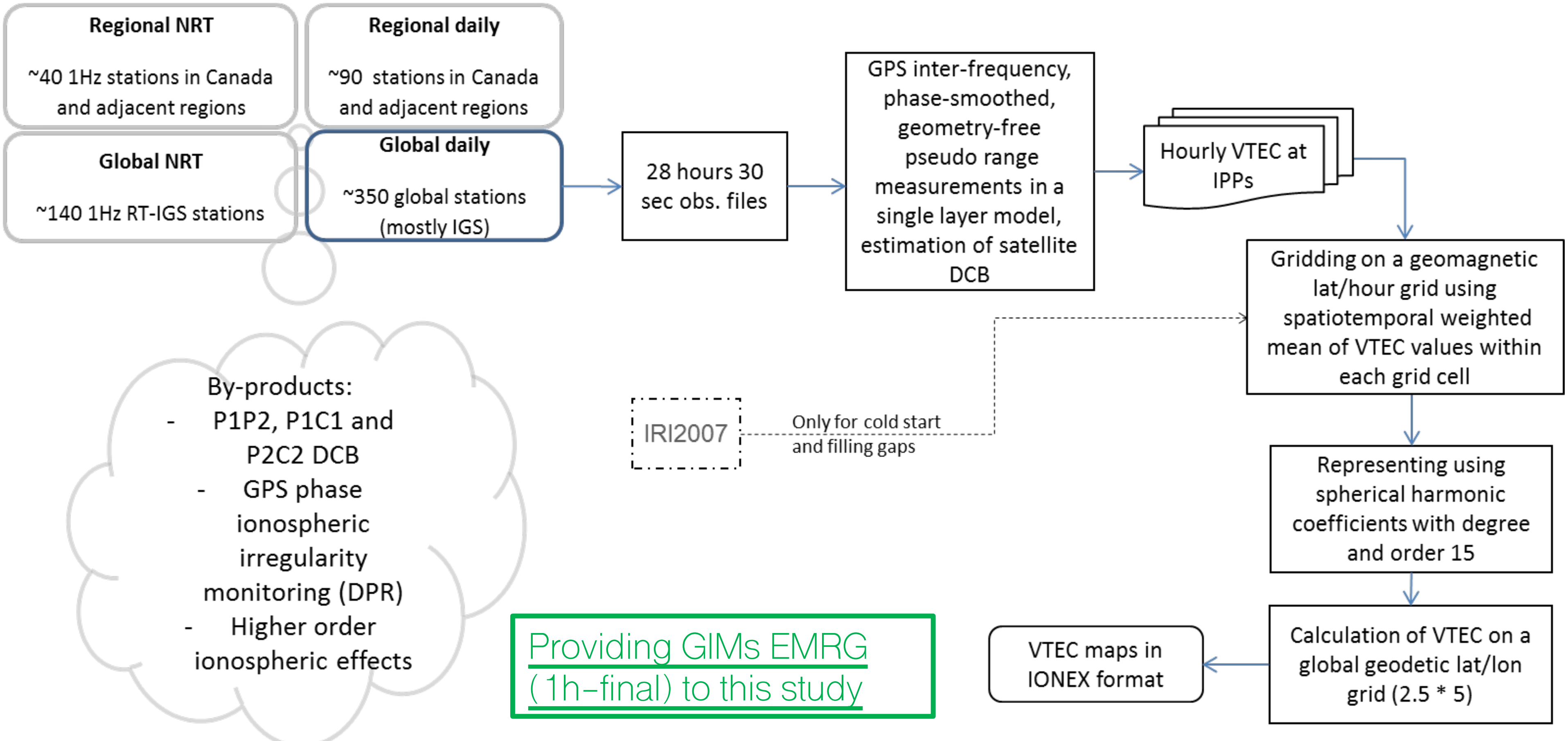
Highlight: estimate the TEC at each grid point only using the nearby data so as to improve its accuracy.

Providing GIMs CASG (2h-final) to this study

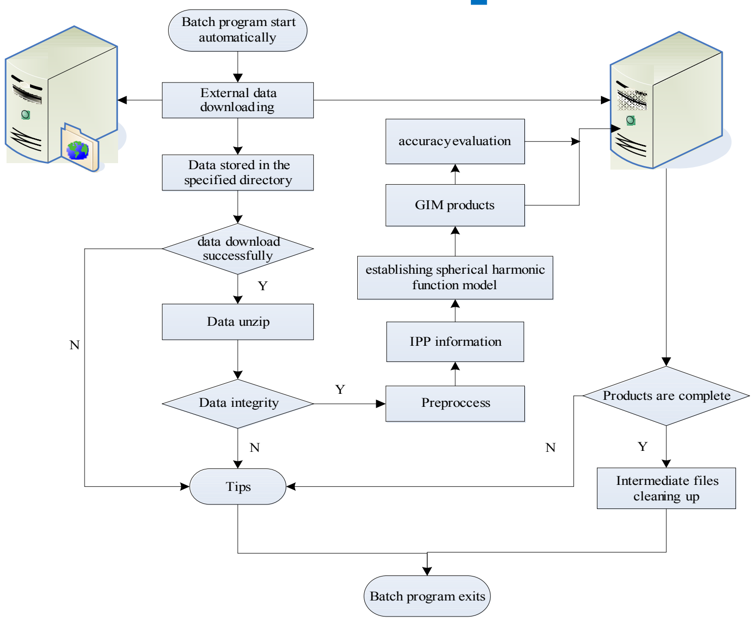
(see for instance Zishen Li, Yunbin Yuan, Ningbo Wang, Manuel Hernandez-Pajares, Xingliang Huo(2015). SHPTS: towards a new method for generating precise global ionospheric TEC map based on spherical harmonic and generalized trigonometric series functions. Journal of Geodesy.

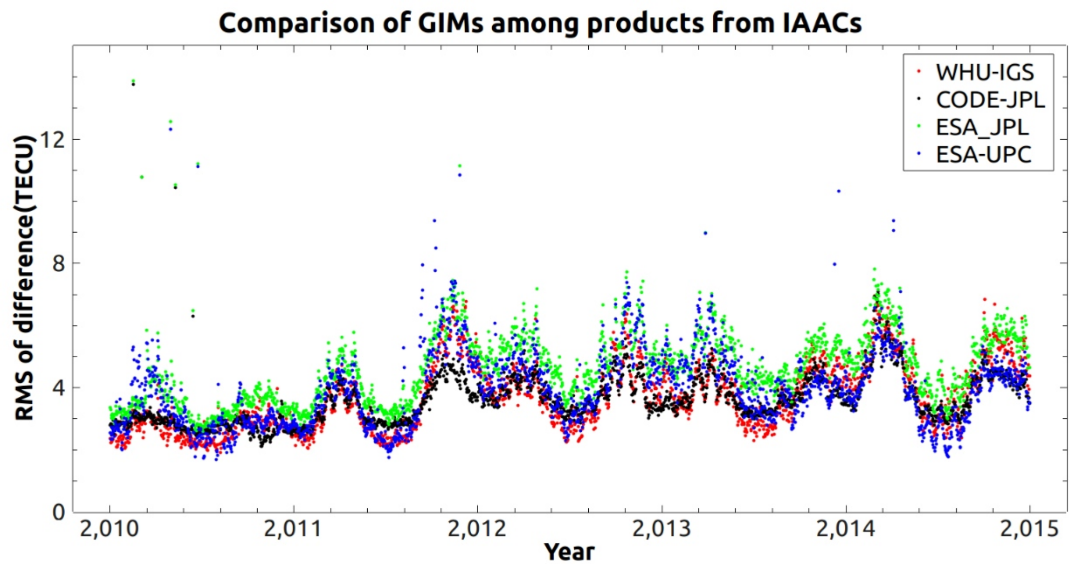
Natural Resources Canada

Canadian Geodetic Survey of Natural Resources Canada (NRCan) has developed a number of products from GPS sensing of the ionosphere. Figure below lists the products generated with a summary of processing steps for global daily product. The global daily product (emrg) submission to IGS data centers has resumed since April 2015 and is considered for comparisons in this presentation.

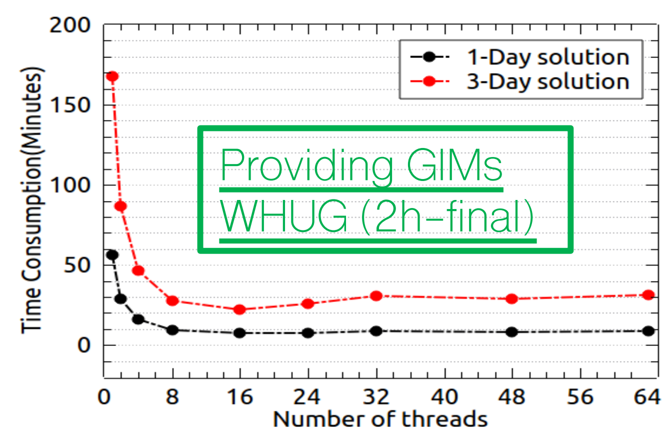


Global ionospheric VTEC maps from WHU





Multithreaded parallel estimation



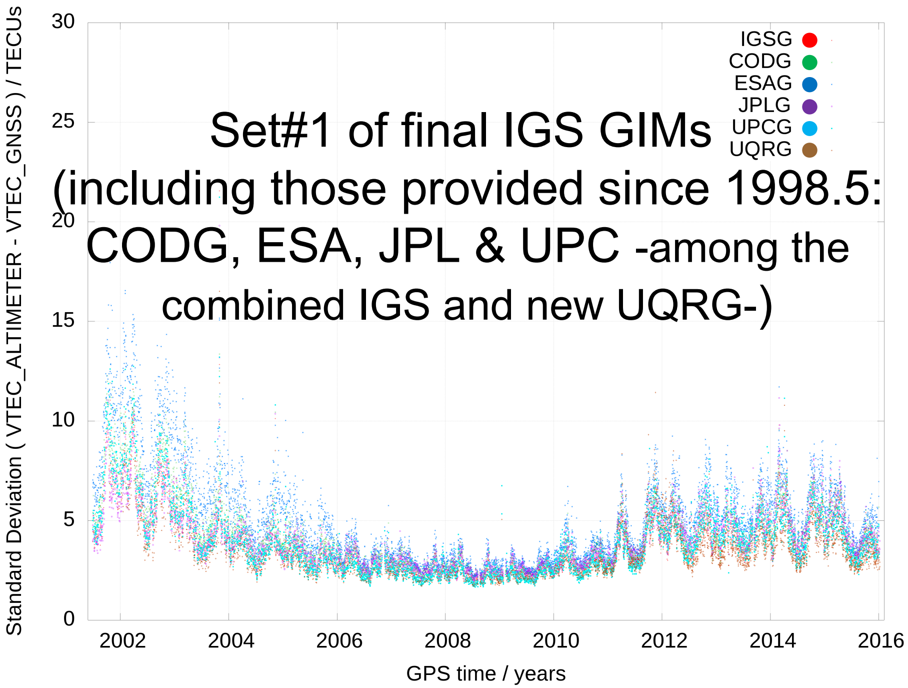
$$\begin{cases} \sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\frac{\tilde{P}_{nm}(sin\beta)(\tilde{C}_{nm}cos(ms)+\tilde{S}_{nm}sin(ms))}{M} - DCB^{SV} - DCB_{rcvr} = \rho_2' - \rho_1' \\ \sum_{n=0}^{n_{max}}\sum_{m=0}^{n}\tilde{P}_{nm}(sin\beta)(\tilde{C}_{nm}cos(ms)+\tilde{S}_{nm}sin(ms)) \geqslant c \end{cases}$$

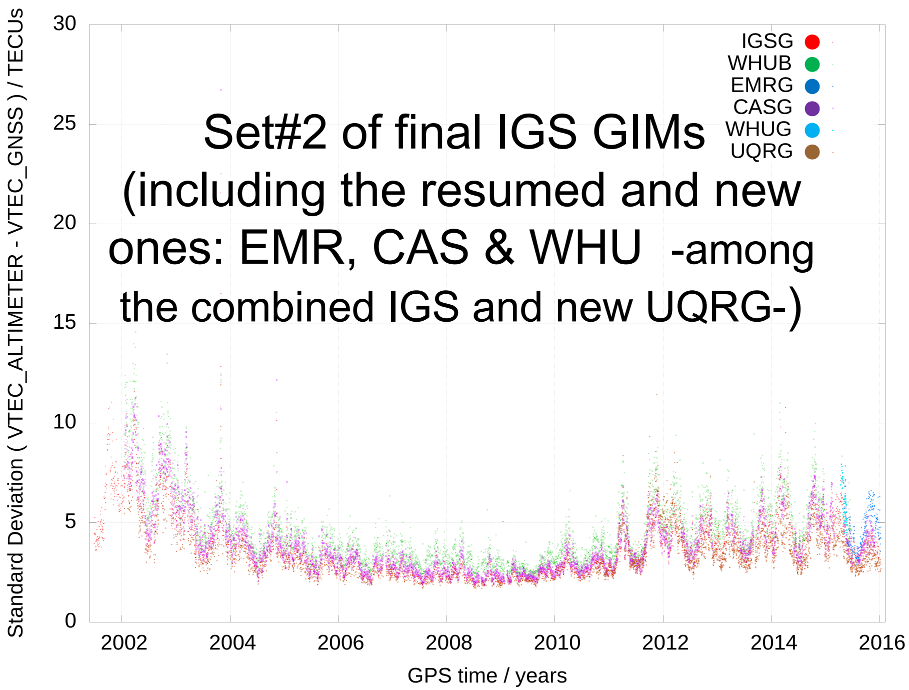
c is a non-negative constant and varies with latitudes and seasons. Implement inequality-constrained least square (ICLS) method to eliminate non-physical negative values.

Zhang, H., P. Xu, W. Han, M. Ge and C. Shi, Eliminating negative VTEC in global ionosphere maps using inequality-constrained least squares, *Advances in Space Research* Vol. 51, No. 6, 2013, pp. 988-1000.

website: http://ionosphere.cn

VTEC GIMS Std. Dev. regarding JASON* VTEC (daily values, since days 2001.6 to 2016.0)





- ✓The discrepancies of all available IGS VTEC GIMS vs +190 millions of altimeter direct VTEC measurements over the seas during the last 15 years, have been analyzed.
- ✓An overall general agreement is found between the 7 analysis centers, with VTEC discrepancies (daily Standard Deviations) typically ranging from 3 to 10 TECUs, depending on the Solar Cycle phase.

IRI
International Reference Ionosphere

Cooperative IGS and GIRO
Monitoring for Rapid Real-Time Insight into Glol
Ionospheric Weather

- Real-Time Assimilative Modeling with GIRO and IRI
  - GIRO /Global Ionosphere Radio Observatory/
  - IRI /International Reference Ionosphere/
  - NECTAR assimilation algorithm
  - GAMBIT analysis environment for IRTAM

GIRO + IRI + NECTAR =

IRTAM

(IRI-based Real-Time Assimilative Modeling)

- 3D Real-Time Ionosphere with IRTAM
- Cooperation: IGS VTEC and GIRO NmF2 & hmF2
  - Slab thickness
  - Adding **B0**
    - 3D accuracy
    - Topside half-thickness
  - Outlook

IGS INTERNATIONAL GNSS SERVICE

IRI
International Reference Ionosphere

GIRO

IRTAM

Fast Chars

LATEST 24-HR MOVIES

DIDBASE GIRO WEB PORTAL

DRIFTBASE GIRO WEB PORTAL

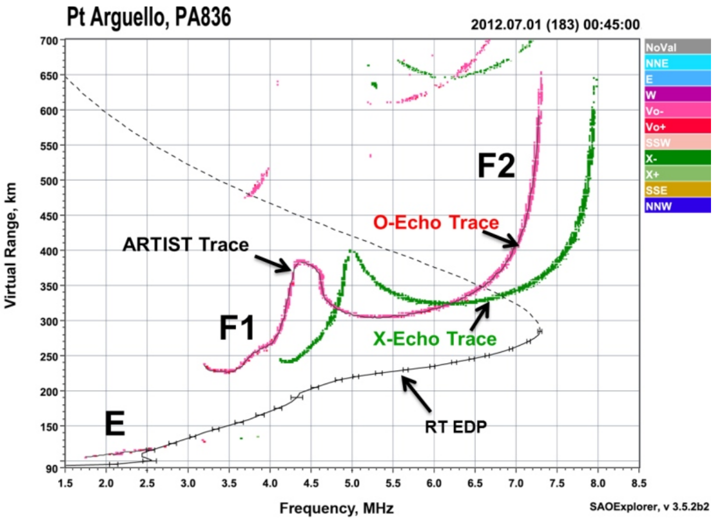
LATEST WORLD IONOGRAM

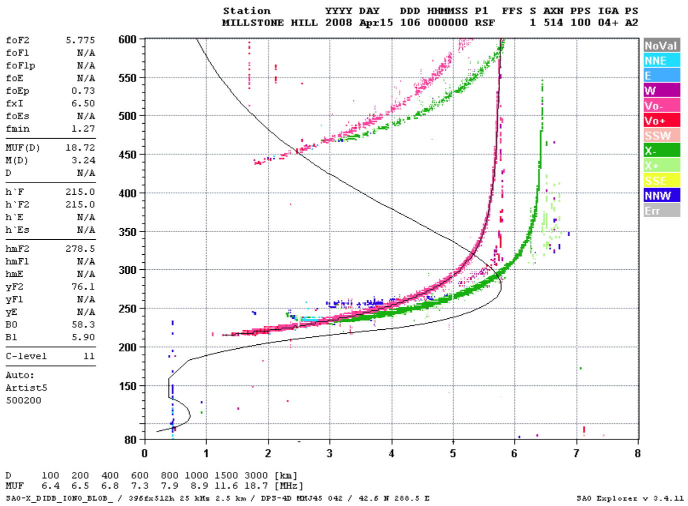
HF Ionosonde

- First multi-frequency ionogram: 1931
- 1936: five ionosondes in the world
- 1957 (IGY): 150 ionosondes in the world
- 2016: <unknown #> ionosondes…
  - 231 ionosonde locations in NOAA SPIDR
  - 160 Lowell Digisondes®

Wannalancit Building
Lowell, Dec 2015
Home to Digisonde®

Digisonde DPS4D





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IRI
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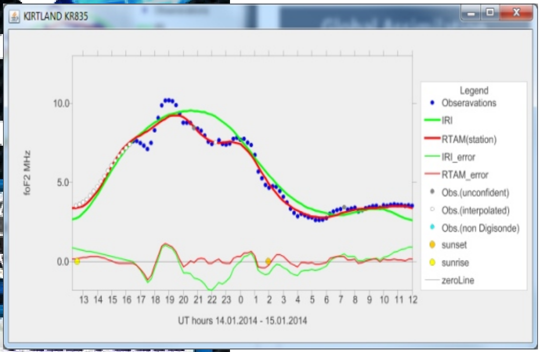
Real-Time IRI Configurations

REAL TIME IRI Assimilative Mapping
IRTAM

NECTAR

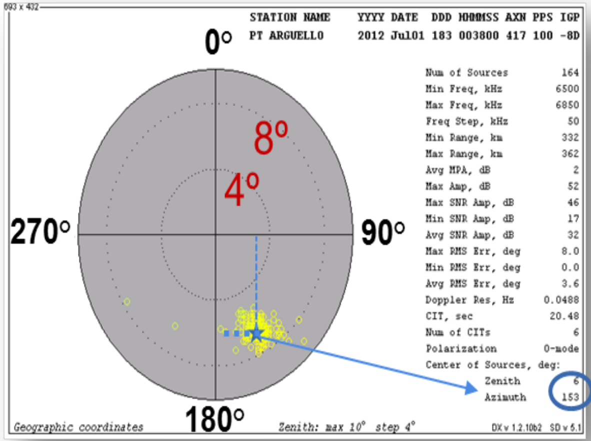
A. Single-Site Assimilation	B. Single-Site Assimilation with local tilt measurement	C. Global Assimilation



13 real-time adjustments to IRI coefficients *in the vicinity of ionosonde*

(corrections valid for ~200 km)

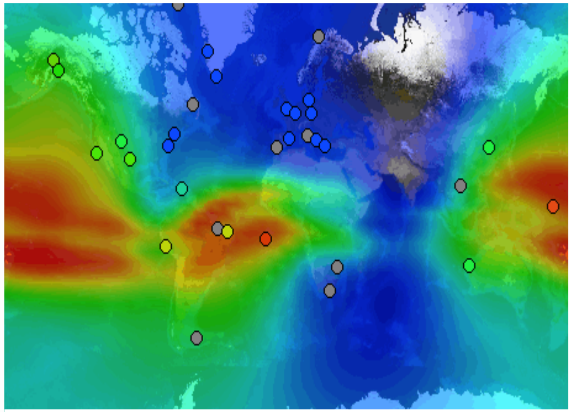
No TIDs



Local tilt evaluation by Digisonde HF skymapping

for IRI transformation

Sensitive to TID passages



988 real-time adjustments to IRI using all available Digisondes

IRTAM

These charts make use of IARPA data from the HFGeo program. The IARPA Program Manager is Chris Reed.”

IRI
International Reference Ionosphere

Next Step: Above Peak Sensing

SLAB THICKNESS τ

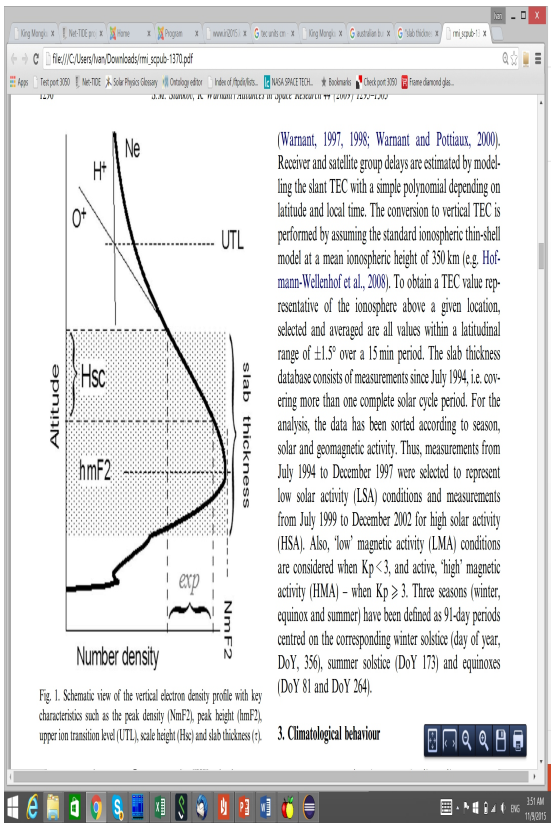


Fig. 1. Schematic view of the vertical electron density profile with key characteristics such as the peak density (NmF2), peak height (hmF2), upper ion transition level (UTL), scale height (Hsc) and slab thickness (τ).

(Warnant, 1997, 1998; Warnant and Pottiaux, 2000). Receiver and satellite group delays are estimated by modelling the slant TEC with a simple polynomial depending on latitude and local time. The conversion to vertical TEC is performed by assuming the standard ionospheric thin-shell model at a mean ionospheric height of 350 km (e.g. Hofmann-Wellenhof et al., 2008). To obtain a TEC value representative of the ionosphere above a given location, selected and averaged are all values within a latitudinal range of ±1.5° over a 15 min period. The slab thickness database consists of measurements since July 1994, i.e. covering more than one complete solar cycle period. For the analysis, the data has been sorted according to season, solar and geomagnetic activity. Thus, measurements from July 1994 to December 1997 were selected to represent low solar activity (LSA) conditions and measurements from July 1999 to December 2002 for high solar activity (HSA). Also, 'low' magnetic activity (LMA) conditions are considered when $Kp < 3$, and active, 'high' magnetic activity (HMA) – when $Kp \geqslant 3$. Three seasons (winter, equinox and summer) have been defined as 91-day periods centred on the corresponding winter solstice (day of year, DoY, 356), summer solstice (DoY 173) and equinoxes (DoY 81 and DoY 264).

3. Climatological behaviour

Stankov and Warrant, 2009

Same TEC
Different
*N*mF2

Thicker slab
Thinner slab

Complementing GIRO with GNSS

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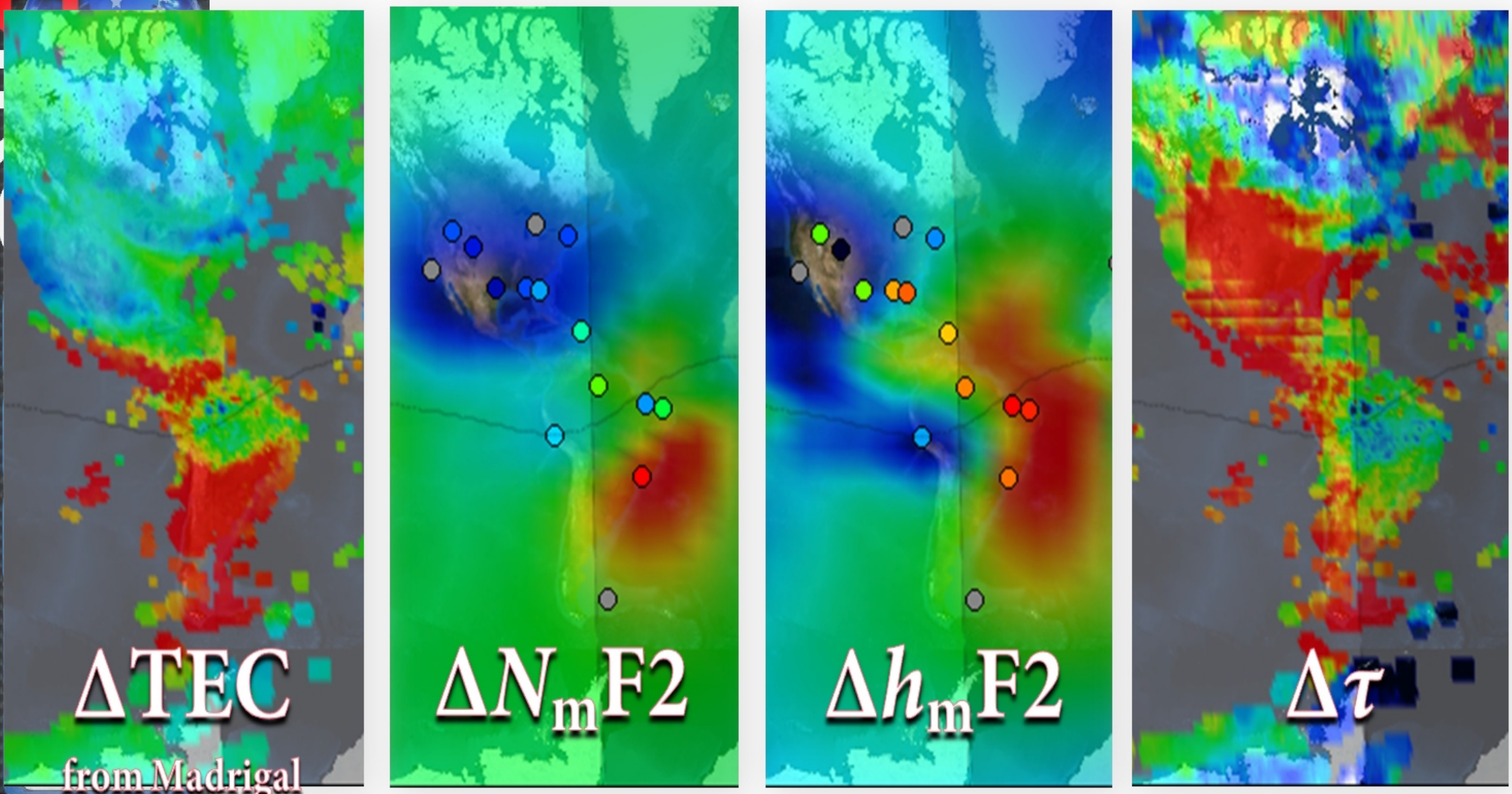
LATEST WORLD IONOGRAM

Total Electron Content | Peak Electron Density | Peak Density Height | Slab Thickness



Deviation from expected quiet-time behavior

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IRI
International Reference Ionosphere

GIRO

IRTAM

Fast Chars

LATEST 24-HR MOVIES

DIDBASE GIRO WEB PORTAL

DRIFTBASE GIRO WEB PORTAL

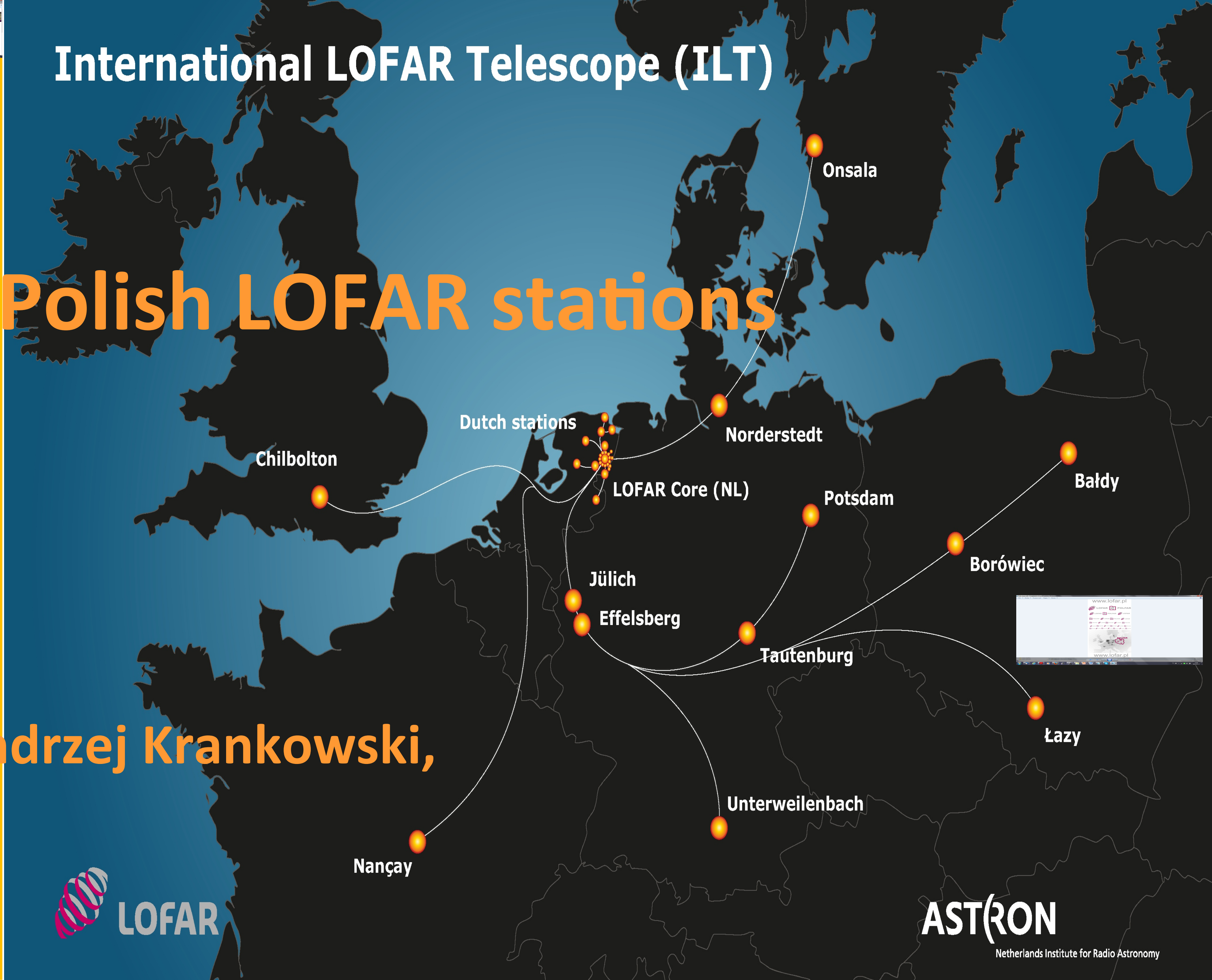
LATEST WORLD IONOGRAM

Outlook

- Cooperative real-time newscast using GNSS VTEC and GIRO F2 layer profile
  - Implementation is imminent
  - Current objective at GIRO: assimilate shape parameter B0
  - Current objective at IGS: Service integration with IRTAM
  - Services at Lowell GIRO Data Center and UWM IGS RTS node
- Applications to space weather research and practice
  - Intriguing capability of sensing topside ionosphere using ground observatories
- GAMBIT environment in open source domain for data access and visualization

Polish LOFAR stations

Andrzej Krankowski,



Bałdy PL612 Station

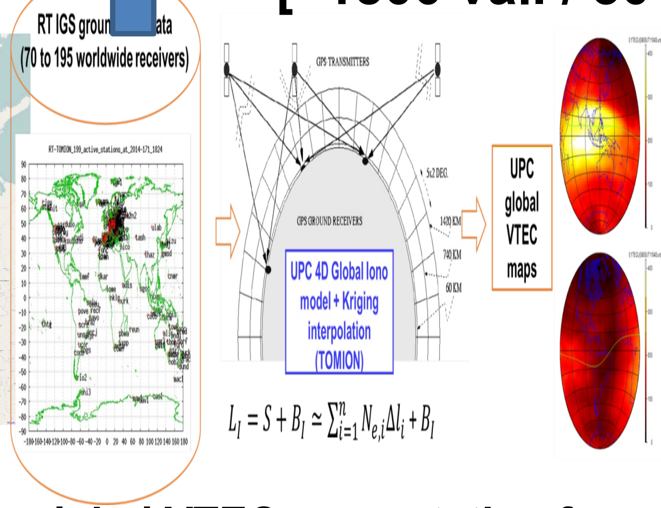
European TEC maps based on SRRC\UWM and UPC-IonSAT

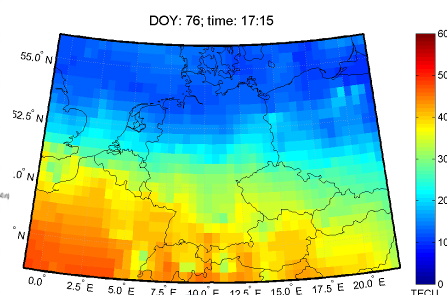
Providing RIMs for ILT in real time (15min-time resolution) to this study

From each obs. we get one STEC value: V=S/M=(Li-Bi)/M. [~1500 val. / 30 s]

Interpolation by Splines

126 EPN Stations





Natural neighbour Interpolation

New European VTEC maps

Layout summarizing the global VTEC computation from ground G data by means of the UPC TOMION software, including the mai tomographic model equation[*]

[*](data: ionospheric combination of carrier phases LI, and length intersection wi each voxel, Δli; unknowns: its ambiguity BI, the STEC, S, which includes the mean electron density within each given voxel, Ne,i).

(see for instance Hernandez-Pajares, M., Juan, M. and Sanz, J., 1999. *New approaches in global ionospheric determination using ground GPS data*. Journal of Atmospheric and Solar-Terrestrial Physics 61, pp. 1237–1247.).

European TEC maps based on SRRC\UWM and UPC-IonSAT: IONEX

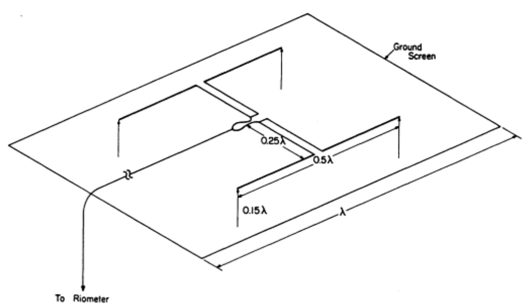
```
     1.0            IONOSPHERE MAPS     MIX                 IONEX VERSION / TYPE
cmpcmb v1.2    SRRC/UWM and IONO/UPC       31-may-16 12:13 PGM / RUN BY / DATE
European ionex file for ILT                                 COMMENT
Regional (european) ionosphere maps for day 076, 2015       DESCRIPTION
Created using natural neighbour interpolation               DESCRIPTION
Contact address: Andrzej Krankowski                         DESCRIPTION
                 Space Radio-Research Diagnostics Centre    DESCRIPTION
                 University of Warmia and Mazury (SRRC/UWM) DESCRIPTION
                 Prawochenskiego st. 9                      DESCRIPTION
                 10-957-Olsztyn, POLAND                     DESCRIPTION
                 e-mail:  kand@uwm.edu.pl                   DESCRIPTION
                                                            DESCRIPTION
  2015     3    17     0    15     0                        EPOCH OF FIRST MAP
  2015     3    17    23    45     0                        EPOCH OF LAST MAP
   900                                                      INTERVAL
    95                                                      # OF MAPS IN FILE
  COSZ                                                      MAPPING FUNCTION
     0.0                                                    ELEVATION CUTOFF
combined TEC calculated as weighted mean of input TEC valuesOBSERVABLES USED
   126                                                      # OF STATIONS
    32                                                      # OF SATELLITES
  6371.0                                                    BASE RADIUS
     2                                                      MAP DIMENSION
   450.0 450.0   0.0                                        HGT1 / HGT2 / DHGT
     58    46  -0.5                                         LAT1 / LAT2 / DLAT
     -1    22   0.5                                         LON1 / LON2 / DLON
    -1                                                      EXPONENT
TEC values in 0.1 tec units;  9999, if no value available   COMMENT
                                                            END OF HEADER
     1                                                      START OF TEC MAP
  2015     3    17     0    15     0                        EPOCH OF CURRENT MAP
    58.0  -1.0  22.0   0.5 450.0                            LAT/LON1/LON2/DLON/H
   72   72   72   72   72   74   72   73   72   71   71   73   74   75   77   80
   79   75   73   73   72   79   78   79   81   83   85   86   87   84   82   81
   81   81   84   90   94   95   93   92   92   92   93   95  100  105  102
    57.5  -1.0  22.0   0.5 450.0                            LAT/LON1/LON2/DLON/H
   76   76   76   77   80   82   81   79   74   72   73   74   74   74   76   84
   83   81   76   74   73   82   82   85   87   90   92   96   95   88   89   95
   96  100  102  103  101   99   95   93   92   92   94   96  100  100   98
    57.0  -1.0  22.0   0.5 450.0                            LAT/LON1/LON2/DLON/H
   77   78   79   80   83   86   87   84   81   74   75   76   77   79   83   85
   85   85   82   77   76   82   90   93   97  102  107  106  101   96   98   99
```

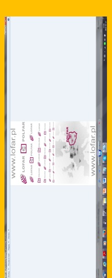
Additional Diagnostics

1. **Scintillation receiver**

2. **Radio receiver for ionosonde and DAB** *Digital Audio Broadcasting*

3. **Riometr**





Conclusions

1. Long series of IGS VTEC maps offers a very good source of information about the ionosphere with high spatial and temporal resolution

2. Future improvements are determined by users' requirements (the number of users has significantly increased during the last 17 years)

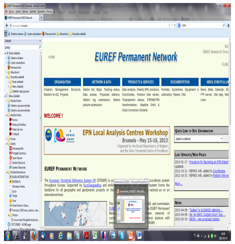
3. 17 years of continuous time series of TEC measurements may be applied to update ionospheric models, e.g., IRI model

4. COSMIC occultation data gives a new opportunity to study/model the ionosphere and to validate IGS TEC maps

Conclusions

5. A long time series of accurate global VTEC values are freely available since 1998 for scientific or technical use, with latencies of about 12 days (final product) or 1 day (rapid product). Thanks to the cooperative effort developed within the IGS framework and the international scientific community this open service will hopefully continue its evolution during the next years, sensitive to both new user needs and scientific achievements.

Acknowledgments



The author is particularly grateful for the GNSS data provided by IGS/EPN and UNAVCO

Thank you for your attention