Climate VTEC maps in cooperation of IGS' GNSS and GIRO sensor networks as a step towards VTEC assimilation into IRI

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Introduction

Mapping is a computational process that synthesizes, using fragmentary data available from a sparse network of sensors, the underlying 2D continuous map of the observed physical quantity.

Real-time mapping system must perform sensor data collection and associated mapping computations with sufficiently low latency from the real-time.

Requirements for real-time global mapping:

- Adequate computing performance
- Fast and reliable communication networks
- Strict timing rules for system components latencies
- Mitigation protocols for any potential issues

Objectives

1. **Introduction of 30-day average empirical (climate) TEC maps into GAMBIT Explorer software** in order to build deviation maps for ionosonde-derived global maps of the bottomside ionospheric plasma – **fulfilled** (presented at EGU General Assembly in Vienna in April 2018) – full data availability since 2010 until now
2. Public release of updated GAMBIT Explorer UserApp v0.9.04 compatible with climate VTEC maps - **fulfilled**
3. Ionospheric weather nowcast based on near real-time data products from IGS and GIRO sensor networks – **fulfilled** (presented at AT-RASC at Gran Canaria in June 2018)
4. System developement for enhanced latency, stability, and reliability – **advanced works in progress**
5. Full assimilation of empirical VTEC data into IRI – **future works**

IRI and IGS IONO Cooperation

Comparison of the IGS' "weather" VTEC maps to their quiet-time "climate" counterpart allows rapid evaluation of the anomalous near-space plasma dynamics as it responses to a wide variety of effects in the Sun-Earth system, ranging from the forces acting in the outer space to the processes on the surface and even underneath the Earth's crust.

Development of such global reference quiet-time VTEC maps proved to be a difficult task, given the staggering complexity and dynamics of the constituent subsystems and the intersystem coupling mechanisms.

We approached the task building a reference daily empirical 30-day running average VTEC, which smooths out effects from any ongoing events (that would otherwise distort the presentation of ionospheric/plasmaspheric climate) while still preserving the specifics of the annual cycle.

IGS IONO Working Group

Since 1998, the **IGS Iono Working Group** has been continuously releasing global VTEC maps in rapid, final, and predicted schedules.

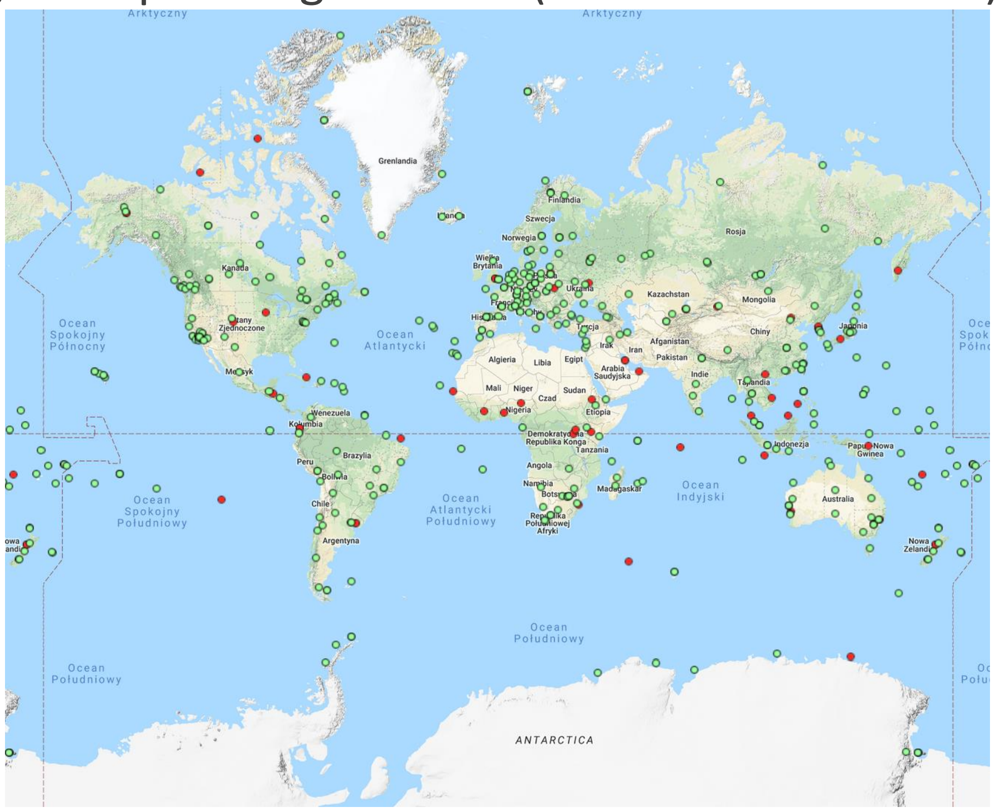
The IGS Ionosphere Combination and Validation Center at University of Warmia and Mazury is responsible for an ensemble analysis of the global VTEC maps synthesized independently by several ISG Associate Analysis Centers by applying the observation uncertainty weights determined by validating the VTEC data against the original slant TEC measurements.

Products:

- Final GIM: resolution - 2 hours x 5 deg. x 2.5 deg (UTxLon.xLat.); latency of 11 days
- Rapid GIM: resolution - 2 hours x 5 deg. x 2.5 deg; latency of less than 24 hours
- Predicted GIM for 1 and 2 days ahead (pilot product) - resolution - 2 hours x 5 deg. x 2.5 deg; availability 24 and 48 hours in advance

IGS IONO Working Group

All operating and upcoming IGS sites (for 24 October 2018):



For further information please refer to: http://www.igs.org/

IRI

The **International Reference Ionosphere (IRI)** is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI).

For given location, time and date, **IRI provides monthly averages of the electron density, electron temperature, ion temperature, and ion composition** in the altitude range from 50 km to 2000 km. Additional parameters given by IRI include the Total Electron Content, the occurrence probability for Spread-F and the F1-region, and the equatorial vertical ion drift.

The major data sources are the worldwide network of ionosondes, the powerful incoherent scatter radars (Jicamarca, Arecibo, Millstone Hill, Malvern, St. Santin), the ISIS and Alouette topside sounders, and in situ instruments on several satellites and rockets. For further information please refer to: https://iri.gsfc.nasa.gov/

GIRO

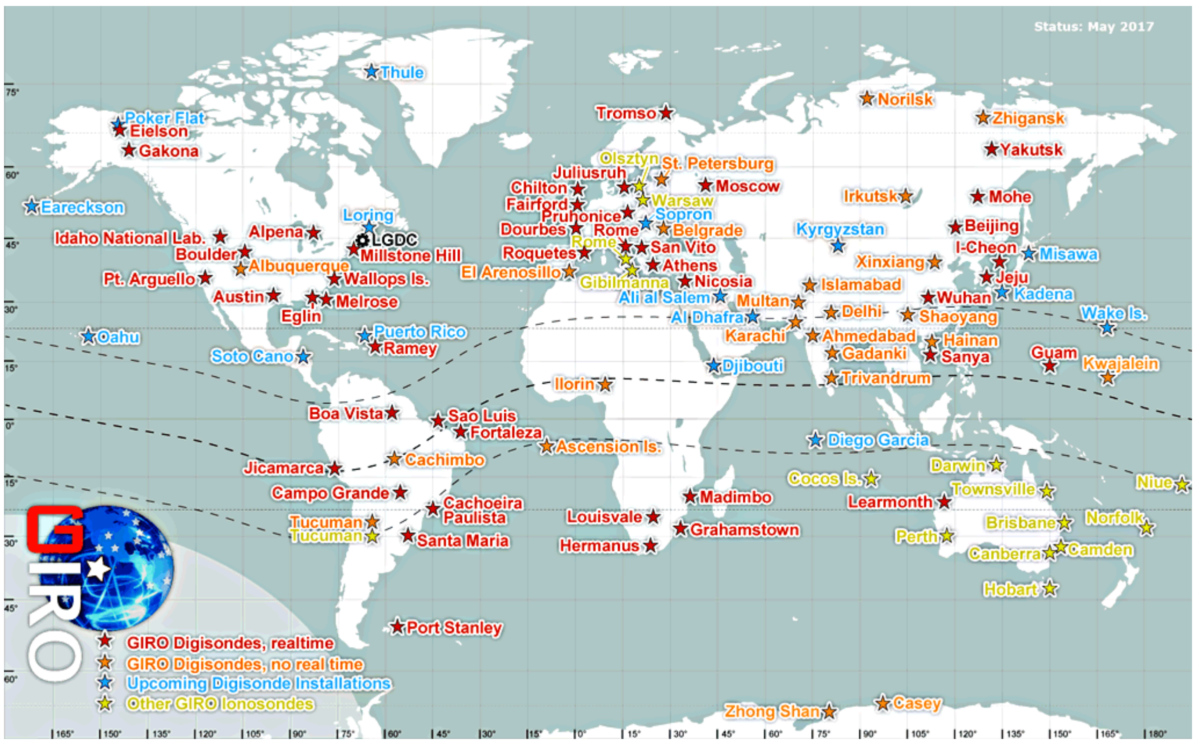
GIRO – Global Ionosphere Radio Observatory

The Lowell GIRO Data Center (LGDC) implements a suite of technologies for post-processing, modeling, analysis, and dissemination of the acquired and derived data products:

- **IRTAM** – IRI-based Real-time Assimilative Model – that builds and publishes every 15-minutes an updated "global weather" map of the peak density and height in the ionosphere, as well as a map of deviations from the classic IRI climate
- **GAMBIT** – Global Assimilative Model of Bottomside Ionosphere Timelines Database and Explorer holding 15 years worth of IRTAM computed maps at 15 minute cadence
- 17+ million ionograms and matching ionogram-derived records of URSI-standard ionospheric characteristics and vertical profiles of electron density
- Data and software for Traveling Ionospheric Disturbance (TID) diagnostics

GIRO

All operating and upcoming GIRO sites (updated May 2017):



For further information please refer to: http://giro.uml.edu/

GAMBIT Explorer

Global Assimilative Model of Bottomside Ionosphere Timeline

Online repository of real-time and retrospective global 3D ionospheric weather specification generated using the Global Ionosphere Radio Observatory (GIRO) sensor measurements

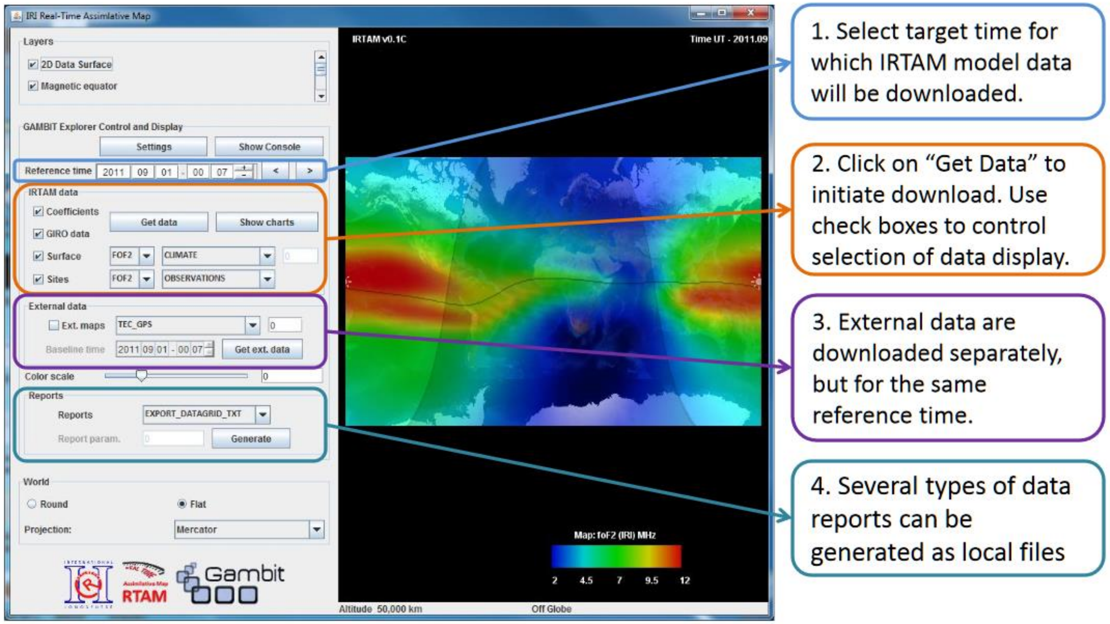
Open Academic-Use Access to retrospective ionospheric weather data in display and numerical formats

Data acquisition, quality control, processing, modeling, analysis, visualization, and data and facility management resources are **designed, developed, and operated by the University of Massachusetts Lowell personnel** for the GAMBIT project

GAMBIT Explorer

GAMBIT is a single frame application with all controls available on the main panel

For further details concerning GAMBIT Explorer features please refer to: http://giro.uml.edu/GAMBIT/GAMBIT-X_UserGuide-v01C.pdf



Data acquisition and methodology

Two separate sensor networks:

- IGS 501 permanent GNSS receivers that provides VTEC measurements for the global ionospheric maps
- GIRO 60 online high-frequency (HF) ionosonde sounders that provide data for 3D mapping of the bottomside ionospheric plasma density by the IRI-based IRTAM

Combination of the VTEC from IGS and NmF2 from GIRO allows computation of an equivalent slab thickness τ.

VTEC

STEC acquisition at each IGS permanent GNSS station is based on geometry free (P4 and Φ4) GPS combination. Corresponding VTEC value is then projected on single thin layer basing on the point angle of GPS signal piercing that ionosphere layer. The projection is performed with formula:

$$VTEC = STEC * \sqrt{1 - \left(\frac{R_e}{R_e + h_{ion}} \cos \varepsilon\right)}$$

where $VTEC$ and $STEC$ are vertical and slant total electron content values respectively, R_e is the radius of the Earth, h_{ion} is the height of single thin ionospheric layer (assuming 450km) and ε is the elevation angle between the receiver and a satellite.

30 day mean VTEC

Joint project of IGS Ionospheric Working Group and International Reference Ionosphere

30 days running average VTEC global maps for GAMBIT software

Reliable source of ionospheric climate data

4 deg lat x 8 deg lon x 15 minutes resolution compatible with NASA WorldWind

A step towards TEC data assimilation into IRI and real-time TEC computations

Publicly available free of charge in standard IONEX format at:

https://igsiono.uwm.edu.pl/data/gambit/*yyyy*/gmbt*ddd*0.*yy*i

where *yyyy/yy* is the year and *ddd* is day of year

…and through GAMBIT software:

http://giro.uml.edu/GAMBIT/

Availability from 304/2010 until now

30 day mean climate VTEC

```
  2011     9     1     0     0     0                         EPOCH OF FIRST MAP
  2011     9     1    24     0     0                         EPOCH OF LAST MAP
   900                                                       INTERVAL
    97                                                       # OF MAPS IN FILE
  COSZ                                                       MAPPING FUNCTION
     0.0                                                     ELEVATION CUTOFF
combined TEC calculated as weighted mean of input TEC valuesOBSERVABLES USED
   250                                                       # OF STATIONS
    32                                                       # OF SATELLITES
  6371.0                                                     BASE RADIUS
     2                                                       MAP DIMENSION
   450.0 450.0   0.0                                         HGT1 / HGT2 / DHGT
      86   -86    -4                                         LAT1 / LAT2 / DLAT
    -180   180     8                                         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
  2011     9     1     0     0     0                         EPOCH OF CURRENT MAP
    86.0-180.0 180.0   8.0 450.0                             LAT/LON1/LON2/DLON/H
   66   65   66   65   64   65   66   64   63   65   66   67   64   60   56   54
   53   52   51   49   47   47   46   45   46   45   45   45   47   48   50   51
   53   54   54   55   57   60   62   62   61   61   63   64   66   66
    82.0-180.0 180.0   8.0 450.0                             LAT/LON1/LON2/DLON/H
   84   83   83   83   81   80   78   78   76   72   69   68   67   62   56   53
   50   47   45   43   40   40   39   37   37   37   39   41   43   44   46   48
   50   51   51   53   56   60   65   68   68   70   74   79   81   84
    78.0-180.0 180.0   8.0 450.0                             LAT/LON1/LON2/DLON/H
   97   98   99   99  100   97   92   89   84   81   79   75   72   66   59   54
   51   46   44   41   38   37   36   35   34   34   37   39   41   43   44   46
   49   50   51   53   57   62   69   74   76   80   86   92   95   97
    74.0-180.0 180.0   8.0 450.0                             LAT/LON1/LON2/DLON/H
  102  103  104  107  110  109  103   98   90   86   84   80   77   70   64   57
   52   48   44   41   38   37   36   35   36   37   39   40   40   41   42   44
   46   48   50   53   57   64   70   74   78   82   90   97  100  102
    70.0-180.0 180.0   8.0 450.0                             LAT/LON1/LON2/DLON/H
  101  100  101  105  110  110  109  103   95   88   86   80   75   68   63   59
   54   50   47   45   45   45   45   44   41   42   40   40   37   35   35   39
   41   41   44   50   57   67   73   79   86   88   96  100  101  101
```

Slab thickness and NmF2

The ionospheric slab thickness is defined as the ratio of the total electron content (TEC) to the F-region peak electron density (NmF2). It represents the equivalent thickness of the ionosphere having a constant uniform density equal to that of the F2 peak. Slab thickness τ at certain point can be calculated using following formula:

$$\tau = \frac{VTEC}{NmF2}$$

Slab thickness and NmF2

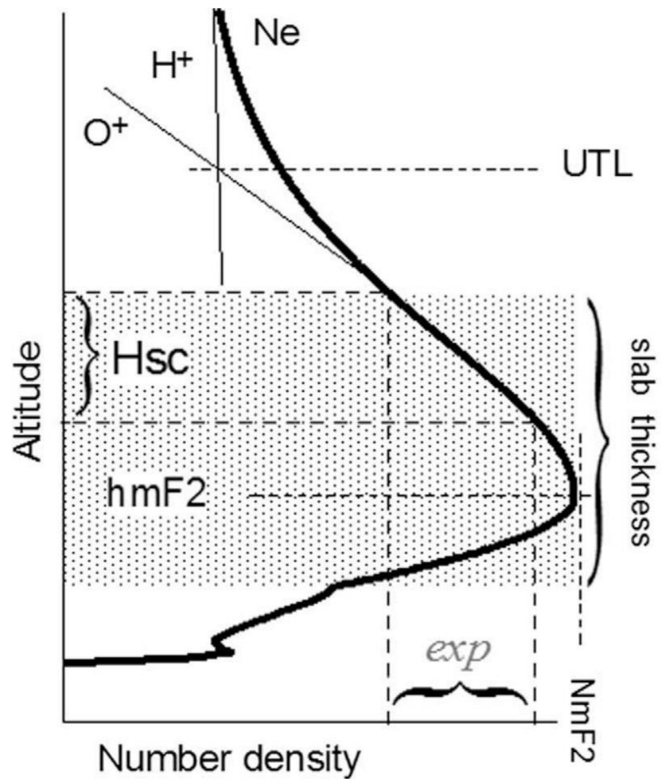
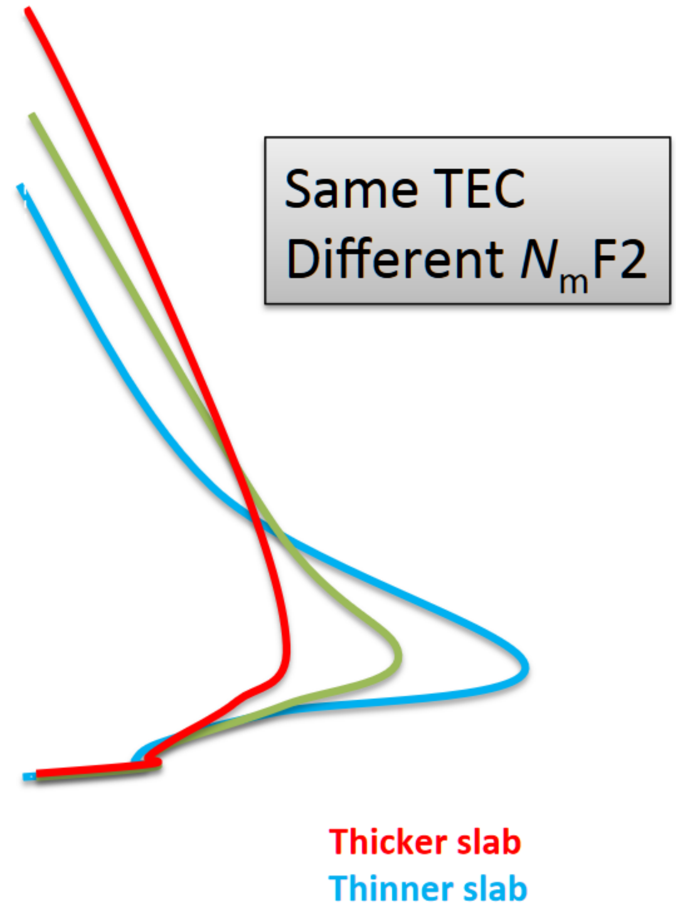
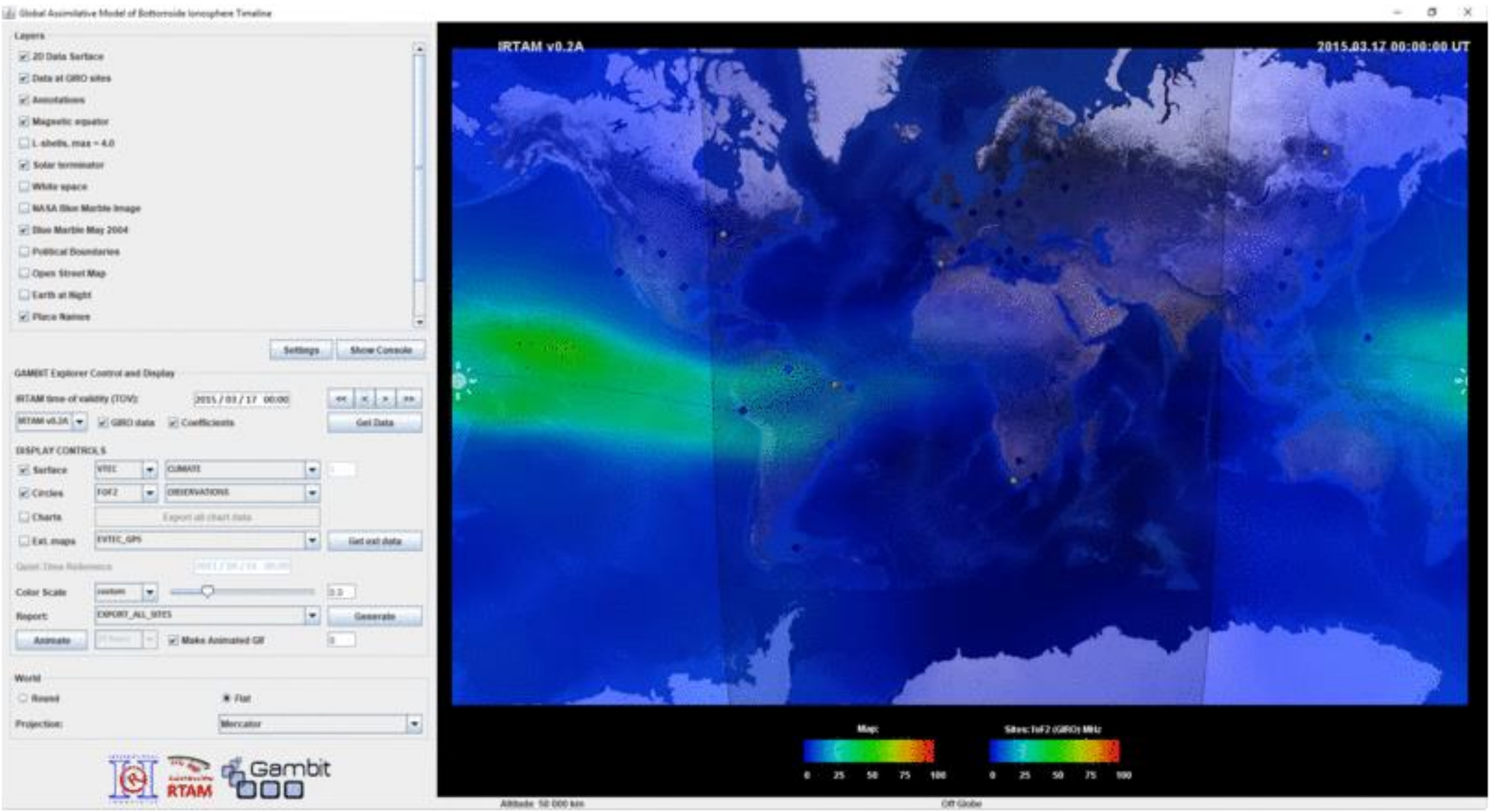


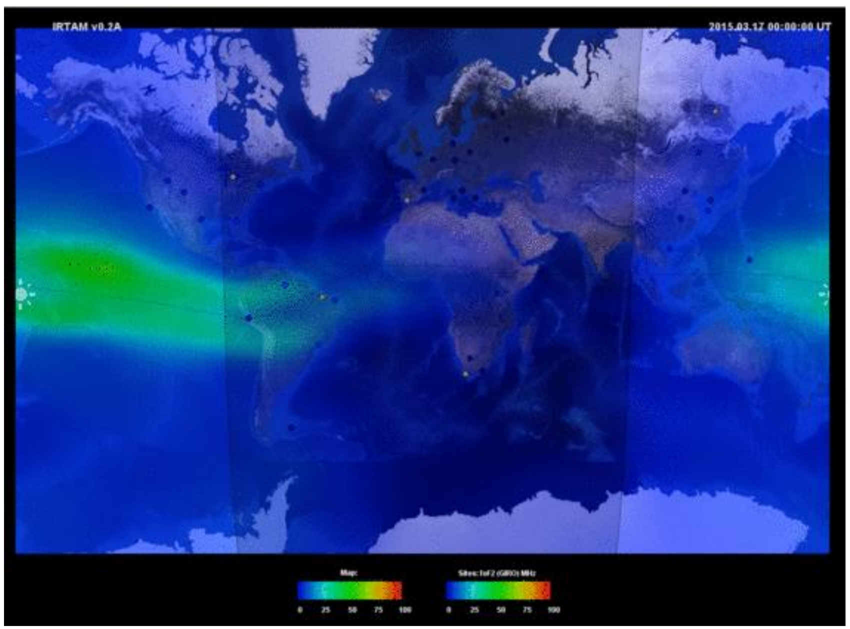
Fig. 1. Schematic view of the vertical electron density profile with key characteristics such as the peak density (NmF2), peak height (hmF2), upper ion transition level (UTL), scale height (Hsc) and slab thickness (τ).

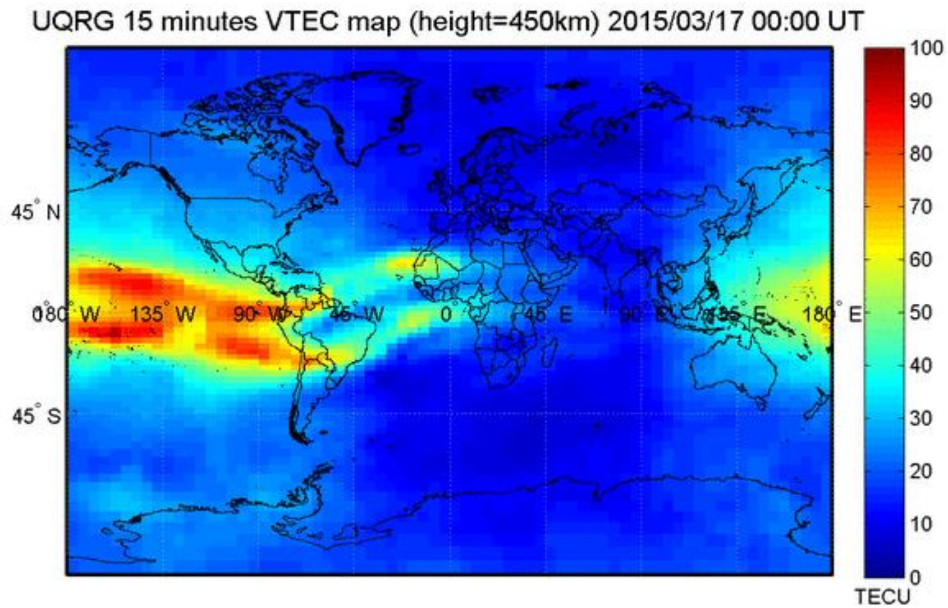


Early results

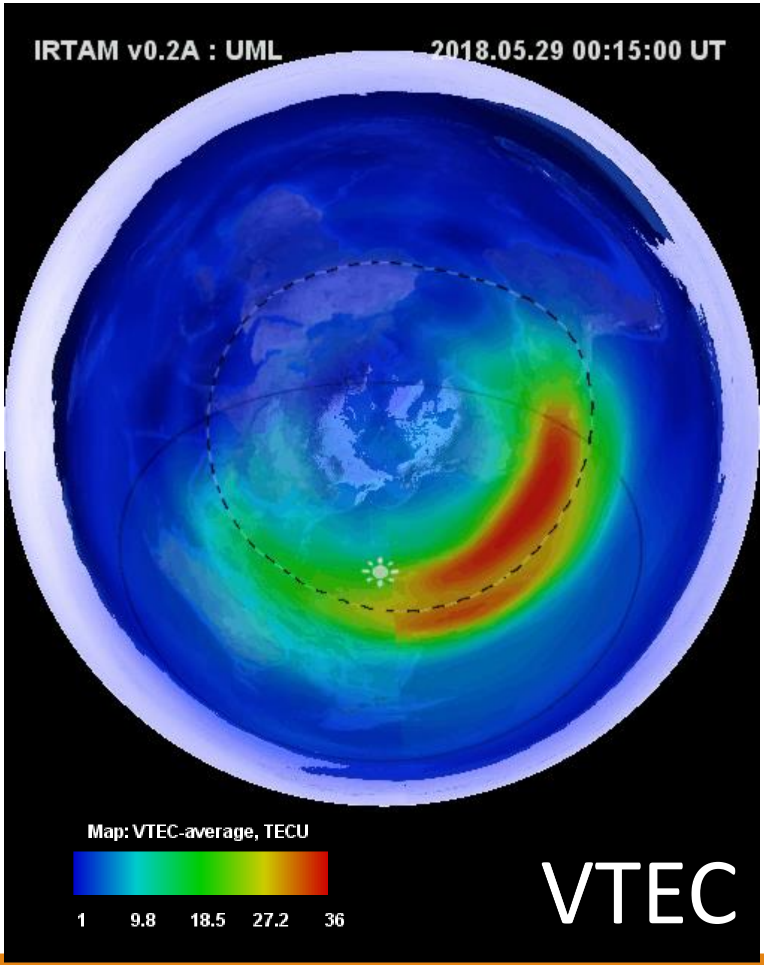


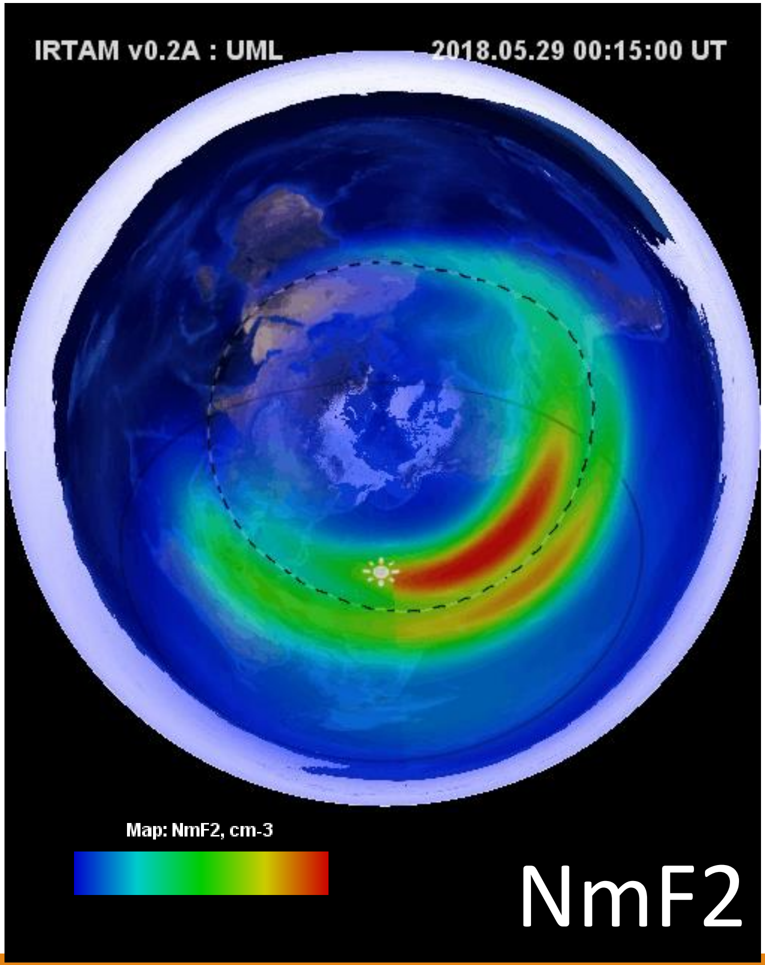
Early results



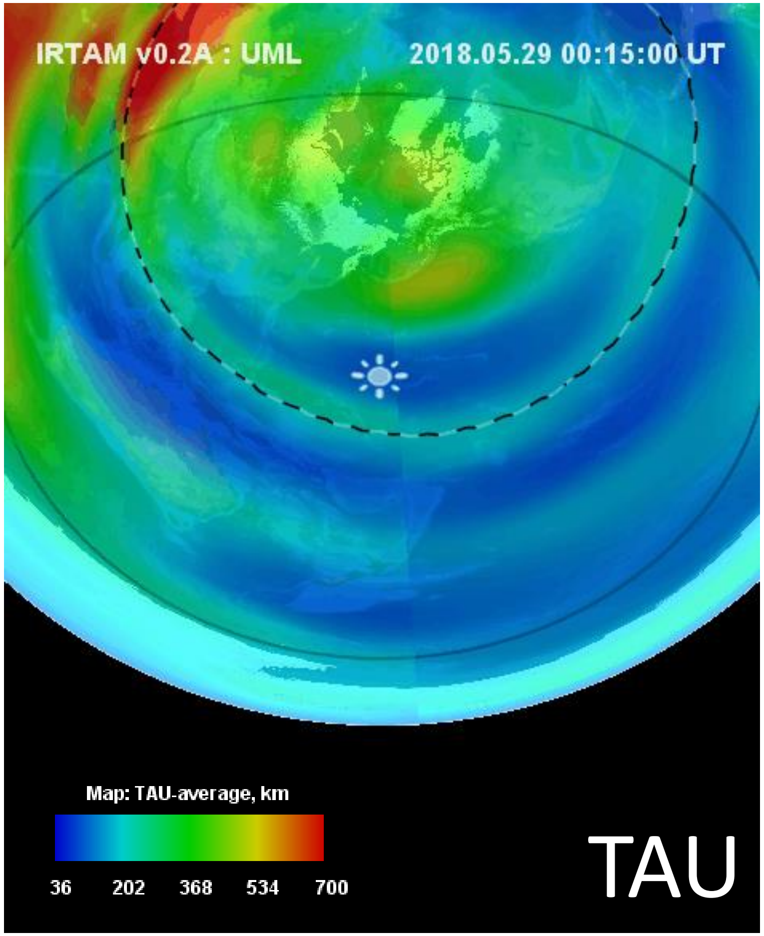


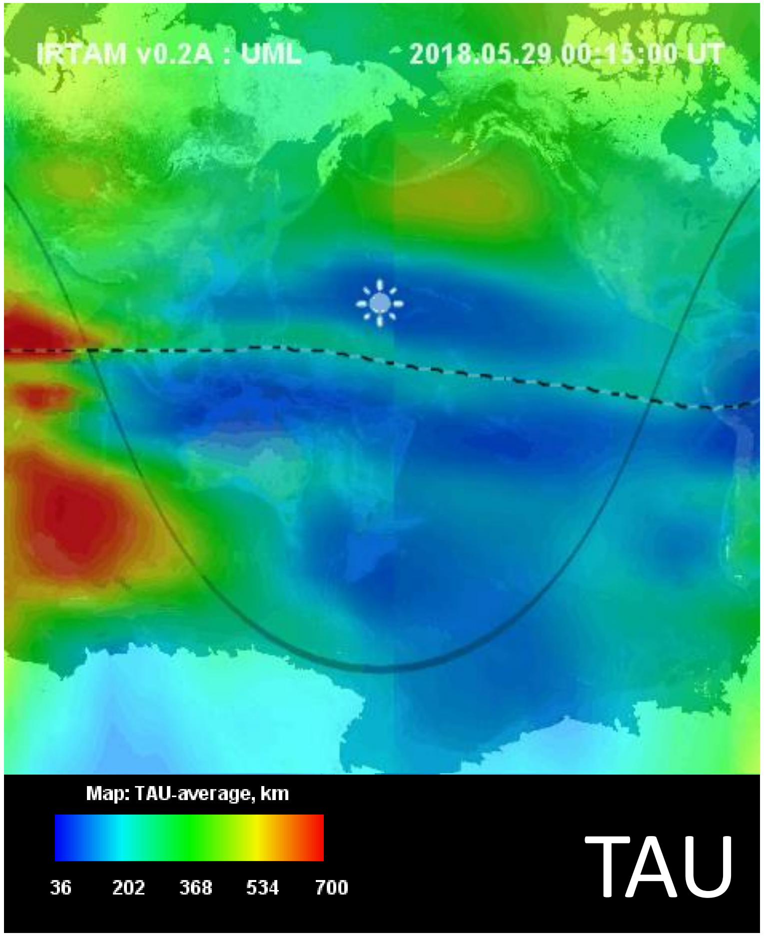
Early results





Early results





Future works

1. Final implementation of ionospheric weather nowcast based on near real-time data products from IGS and GIRO sensor networks in GAMBIT Explorer
2. System development for enhanced latency (towards near-real-time computation), stability, and reliability
3. Full assimilation of empirical VTEC data into IRI
4. Further developement goals yet to be decided due to any users needs and changes in state-of-the-art to occure in the future

Summary

Comparison of the "weather" VTEC maps to their quiet-time "climate" counterpart is a powerful instrument which allows rapid evaluation of the anomalous near-space plasma dynamics as it responses to a wide variety of effects in the Sun-Earth system, ranging from the forces acting in the outer space to the processes on the surface and even underneath the Earth's crust.

Future work will be mainly concentrated on improving each link of a chain between data acquisition and final product delivery in order to lower latencies as much as possible at as many chain links as possible. Constant improvement of available computational power and optimization of data acquisition, data control, validation and mapping algorithms is necessary to establish an autonomous computation routine that meets the strict criteria of real-time mapping system.

Thank you for your attention

IN CASE OF ANY CONCERNS, THAT I WILL NOT BE ABLE TO ANSWER, PLEASE CONTACT:

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