Natural Resources Canada · Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7941

Status of the existing monitoring and forecasts for GNSS systems

L. Nikitina, D.W. Danskin, R. Ghoddousi-Fard, P. Prikryl

2015

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7941

Status of the existing monitoring and forecasts for GNSS systems

L. Nikitina, D.W. Danskin, R. Ghoddousi-Fard, P. Prikryl

2015

doi:10.4095/296982

Recommended citation
Nikitina, L., Danskin, D.W., Ghoddousi-Fard, R., and Prikryl, P., 2015. Status of the existing monitoring and forecasts for GNSS systems; Geological Survey of Canada, Open File 7941, 46 p. doi:10.4095/296982

Contents

Executive summary

This report is a review of the monitoring and forecasts services for global navigation satellite systems (GNSS) that were publically available on the internet at the end of 2014. GNSS signals can be affected by ionospheric scintillation and distribution of electron density in the ionosphere caused by space weather disturbances. The intent of this document is to give description of available services and models, which may be useful in evaluating space weather effects on GNSS. In addition, some models which are available to evaluate the electron density distribution are summarized. A brief background is presented to explain the terminology, methodology and context of the GNSS field.

Based on the review of the existing models we can conclude that

- some models include the long-term variation of the solar activity (like 27 –days variation and 11 years solar cycle variation);
- some empirical statistical models include the solar activity using Sunspot number and F10.7;
- the authors of some TEC models discuss the possibility of including the geomagnetic indices into ionospheric forecast;
- probabilistic models of scintillation could provide an estimation of the probability of scintillation in the ionosphere based on anticipated/forecasted ionospheric conditions;
- the existing TEC models that include diurnal and seasonal time variation cannot describe disturbances of the ionosphere and their impact on the GPS systems during space weather events because they are based on typical values assumed in climatology.

The document concludes by considering what services existed at the end of 2014 that may be used to determine if GNSS signals may be subject to an irregular ionosphere and potential disruption.

1. Introduction

This report is a review of the monitoring and forecasts services for GNSS systems that were publically available on the internet at the end of 2014. The intent of this document is to give description of available services and models, which may be useful in evaluating space weather effects on GNSS. A brief background is necessary to understand the terminology, methodology and context of the field.

The term ‘global navigation satellite systems’ (GNSS) refers to a constellation of satellites that provide radio wave signals from space to ground or space based receivers, which process the signal to determine accurate position and time. GNSS receivers use the timing and positioning data encoded in the satellites signals to resolve the receiver’s location. The USA’s NAVSTAR Global Positioning System (GPS) and Russia’s Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) are two of systems available at the end of 2014.

Our modern society has become increasingly dependent on technological systems such as GNSS. Certain applications including marine navigation, aviation, and highway traffic management often rely on the precision positioning of GPS. GPS is used not only for position but as a source of accurate timing. Many computers have GPS antenna to provide accurate timing on local networks through network time protocol (NTP).

The GNSS signals propagate through the ionosphere and atmosphere to receivers on the Earth and its vicinity. The ionosphere is the ionized part of the Earth’s atmosphere situated above ~50 km from the surface. The ionospheric disturbances are capable of causing range errors, phase and amplitude fluctuations of satellite signals that may lead to degradation of the system performance, its accuracy and reliability.

The ionosphere is a dispersive medium with the radio signal propagation dependent on the electron density and local geomagnetic field between the receiver and the satellite. The free electrons in the ionosphere affect the propagation of radio waves depending on the frequency of the radio waves. At frequencies below about 30 MHz the ionosphere acts almost like a mirror, reflecting radio waves. At higher frequencies, such as those used by GNSS, the radio waves pass through the ionosphere, and the speed of propagation of a radio wave depends on the electron density (Klobuchar, 1991).

The interaction between radio waves and the ionospheric plasma can be complex and is one of the factors affecting accuracy and vulnerability in satellite-based positioning. The resulting range error can vary from less than 1 meter to more than 100 meters with dependency on the time of day, season, geographic location of receiver, viewing direction between satellite and receiver, solar activity and geomagnetic disturbances. For assessment of the ionosphere conditions, the GNSS community typically uses two parameters to characterize the ionosphere, namely the total electron content (TEC) and radio wave scintillations. The scintillations can be of two types, amplitude and phase. These parameters will be described in details in chapter 2. In chapter 3 we provide some examples how space weather affects the ionospheric parameters. Chapter 4 is the review of the services and models which may be used for TEC and scintillations assessment.

2. Physical parameters of the ionosphere and navigation systems performance

2.1. Total electron content

The total electron content (TEC) is the number of free electrons in the ionosphere per meter squared that a radio wave passes through. TEC is computed according to:

$$TEC = \int n_e(h)dh \tag{1}$$

where n_e is the electron density. TEC is commonly expressed in TEC units (TECU), TECU=10^{16} el/m^2.

TEC depends of the amount of solar radiation and transport due to local electric fields and day-night asymmetry. TEC has a strong diurnal variation because on the night side of the earth, in the absence of solar illumination, the free electrons recombine with the ions, thereby reducing the TEC. Solar extreme ultraviolet (EUV) radiation at wave length < 130 nm significantly ionizes the neutral gas of the upper atmosphere increasing the electron density. There are also seasonal variations in TEC and variations that follow the solar activity (27-day rotational period of the sun and 11 year cycle of solar activity).

Evaluation of TEC depends on the viewing direction between the receiver and satellite. To make the geometry dependent slant TEC (STEC) values free of viewing direction, the data must be transformed to vertical TEC (VTEC). Assuming ionosphere is a single layer spherical shell, the corresponding mapping function *m(e)* converting slant TEC to vertical TEC can be given by (2) [see, e.g. Jakowski, 1996].

$$m(e) = STEC/VTEC = \left(1 - \left(\frac{R_E \sin z}{R_E + H}\right)^2\right)^{-1/2} \tag{2}$$

where *m(e)* is a mapping function dependent on elevation angle e, which is the complement of the zenith angle (z), *STEC* is the slant TEC along the ray path, *VTEC* is the vertical TEC at the ionospheric pierce point, R_E is the Earth radius in kilometers, H is the shell height of the ionosphere single-layer approximation in kilometers and z is the zenith angle in radians (See Figure 1). The ionospheric piercing point is where the straight line trajectory of the radio wave between satellite and receiver intersects the ionosphere shell.

Total electron content and its variability is one of the most important features of the ionosphere. Many monitoring services and models of the ionosphere provide TEC maps such as the one shown in Figure 2 to represent ionosphere conditions.

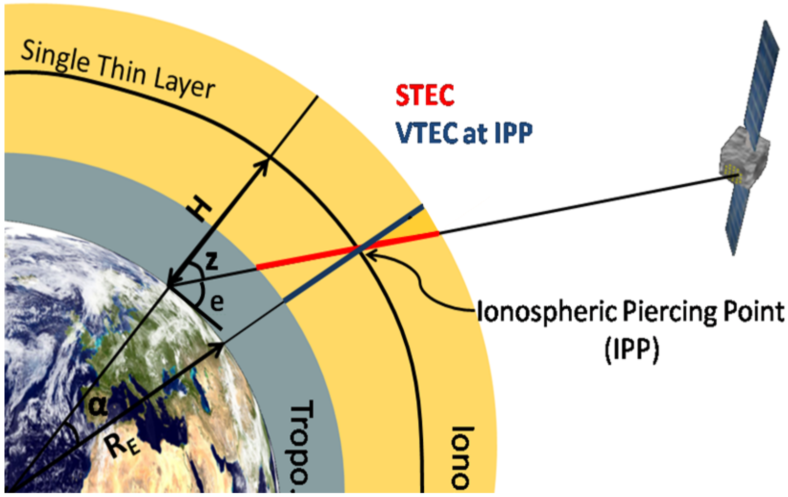


Figure 1. Ray tracing scheme for trans- ionospheric propagation. STEC is the slant TEC above a given point on the Earth surface, VTEC is the vertical TEC, H is the altitude of the Ionospheric Piercing Point, z and e are the zenith and the elevation angle.
Retrieved from http://www.gnss.be/ionosphere_tutorial.php .

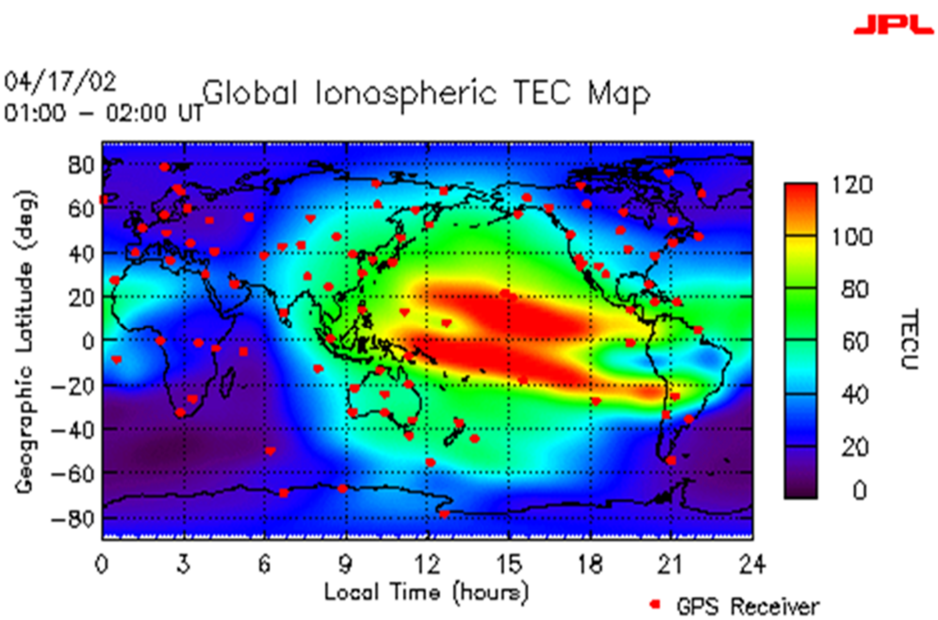


Figure 2. Global ionospheric TEC map produced by JPL. Taken from
http://iono.jpl.nasa.gov/images/gim_demo.gif

2.2. Scintillation

The ionospheric dynamics is largely driven by coupling processes between the solar wind and the Earth's magnetic field resulting in ionospheric convection, energetic particles precipitations causing aurora, and ionospheric irregularities. Electron density irregularities causing rapid fluctuations of radio signal amplitude and phase called scintillation. Scintillation can affect the performance of radio communication and navigation systems. Strong amplitude fluctuations may cause loss of lock of signals resulting in a reduced availability of GNSS signals. When the number of signals from different satellites is reduced to less than four no position solution is possible. Thus, ionospheric scintillations may have a strong impact on continuity, accuracy and availability of GPS services.

Scintillation activity is most severe and frequent in and around the equatorial regions, particularly in the hours just after sunset. In high latitude regions, scintillation is frequent as well. Scintillation is usually quantified by two values. S4 is a measure of the level of the amplitude scintillation, while σ_φ is the standard deviation of the detrended carrier phase measurements hence σ_φ is a measure of phase scintillation.

S4 is commonly used to classify the amplitude scintillation events:

- Weak or no scintillation if S4 < 0.3;
- Medium scintillation if 0.3 < S4 <0.7;
- Strong scintillation if S4 > 0.7.

With strong scintillation, the receiver loses lock with the GNSS signals, which prevents the receiver from determining its position and time.

Ghoddousi-Fard et al., [2013] proposed mDPR and sDPR indices for phase scintillation activity at high latitudes. These indices are introduced for the Canadian Geodetic Survey of Natural Resources Canada (NRCan). To calculate these indices, 1-Hz GPS stations data are being used in near-real-time to derive phase rate variation statistics by means of mapped-to-zenith absolute mean (mDPR) and standard deviation (sDPR) of delta phase rate over 30 sec defined as (3),(4):

$$mDPR = \frac{|\langle f(I_g,\varepsilon_g)\rangle|}{m(e)} , \quad (3)$$

$$sDPR = \frac{\sqrt{\langle f(I_g,\varepsilon_g)^2\rangle - \langle f(I_g,\varepsilon_g)\rangle^2}}{m(e)} \quad (4)$$

where $f(I_g,\varepsilon_g)$ is the rate of the geometry-free GPS dual frequency phase at two consecutive moments which contains contributions from GPS phase ionospheric effects variations (I_g) and the phase multipath and noise (ε_g).

2.3. Criteria of the navigation system performance

Commonly, the performance of a satellite navigation system is assessed according to four criteria (see, e.g. http://egnos-portal.eu/discover-egnos/about-egnos/what-gnss):

- ***Accuracy*** refers to the difference between the measured and the real position, speed or time of the receiver;
- ***Integrity*** refers to a system's capacity to provide confidence thresholds as well as alarms in the event when anomalies occur in the positioning data;
- ***Continuity*** refers to a navigation system's ability to function without interruption;
- ***Availability*** refers to the percentage of time during which the signal fulfils the accuracy, integrity and continuity criteria.

GPS signal must transit the ionosphere to communicate with ground receivers. The signal propagation is advanced in phase by the electron density profile in the ionosphere. The phase of the carrier arrives at the receiver earlier than it would have had the signal traveled from the satellite in a complete vacuum. This early arrival is termed a **phase advance**.

On the other hand, the signal that is modulating the carrier (the pseudorandom noise codes and navigation message) is delayed by the ionosphere. The composite signal can be thought of as being formed by the superposition of sine waves with close frequencies, and the delay of the modulation is called the **group delay**. The magnitude of the group delay is identical to the magnitude of the phase advance.

The change in propagation speed as the wave traverse through the ionosphere introduces a range delay, which is equivalent to measuring a slightly longer distance to the satellite and a phase advance in its observables. To obtain very accurate positions from GPS, this ionospheric delay/advance must be taken into account.

GPS systems operate at two frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz). Dual frequency receivers are able to process both L1 and L2 frequencies and are capable of computing the ionospheric parameters. Frequency L5 (1176.45 MHz) is used as well for some special applications and is considered instead of L2 frequency for future GPS systems.

Accuracy of GPS system

The accuracy is the difference between the indicated readings and the true position. The GPS accuracy depends on many factors including the number and position of the satellites as well as the design of the receiver. Typically the vertical accuracy is 2-3 times worse than the horizontal accuracy.

Other terms used in reference to GPS error sources are (see, e.g. http://www.radio-electronics.com/info/satellite/gps/accuracy-errors-precision.php)

- ***Propagation errors***

  Atmospheric and ionospheric disturbances distort the signals before they reach a receiver.

- ***Signal multipath***
  Errors can be introduced when signals are reflected of buildings and other large objects such as large rocks. As the less direct path will be longer and take extra time, this can add errors into the system if the receiver recognizes the reflected signal.

- ***Receiver clock errors***
  GPS error source is due to inaccurate time-keeping by the receiver's clock and discrepancies between the GPS receiver's onboard clock and GPS time.

- ***GPS satellite orbit errors***
  GPS receiver position error includes an ephemeris error if the satellite deviates from the positions estimated in the ephemeris data for the satellite.

- ***Number of satellites visible***
  The more satellites available to provide readings, the greater level of certainty and accuracy. Usually at least four satellites are used for accurate positioning.

- ***Satellite position geometry***
  The geometry of the satellite positions can have an impact on the GPS error. This geometry changes with time and location due to the relative motion of user and satellites. The optimum situations occur when the satellites have wider angles relative to each other. Poorer estimates of position are obtained when the satellites have small angles between them.

Most GPS receivers indicate their accuracy within 10-50 feet (3 to 15 meters), 95% of the time. The US Standard Positioning Service (SPS) is a standard positioning service available to a civilian GPS receiver that has no differential corrections. The dynamics of GPS signal accuracy for SPS during 2001-2013 based on the USA Airforce data is shown in Figure 3.

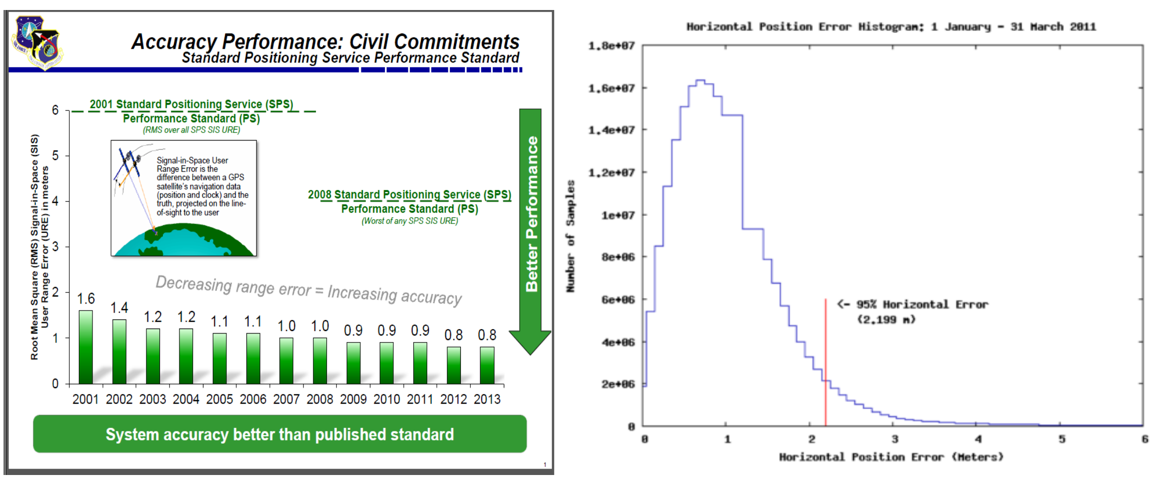


Figure 3. Dynamics of GPS signal accuracy from 2001 to 2013 based on the USAF data. Plots are retrieved from http://www.gps.gov/systems/gps/performance/accuracy/ on June, 11th, 2015. The horizontal accuracy of GPS SPS is often within ~1 m.

Integrity

Integrity is the level of trust in the navigation system (see, e.g. www.insidegnss.com/auto/sepoct08-gnsssolutions.pdf). Integrity can be expressed quantitatively using three parameters.

- The integrity risk is the probability that the system generates an unacceptable error without providing a timely warning that the system output cannot be trusted. Such an event is called ‘loss of integrity’ or ‘misleading information’.
- The alert limit, which defines the magnitude of error that, if exceeded, is unacceptable from a safety standpoint. Both horizontal alert limit (HAL) and a vertical alert limit (VAL) exist.
- Time to alert which is defined as the time between the occurrence of potential misleading information and the time of the alert issuing.

Continuity

The loss of continuity risk is the probability that the system will stop providing navigation outputs of the specified quality during the monitoring period (see, e.g. www.insidegnss.com/auto/sepoct08-gnsssolutions.pdf). Loss of continuity can occur when a navigation system or an individual satellite stops working or broadcasting signals. In other cases, continuity is lost when integrity monitors detect a real or imaginary fault, which leads to measurement exclusion. For applications that cannot be interrupted without some level of danger, such as aircraft precision approach and landing, loss of continuity poses safety hazards.

Availability

The most common definition of availability is the long-term average probability that the accuracy, integrity, and continuity requirements are met. In many cases, system availability implies signal availability, which is expressed as the percentage of time that the system’s transmitted signal are accessible for use. In addition to transmitter capability, environmental factors such as signal attenuation, blockage of signal, or the presence of interfering signals might affect availability.

2.4. Range error for the single frequency GPS

The ionospheric range error is a function of the signal frequency *f* and the electron density along the signal path. The ionospheric range error for the single frequency GPS is defined as [e.g., Jakowski, 1996]

$$d_I = \frac{K}{f^2} TEC \tag{5}$$

where *K* is a constant, K=40.3 $m^3 s^{-2}$. The ionospheric range error can reach about 100 m along ray path.

For single frequency GNSS receivers the ionospheric corrections can be attained using the broadcast data from satellite based augmentation systems such as the US WAAS (Wide Area Augmentation System).
http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/ and the European EGNOS (http://egnos-portal.gsa.europa.eu/) (see 4.1. for details)

3. Space weather effects on the system performance (some examples)

Geomagnetic storms are among the most important and widespread impacts of space weather on the ionosphere and hence GNSS performance. Radio signals, transmitted by modern communication and navigation systems may be heavily disturbed by space weather events. The disturbance in the ionosphere can cause TEC spatial and temporal gradients as well as ionosphere scintillation. The observance of strong ionospheric gradients indicates the development of highly dynamic processes in the Earth's ionosphere-plasmosphere system, with the potential of degraded effects on positioning.

The importance of space weather effects on GPS performance has been discussed widely. For example, analysis of the ionospheric response to four intense geomagnetic storms was provided in [Manucci et al., 2008]; Jakowski et al. (2005) present several case studies of problems arising from the space weather impacts on GNSS-based applications to help the GNSS users to mitigate the above mentioned problems.

3.1. The ionospheric impact of magnetic storms

October 2003 storm was one of the largest space weather events during last decades. Its impact on GPS performance was studied by many scientists. Komjathy et al. (2005) described the influence of this space weather conditions on the WAAS performance during October, 29-31, 2003. Large solar wind conditions with strong interplanetary magnetic field during these days were associated with X-class solar X-ray flares and coronal mass ejections that occurred on October 28 and 29. During the 28th of October, prior to the storm, the ionospheric range delays were less than 35 meters and the WAAS planar fit residuals were less than 2 meters with an RMS (root mean square error) of 0.4 meter. During storm conditions the ionosphere range delay reached 100 m with the planar fit residuals of 25 meters. RMS for WAAS on the active days was as large as 3.4 meters.

The magnetic storm in October 2003 caused ionospheric disturbances, which impacted the Sweden power system resulting in the brief blackout in the power system of Malmö [site of the Royal Observatory of Belgium http://gnss.be/ionosphere_tutorial.php#x2-90000] and caused enhanced TEC. For normal conditions the expected VTEC values for this region is usually between 1 and 7 TECu (<1.1m on L1) during the night, however, during the storm VTEC values reached 70 TECu (11 m on L1) as shown on Figure 4. The NOAA Service Assessment (Service Assessment, 2004) desribed an impact of the Halloween storm on the USA's Wide Area Augmentation System (WAAS). This system was impacted during 15 hours on October 29 and 11 hours on October 30. The ionosphere was so disturbed that the vertical error limit (50 m) defined by the Federal Aviation Agency's Lateral Navigation Vertical Navigation specification was exceeded. As a result, commercial aircrafts were unable to use the WAAS for precision approaches.

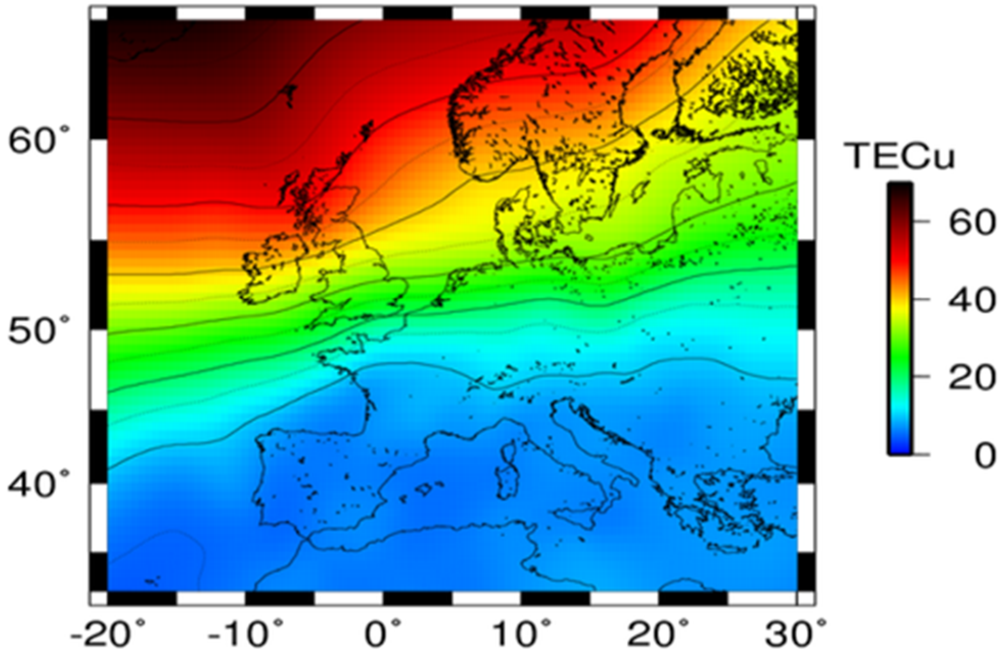


Figure 4. VTEC map during the Halloween storm (from 23:30 to 23:45 on 30th of October 2003). Taken from the site of the Royal Observatory of Belgium. http://www.gnss.be/ionosphere_tutorial.php.

The analysis for TEC distribution during Halloween storm in 2003 was also made for Canada location using Spherical Cap Harmonic Analysis. This analysis shows that during this extreme event VTEC reach to about 100 TECU and the position error reached 19 and 33 m in the horizontal and vertical directions if the ionosphere effect is not corrected [Ghoddousi-Fard et al., 2011].

Figure 5 provides time series of VTEC value at 3 locations in Europe during the week around the geomagnetic storm on 17th March 2015. VTEC for disturbed days (red line) is compared with average value of VTEC for 15 previous days (grey line). The plot shows that VTEC was increased up to 65 TECU, about 30% higher than normal VTEC.

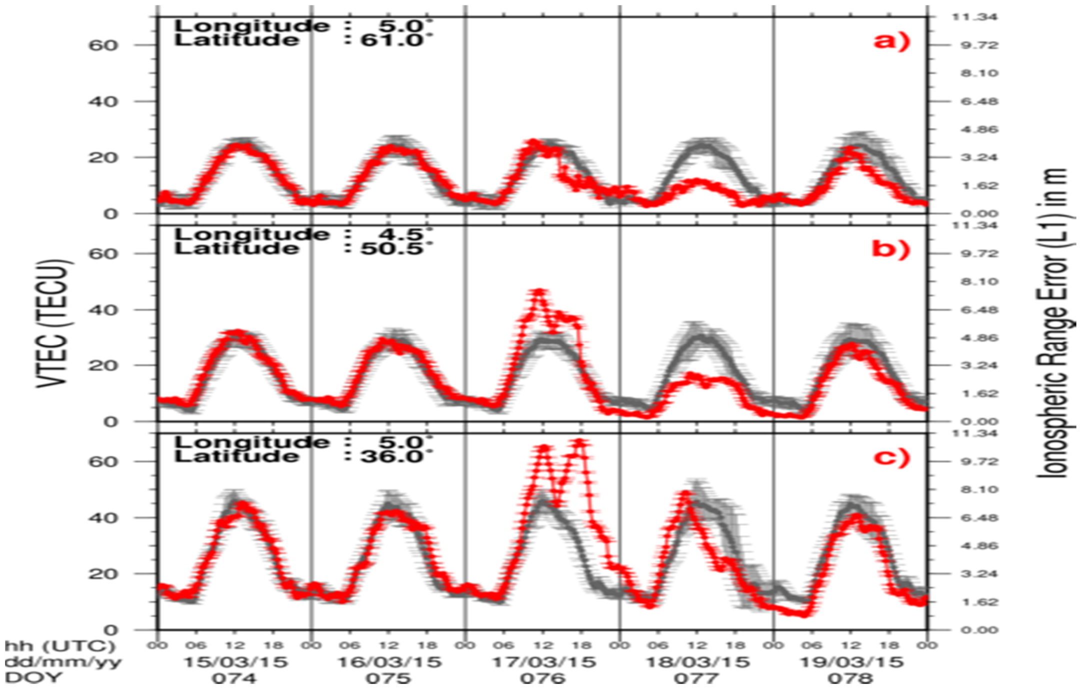


Figure 5. VTEC time series at 3 locations in Europe (North, Brussels, and South) during the week around the geomagnetic storm of 17 March 2015. Grey line indicates the normal ionospheric behaviour based on the median VTEC from the 15 previous days. Taken from the site of the Royal Observatory of Belgium. http://gnss.be/Atmospheric_Maps/ionospheric_event.php?date=2015-03-17

3.2. Scintillation raised during geomagnetic disturbances

The case study by [Prikryl et al., 2013] demonstrates an ionospheric response at high latitudes during changing solar wind conditions not associated with major geomagnetic storms. A moderate solar wind plasma stream from a weak coronal hole was compounded by two ICMEs (interplanetary coronal mass ejection) resulting in disturbed magnetosphere and ionosphere from 30 October to 5 November 2011. The first ICME shock, which was associated with a southward turning of the interplanetary magnetic field (IMF), caused the onset of auroral activity and phase scintillation. The arrival of the second ICME was associated with the strongest southward IMF and resulted in the highest values of auroral electrojet index AE and phase scintillation index exceeding 1 radian at times. The rise in the AE index correlated with an increase in the occurrence of phase scintillation exceeding 0.1 radians in auroral and polar latitudes.

Conclusion for chapter 3:
Severe temporal and spatial changes of the electron density in the ionosphere may significantly degrade the signal quality of various radio systems which even may lead to a complete loss of the signal. By providing specific space weather information, in particular through now-casting and forecasting of the ionospheric state, the reliability of impacted communication and navigation systems shall be improved. In the next chapter international services and models to improve monitoring and forecasting of ionospheric perturbations is discussed.

4. Commonly used ionosphere services and models

In this section, services and models that may be used to assess and correct the level of ionospheric effect on GNSS performance are considered.

4.1. Augmentation services

One option to correct the ionospheric range error in single frequency applications is the provision of range error corrections derived from actual ionospheric monitoring. This is done in Space Based Augmentation Systems (SBAS) which provide ionospheric corrections to users equipped with special GPS receivers. SBAS include Wide Area Augmentation System (WAAS) which is used in the USA, partly in Canada and Mexico, and European Geostationary Overlay Service (EGNOS) in Europe. Other SBAS include also the European Geostationary Navigation Overlay Service (EGNOS) and the Japanese Multi-transport Satellite-based Augmentation System (MSAS) and GPS Aided GEO Augmented Navigation (GAGAN) operated by India. Ionospheric corrections are essential for accurate positioning and navigation.

WAAS

Information about the WAAS is the Wide Area Augmentation System for North America can be found at: http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas/. According to the WAAS performance standard (see WAAS performance standard, 2008), 'WAAS augments GPS SPS (Standard Positioning Service) by broadcasting differential GPS correction messages from GEO satellites. The WAAS Service is specifically designed to meet high accuracy, integrity, continuity, availability standards of aviation users, but is an open service that has the capability to support other applications as well. WAAS provides a ranging function throughout the entire satellite footprint that improves the availability of GPS positioning for SBAS users. WAAS also provides differential correction as well as satellite status from GPS satellites.'

WAAS is intended to enable aircraft to rely on GPS for phases of flight, including precision approaches to any airport within its coverage area. The WAAS receiver uses the WAAS broadcast-corrections in conjunction with GPS signals to determine its position.

EGNOS (European Geostationary Navigation Overlay Service).

The **European Geostationary Navigation Overlay Service** (**EGNOS**) is the European satellite based augmentation system (SBAS) developed by ESA (the European Space Agency), the European Commission (EC) and the European Organisation for the safety of Air Navigation (Eurocontrol) (http://www.essp-sas.eu/introducing_egnos and http://www.egnos-pro.esa.int/index.html). The official start of operations was announced by the European Commission on 1 October 2009. The service supplements GNSS systems by reporting on the reliability and accuracy of the positioning data. The horizontal position accuracy is at the metre level. As it was estimated by EGNOS, a positioning accuracy is within 3 meters while the positioning accuracy for GPS receiver without EGNOS is within 17 meters.

4.2. Services providing TEC

The generation of ionosphere VTEC maps is done at IGS (International GNSS Service) Associate Analysis Centers (Hernandes-Pajares et al., 2008). The contribution to the combined global VTEC maps is mostly provided by

- Jet Propulsion Laboratory (JPL), Pasadena, U.S.A.,
- Center for Orbit Determination in Europe (CODE), University of Berne, Switzerland,
- European Space Operations Center of ESA (ESA/ESOC), Darmstadt, Germany,
- Technical University of Catalonia (gAGE/UPC), Barcelona, Spain.

Here is a description of some monitoring TEC services.

JPL service, Real-Time Ionosphere Maps

Global maps of TEC are produced in real-time by mapping GPS observables from ground stations. http://iono.jpl.nasa.gov/latest_rti_global.html. These Global Ionosphere Maps provide instantaneous “snapshots” of the global TEC distribution, by interpolating, in both space and time, the 6-8 simultaneous TEC measurements obtained from each GPS receiver every 30 seconds. The maps can be produced in a real-time mode, with an update rate of 5 minutes. Screenshot of the service is on Figure 6.

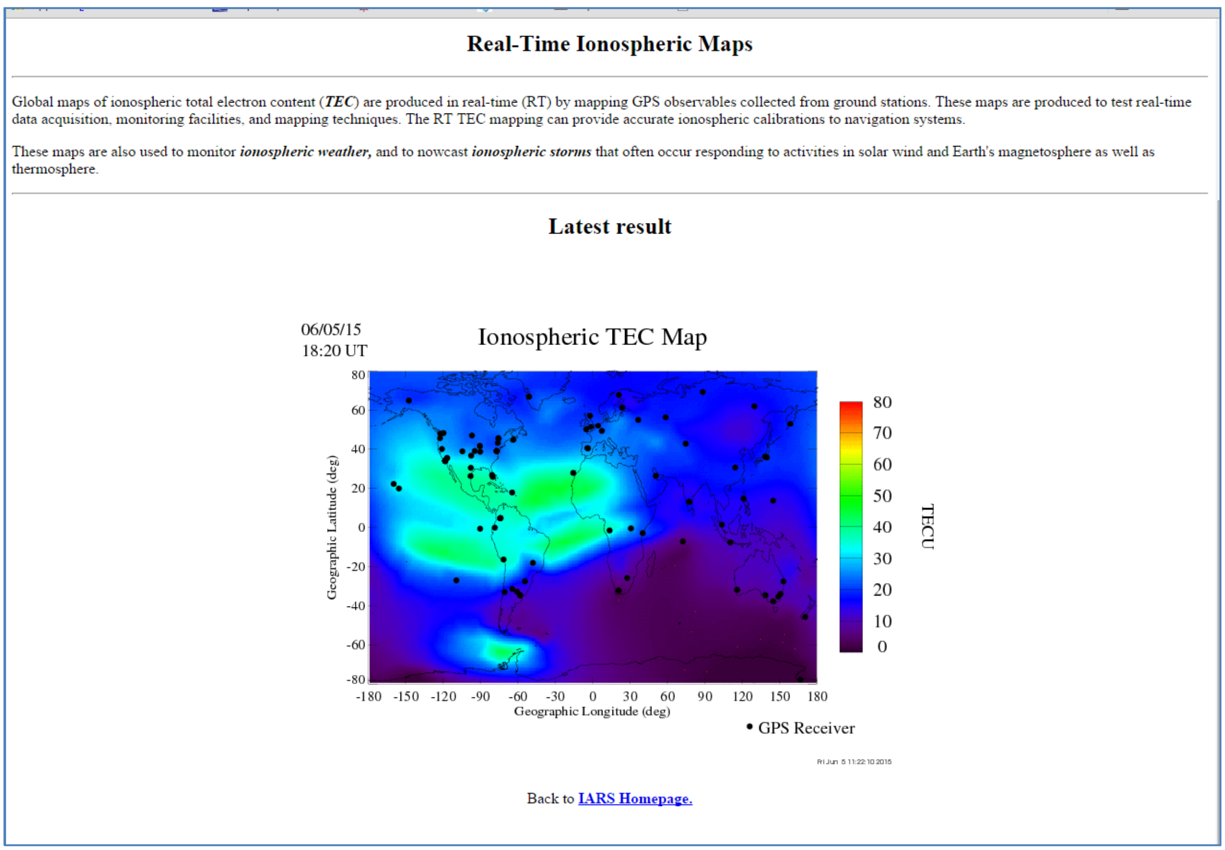


Figure 6. An example of VTEC real-time ionosphere map. Retrieved from http://iono.jpl.nasa.gov//latest_rti_global.html on 5 June 2015.

CODE service

CODE (The Center for Orbit Determination in Europe, http://aiuws.unibe.ch/ionosphere/) at the Astronomical Institute at University of Berne, Switzerland, provides global Ionosphere map (GIMs) on daily bases from 1995. CODE GIMs cover area between 87.5^0 southern and northern latitudes and provides 1-day and 2-days forecast. GIMs (see Figure 7) are produced every hour. This service uses data from about 200 GPS/GLONASS sites. The vertical TEC is modeled using a spherical harmonics expansion up to degree 15.

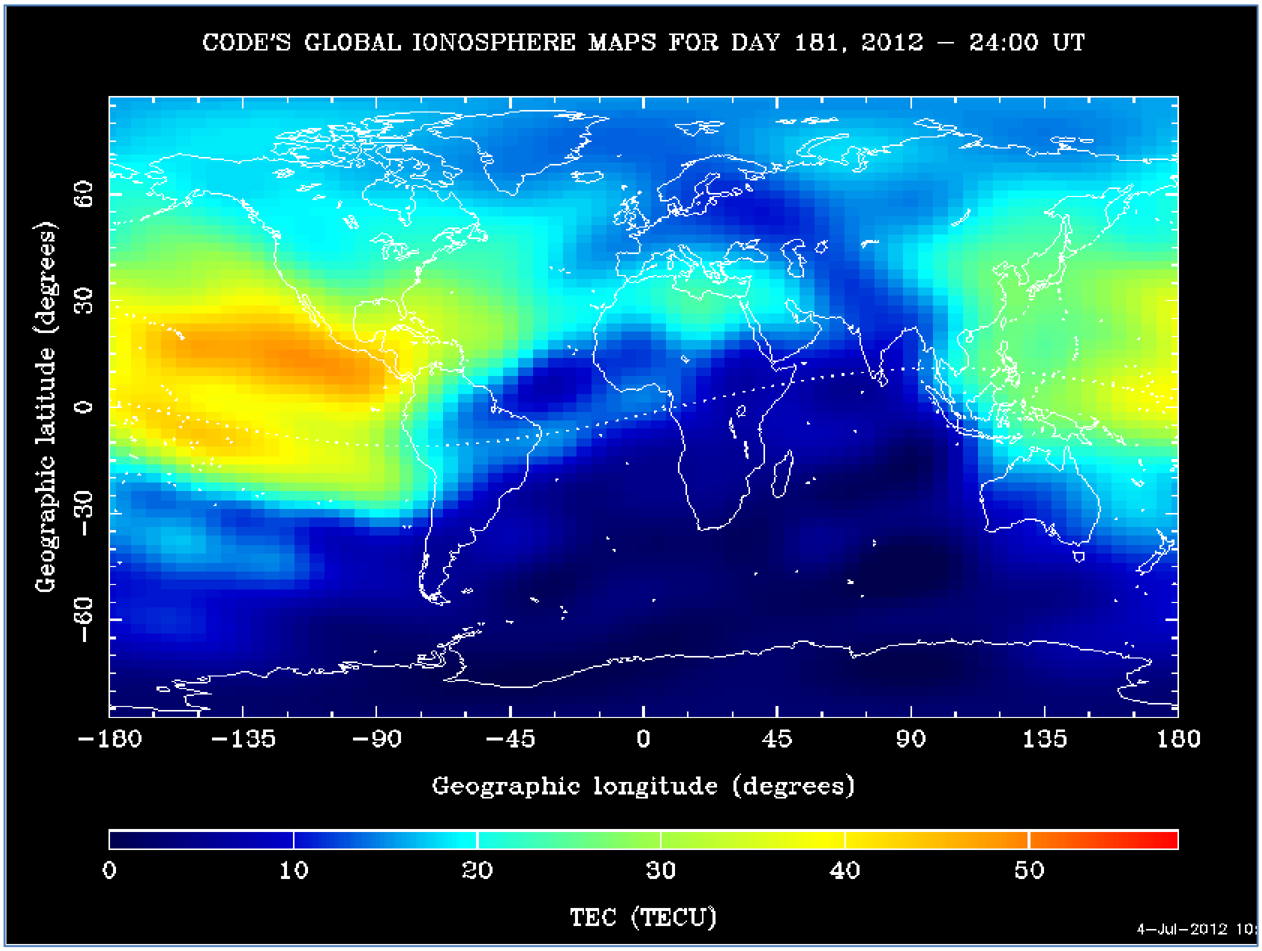


Figure 7. Global Ionosphere map provided by CODE

SWACI (Space weather application center – Ionosphere)

SWACI is a research project of DLR (German Aerospace centre) supported by the State Government of Mecklenburg-Vorpommern (Germany) http://swaciweb.dlr.de/index.php?id=&L=1 (see e.g. [Jakowski et al., 2010] and [Jakowski et al., 2011]). SWACI contributes to the Space Weather European Network (SWENET)of European Space Agency (ESA). SWACI service is based on Neustrelitz model (see e.g.

[Jakowski et al., 2011]). This service carries out the TEC monitoring on a routine base since 1995 over the European area. To ensure a high reliability of the TEC maps also in case of only a few measurements on a greater distances from the measuring points, the measured data are combined with an empirical TEC model which has been developed specifically for the region in view. This service provides TEC maps for Europe as well as Global TEC map together with the rate of change of TEC index. SWACI products include as well 1 hour TEC forecast, TEC Median for 27 days, TEC error, and TEC forecast quality. All the maps have been renewed every 15 minutes (see Figures 8 and 9).

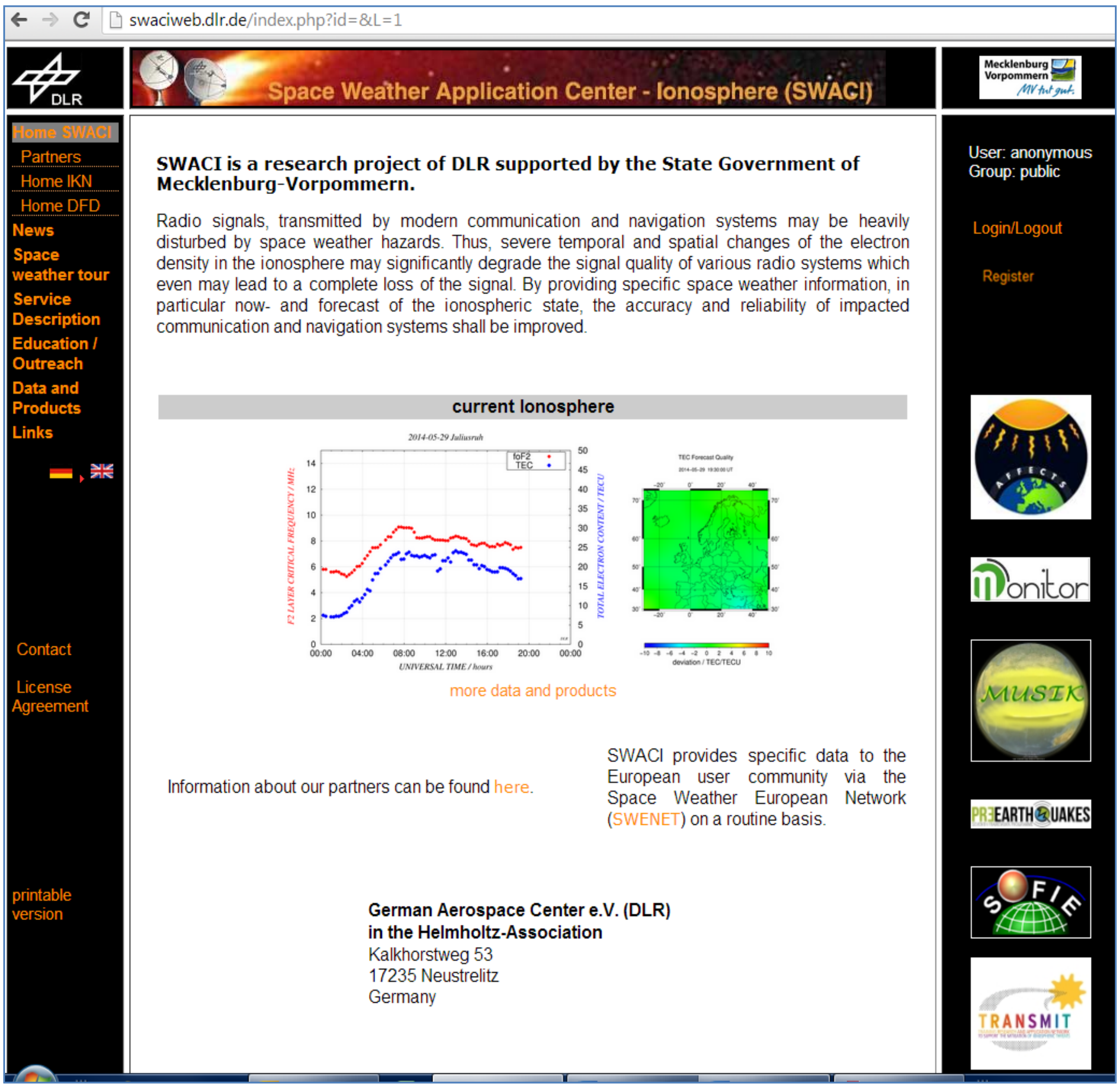


Figure 8. SWACI service. http://swaciweb.dlr.de/home-swaci/?no_cache=1&L=1

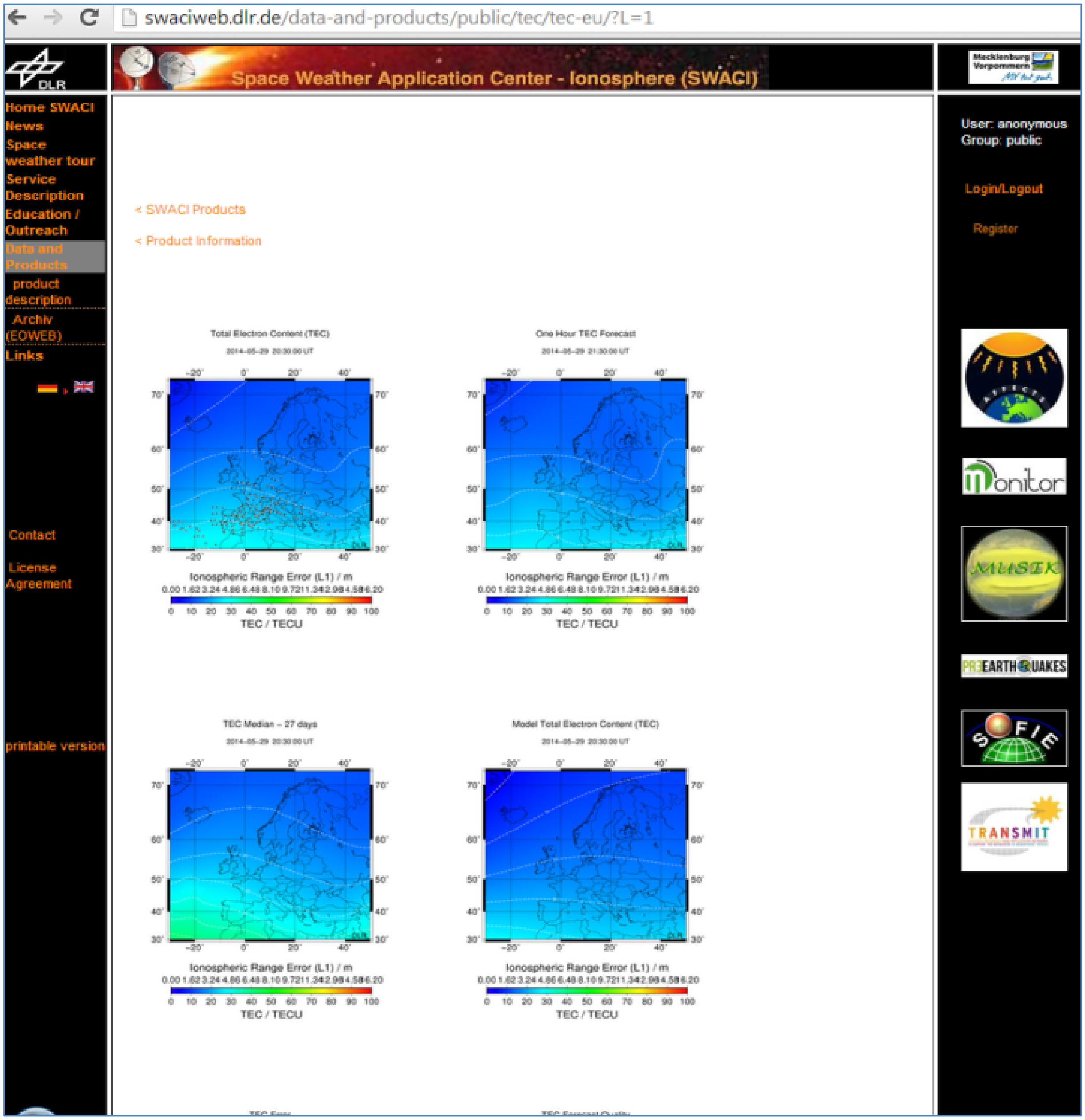


Figure 9. SWACI service provides TEC values with its model, one hour forecast for TEC value and the median TEC value for the last 27 days.

UPC (Technical University of Catalonia) ionospheric VTEC prediction model (test mode)

VTEC monitoring is provided by the Technical University of Catalonia. This service is a part of the International GNSS Service. The UPC IGS products contain 13 global VTEC at a temporal resolution of 2 hours. Each VTEC map is a 2-dimensional with spatial grid points every 2.5/5 ^{o} in the latitude/longitude range assuming a thin shell layer model of the ionosphere at a height of 450 km.

NOAA SWPC service

NOAA SWPC service is developed by National Oceanic and Atmospheric Administration, Space Weather Prediction Center, USA. US-TEC provides vertical TEC and slant path values of the line-of-sight electron content to the GPS satellites in view at the time. This ionospheric product is designed to estimate the signal delay for single and dual frequency GPS applications. It is a local service and should be used for the places covered by the Continental US (CONUS). This service uses data from 63 real-time GPS stations. The US-product includes (see Figure 10): map of the vertical total electron content (VTEC); map of an estimate of the TEC uncertainty; map of the deviation from the recent 10-day average. Vertical TEC over CONUS is provided for a given 15 minute interval in TEC units. New maps are usually available 13 minutes after a given interval.

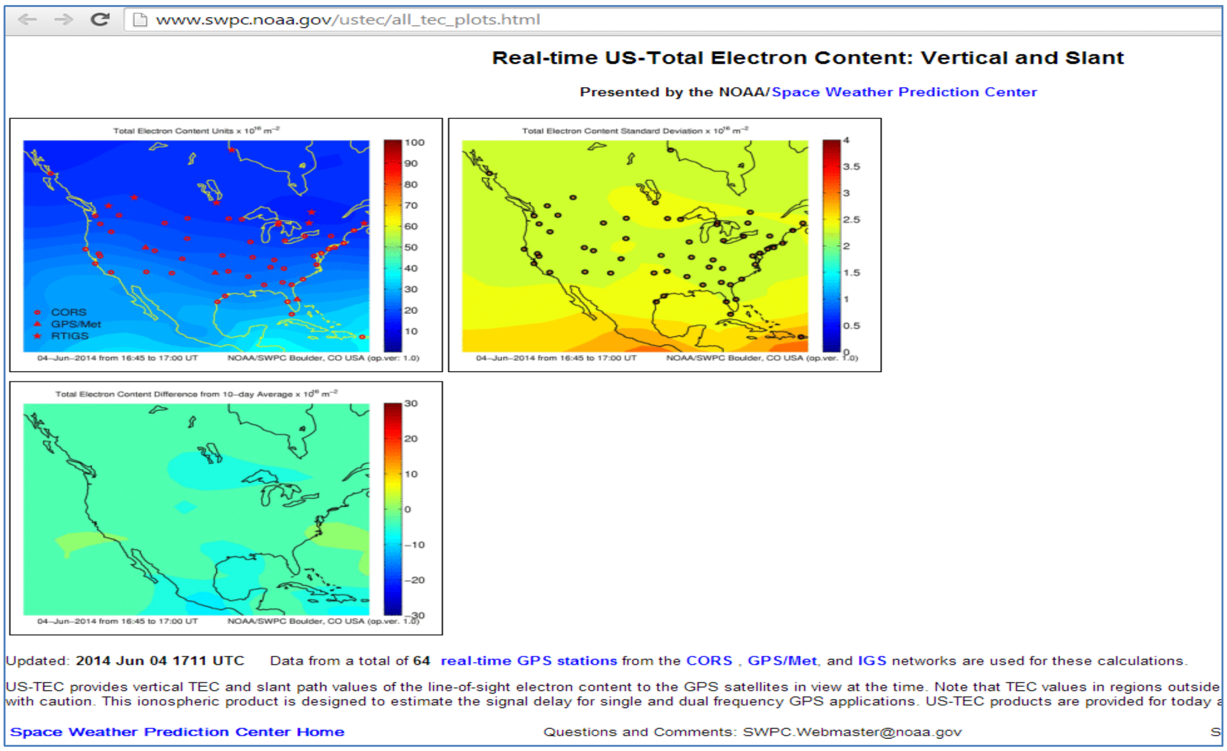


Figure 10. NOAA SWPC service. Retrieved from http://www.swpc.noaa.gov/products/us-total-electron-content on June 04 2014.

Near real-time Ionosphere monitoring over Europe. Sevice provided by the Royal Observatory of Belgium

The on-line service (see Figure 11) provides

- Interactive maps which display animated VTEC maps for a requested period and VTEC value at a given location and time.
- Statistical maps and plots to compare the ionosphere at the date with an average for the 15 previous days
- VTEC time series which demonstrates the VTEC evolution over time, and comparing with the VTEC median of the 15 previous days is used for 24h prediction at three different locations (North of Europe)

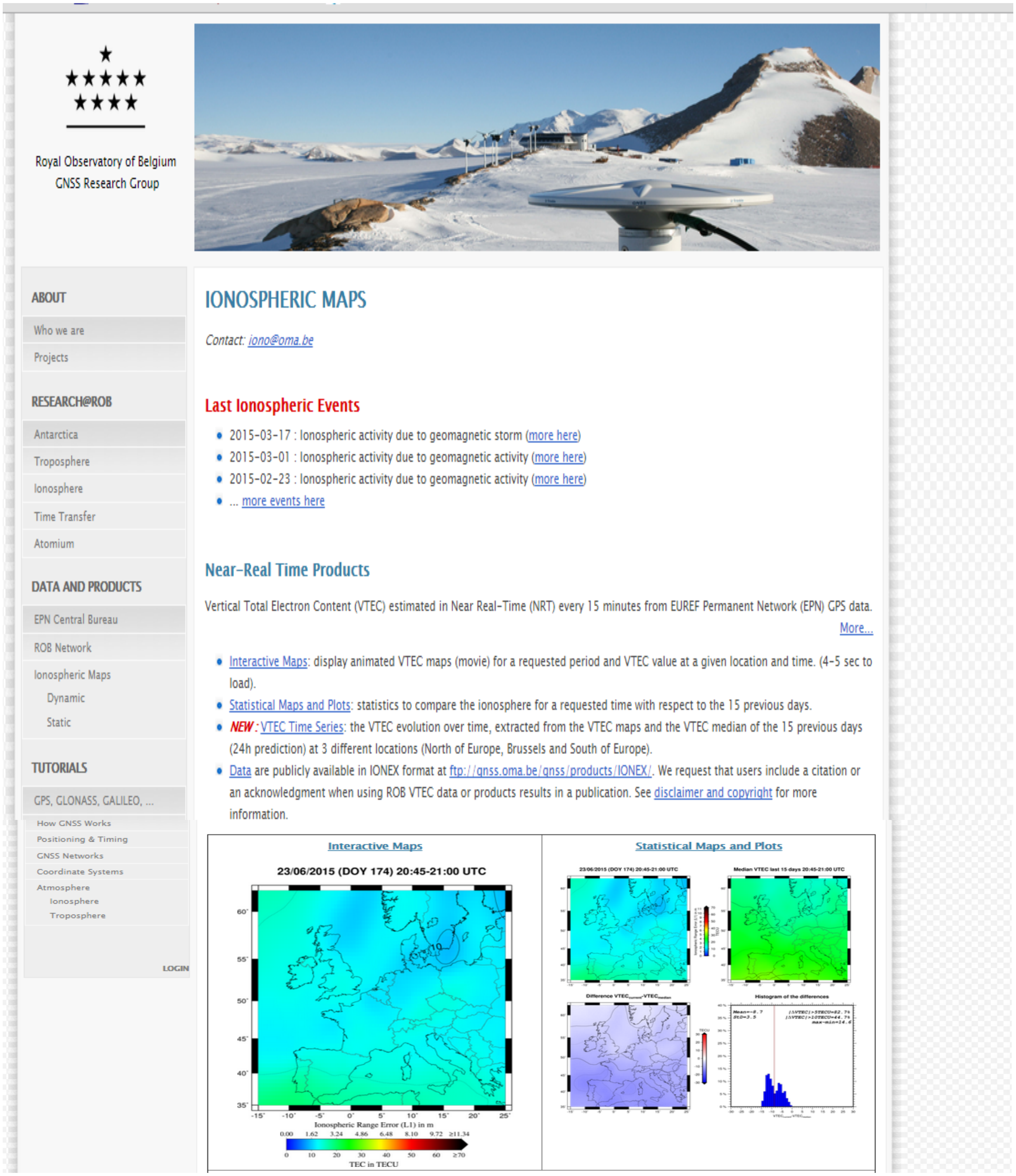
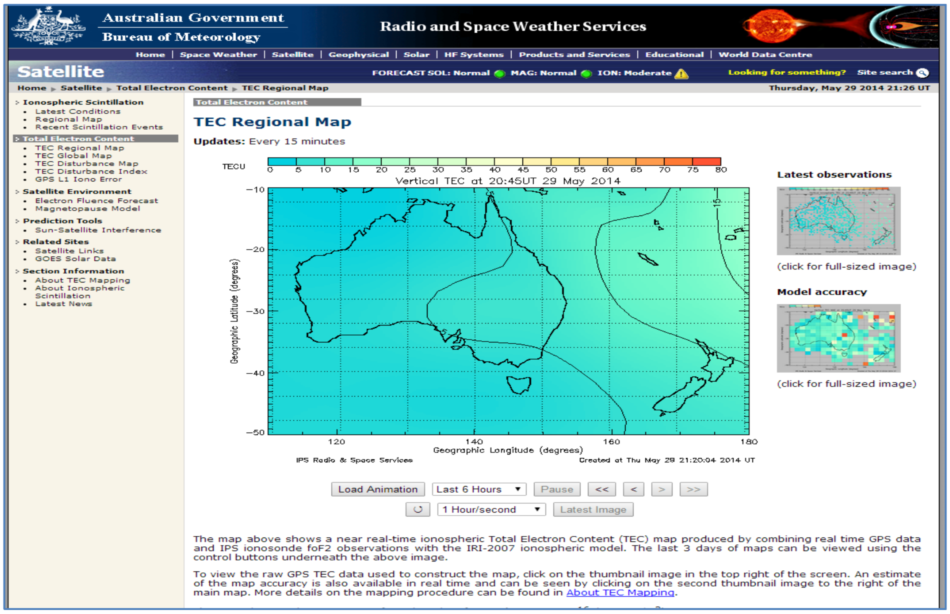


Figure 11. Near real-time ionosphere monitoring, Royal Observatory of Belgium.
http://gnss.be/Atmospheric_Maps/ionospheric_maps.php

On-line service of Australian Government. Bureau of Meteorology. Radio and Space Weather Service (http://www.ips.gov.au)

The on-line service of Australian Government Bureau of Meteorology, Radio and Space Weather Service provides among other services a near real-time ionospheric Total Electron Content (TEC) map. This map shows a near real-time ionospheric TEC map produced by combining real time GPS data and ionosonde foF2 observations with the IRI-2007 ionospheric model. It is updated every 15 minutes.



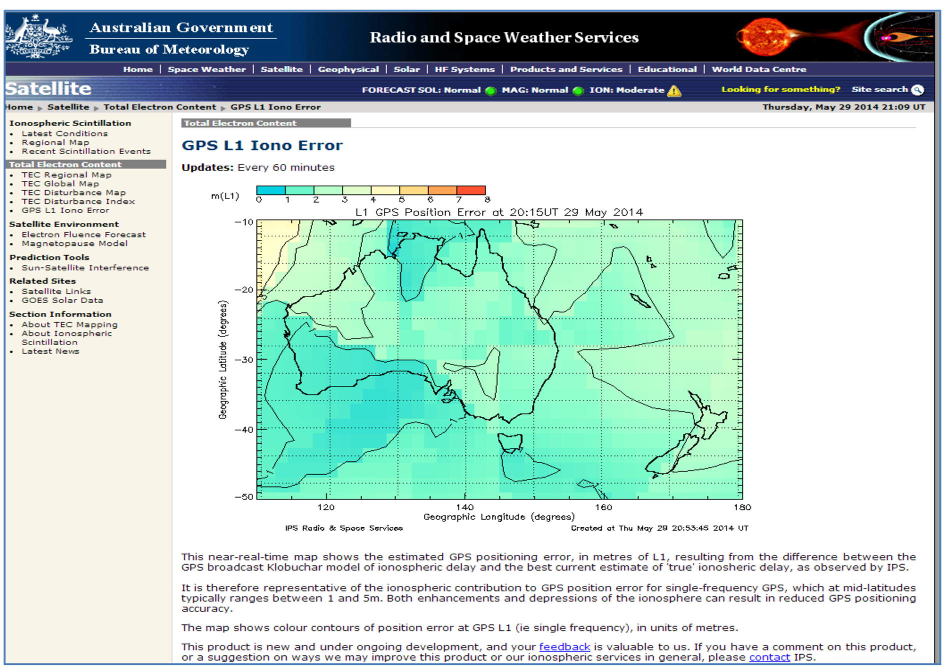


Figure 12. TEC regional map and GPS Iono error provided by the Australian Bureau of Meteorology. http://www.ips.gov.au/Satellite/2/1 and http://www.ips.gov.au/Satellite/2/5

This service provides the raw GPS TEC data used to construct the map and real-time estimation of the map accuracy, TEC disturbances, and 30-day climatology. The maps (see Figure 12, 13) shows colour contours of TEC in units of TECU (1 TECU = 10^{16}electrons/m^2). This service also provides GPS positioning error.

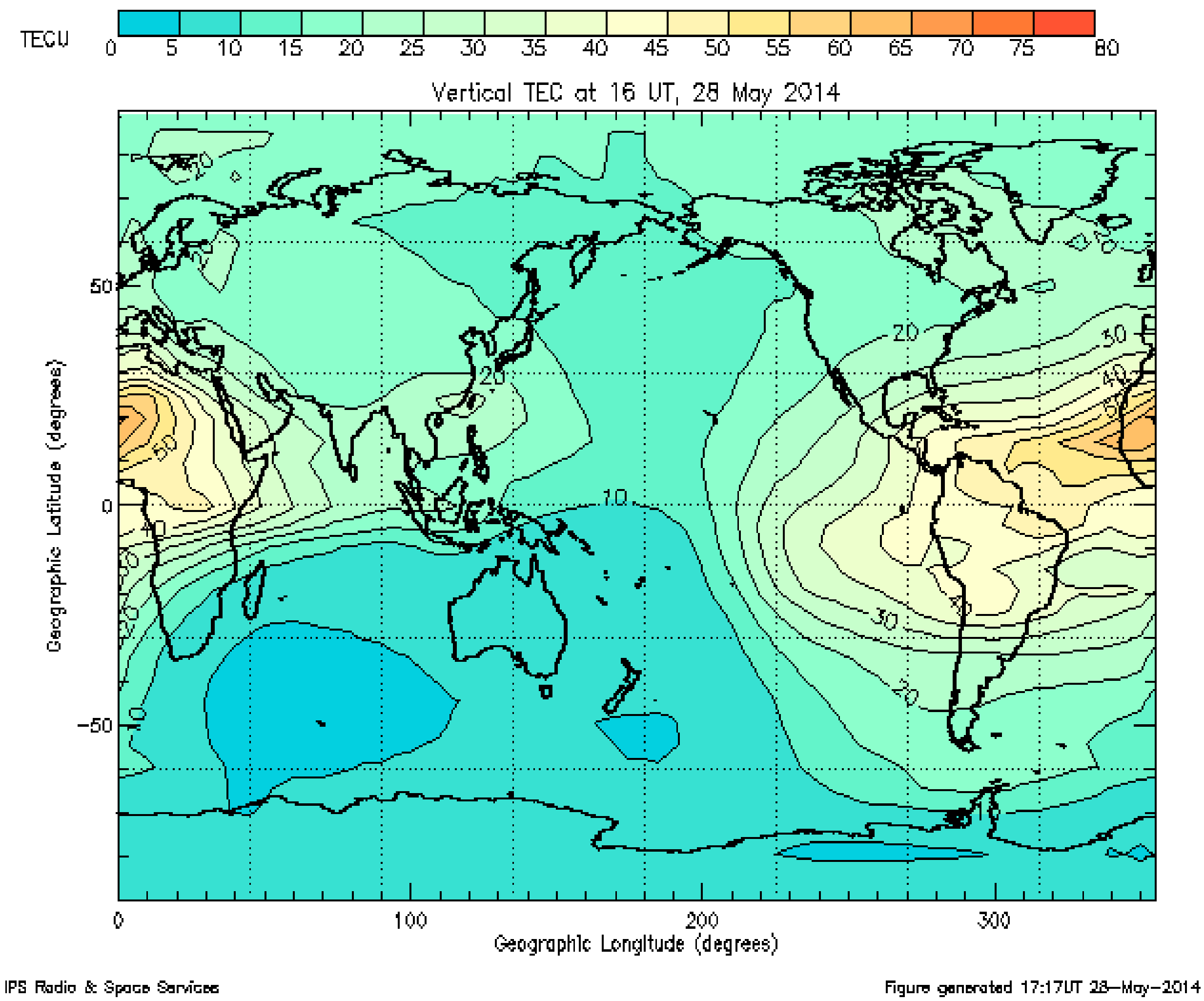


Figure 13. TEC global map provided by the Australian Bureau of Meteorology.
http://www.ips.gov.au/Satellite/2/1 and http://www.ips.gov.au/Satellite/2/5

EMR (Canadian Geodetic Survey of NRCan)

Canadian Geodetic Survey of Natural Resources Canada with participation of Canadian Space Weather Forecast Center (NRCan) has developed a number of products from GPS sensing of the ionosphere. These include:

1) regional near-real-time and daily vertical Total Electron Content (TEC) maps represented using Spherical Cap Harmonic Analysis (SCHA) that covers Canada and adjacent regions,

2) near-real-time global TEC maps from GPS Real Time (RT) IGS stations are represented using Spherical Harmonic (SH) coefficients of degree and order 15 which are also available in 96 daily IONosphere map EXchange (IONEX) format,

3) daily global TEC maps based on data from more than 350 GPS stations which are represented using SH coefficients of degree and order 15 and are also available in IONEX format.

As a by-product of near-real-time global TEC mapping from high rate RT-IGS GPS stations, dual-frequency phase rate measurements are used to derive proxy indices for monitoring the ionospheric irregularities. Schematic regional and global maps of such indices are updated in near-real-time and are being studied to correlate with independent space weather indices. Higher order ionospheric delays are also being estimated in near-real-time and are stored for studies on their amount and spatial variations.

In 2015 NRCan's global VTEC maps are being regularly submitted to IGS data center at NASA's CDDIS (Crustal Dynamics Data Information System) ftp server for public. As a founding member of IGS, NRCan's Canadian Geodetic Survey's products in IGS is still being named as EMR (former name of NRCan) to be consistent with older products file names. One may find background and further details at Ghoddousi-Fard [2014] and IGS[2012,2013,2014,2015].

These TEC maps are produced from GPS observations. This technique implements spherical cap harmonic analysis (SCHA) [Haines, 1985]. It is used to model the distribution of the VTEC in local area. This approach is used for TEC mapping in Canada [Ghoddousi-Fard et al., 2011] (see Figure 14).

Input GPS data for ionospheric content.

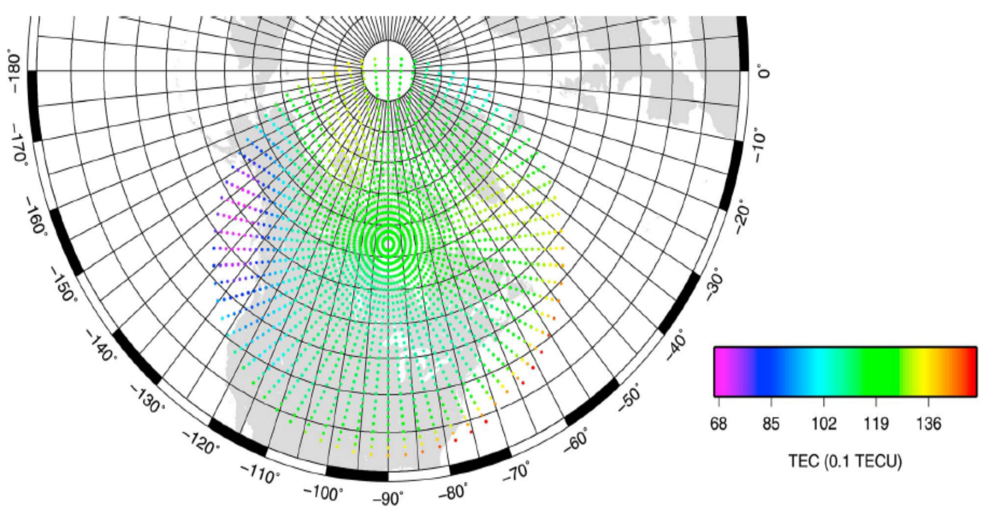


Figure 14. Spherical cap centered over Canada and VTEC values at SCHA grid points at 1400 UTC, DOY 227, 2010. [Ghoddousi-Fard et al., 2011**].**

Output

TEC maps in the form of SCHA coefficients

Description of the model

Estimation method is based on the spherical cap harmonic analysis applied to GPS data.

Forecast possibility

The coefficients of the spherical cap harmonic analysis model could be predicted using the spectral analysis and least squares fitting method applied to many years of SCHA coefficients. Liu et al.(2011) applied frequency analysis for the time series of TEC SCHA coefficients for Arctic ionosphere during 2000-2013. Fast Fourier transform of the TEC coefficients was used to estimate various period components. Apart from the annual and diurnal variation, the primary components in the frequency domain include a component of 11.2 years corresponding to solar cycle period, and 27 days variation corresponding to the Carrington period (solar rotation period). This gives opportunities for the climatological forecast models.

4.3. Correction models

Correction models

If the SBAS service is not available, an ionosphere model can be used to estimate the GPS ionosphere error. There are several empirical ionospheric models which include the Klobuchar model, International Reference Ionosphere (IRI), NeQuick, and Neustrelitz TEC Model (NTCM).

Klobuchar model

Klobuchar model was developed by John A.Klobuchar in 1975 at the Air Force Geophysics Laboratory, U.S. Klobuchar model is the global standard ionospheric correction model which is used to correct ionospheric time-delay in GPS for single frequency users. This model presents the diurnal ionospheric TEC variation with a set of numerical coefficients (Klobuchar, 1991, Jakowski, 1996). These coefficients are updated at 10-day intervals to account for seasonal and solar activity changes. Klobuchar model includes a cosine function approach for the delay of L1 signals propagating through the ionosphere in vertical direction. GPS satellites (operated by Department of Defence, U.S.A) broadcast the parameters of the Klobuchar model to single frequency users.

International reference ionosphere (IRI) www.irimodel .org

The International Reference Ionosphere, IRI, is an international project (http://iri.gsfc.nasa.gov/) sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). In 1968, a group was established by COSPAR to focus in the International Reference Ionosphere which should contain empirically based tables of monthly median vertical profiles of the main plasma parameters (i.e. electron density, positive ion density, and electron and ion temperatures) for chosen location, time, season and space weather condition. The IRI is the international standard for the climatological specification of ionospheric parameters (see [Bilitza, 1990], [Bilitza et al. 1993a, 1993b]). The code for IRI model is available on http://irimodel.org/.

Several steadily improved editions of the model have been released. For example, the on-line form IRI-2012 (see Figure 15 a,b) is an interface to plot the electron and ion (O+, H+, He+, O2+, NO+) densities, total electron content, electron, ion and neutral temperatures, equatorial vertical ion drift and other parameters. This model is supported by NASA, National Space Data Centre, USA.

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. Additionally parameters given by IRI include the Total Electron Content (TEC; a user can select the starting and ending height of the integral), the occurrence probability for Spread-F and also the F1-region, and the equatorial vertical ion drift (Figure 15 a,b).

Comparing to the Klobuchar model, the IRI also includes the equatorial anomaly. The equatorial anomaly is the area with higher TEC in the band between 20^0 southern and northern latitudes. The IRI uses space weather and geomagnetic indices, i.e. Solar radio flux F10.7 index, Sunspot number R12, and magnetospheric Ap index as inputs.

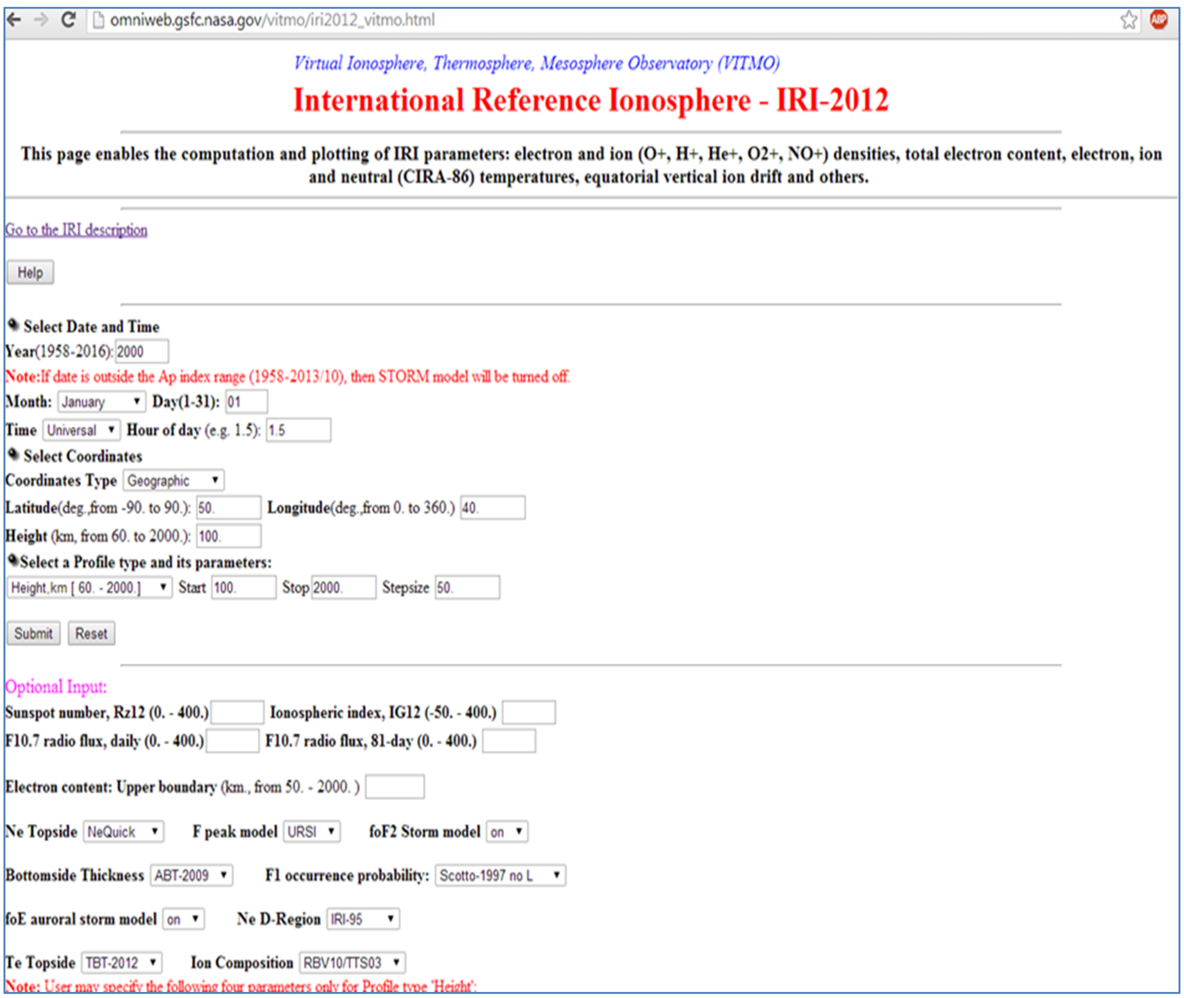


Figure 15a. IRI-2012. Web prediction form of the model.
http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html

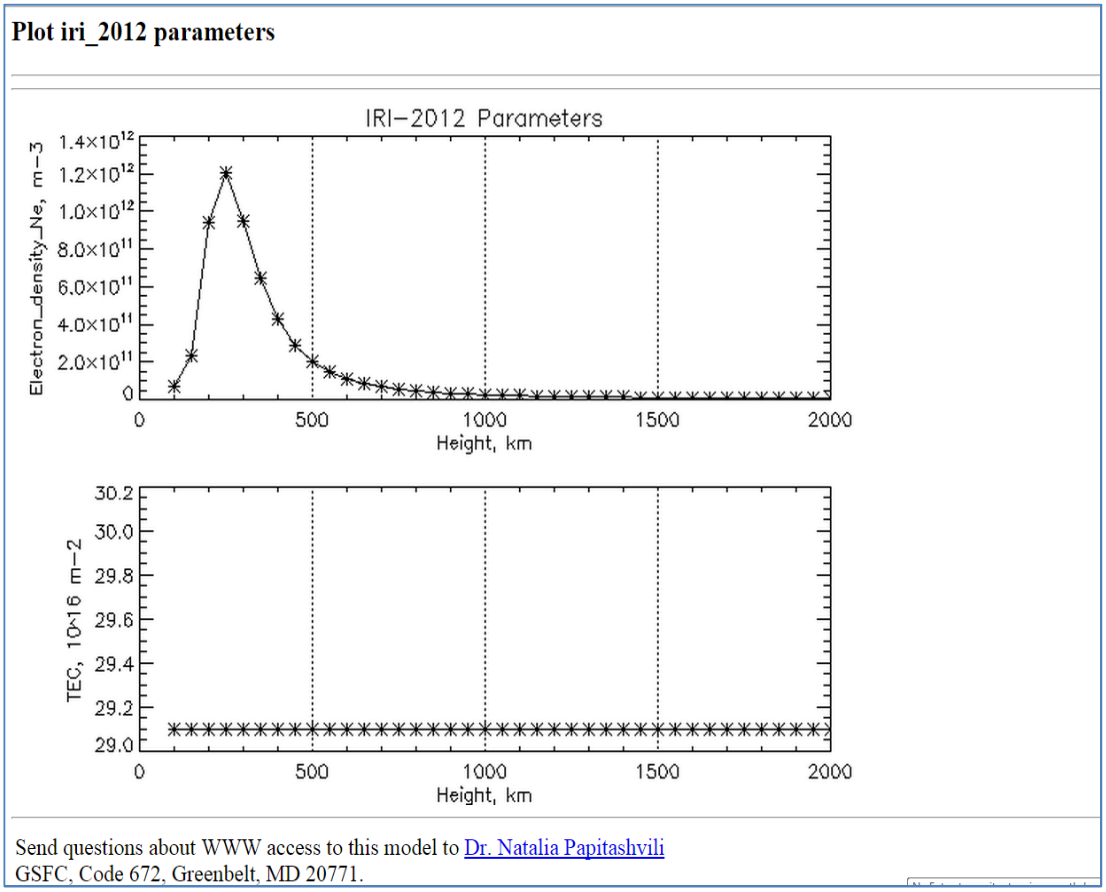


Figure15b. IRI-2012. Plot of the electron density and TEC provided by IRI-2012. Input data: 14 January, 2015, Local time 12h, Location: Ottawa. Picture is produced with use of the IRI-2012 on-line tool http://omniweb.gsfc.nasa.gov/cgi/vitmo/vitmo_model.cgi

NeQuick 3D model (http://t-ict4d.ictp.it/nequick2/nequick-2-web-model)

NeQuick is an ionosphere electron density model developed by Di Giovanni and Radicella in 1990 at the Aeronomy and Radiopropagation Laboratory (now T/ICT4D Laboratory) of the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy, with the collaboration of the Institute for Geophysics, Astrophysics and Meteorology of the University of Graz, Austria. It is available from ICTP site http://t-ict4d.ictp.it/nequick2/nequick-2-web-model. The NeQuick is a quick-run ionospheric electron density model particularly designed for trans-ionospheric radio propagation applications.

This model can provide TEC and electron density profile between any two given points. Input is the monthly-mean solar radio flux. The model is used for assessment analyses in the European Geostationary Navigation Overlay Service (EGNOS) and it has been proposed by European Space Agency (ESA) to aid single-frequency positioning in European GNSS Galileo.

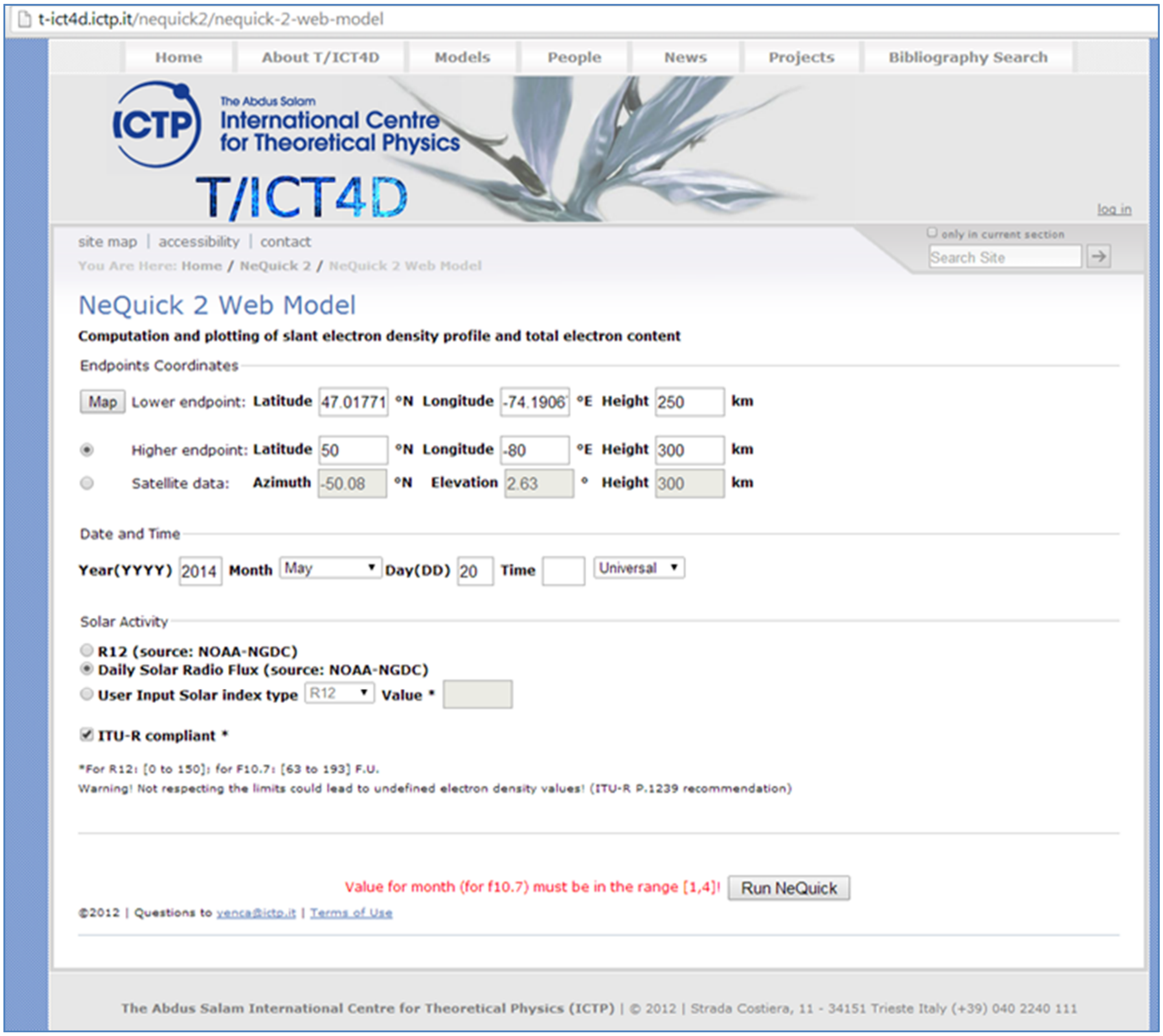


Figure 16. NeQuick model interface. http://t-ict4d.ictp.it/nequick2/nequick-2-web-model .

To describe the electron density of the ionosphere up to the peak of the F2 layer, the NeQuick uses a profile formulation which includes five semi-Epstein layers with modelled thickness parameters. Three profile anchor points are used: the E layer peak, the F1 peak and the F2 peak, that are modelled in terms of the parameters foE, foF1, foF2 and M(3000)F2 (see [Nava et al., 2008] and [Radicella, 2010]). These values can be modelled or experimentally measured. NeQuick is foreseen as the ionospheric correction model for single frequency Galileo users.

The NeQuick provides the electron density for positions in the ionosphere with height, geocentric latitude, geocentric longitude as coordinates on a spherical earth. The model inputs are solar activity (given by monthly-mean sunspot number R12 or 10.7 cm solar radio flux F10.7), season (month) and time (Universal Time UT). The NeQuick package includes routines to evaluate the electron density along any ground-to-satellite straight line ray-path and the corresponding Total Electron Content (TEC) by numerical integration. Screenshot of the NeQuick interface is demonstrated in Figure 16.

Input

- Position (longitude, latitude and height), the epoch (month and UT)
- Solar activity level is introduced by the Zurich sunspot number R12 or by the solar radio flux index F10.7;

Output

- 3D electron density model.

NTCM model

New Neustrelitz TEC (NTCM) model is a part of SWACI project of DLR (German Aerospace centre) supported by the State Government of Mecklenburg-Vorpommern (Germany) http://swaciweb.dlr.de/index.php?id=&L=1 (see e.g. [Jakowski et al., 2010] and [Jakowski et al., 2011]). This model was developed at the Institute of Communications and Navigation, DLR. It is a global TEC model which includes 12 coefficients and may be used for a full solar cycle using F10.7 cm radio flux as input parameter. Regional TEC models were developed for

- European region: NTCM-EU
- Northern polar region NTCM-NP
- Southern polar region NTCM-SP

This climatology model is based on the global TEC data for a half of solar cycle (1998-2007).

Description of the model

It is an empirical model based on 12 parameters which are defined by the least squares fitting procedure. According to a general approach, TEC is a product of five variations

$$TEC = F1 \bullet F2 \bullet F3 \bullet F4 \bullet F5,$$

where
F1 is the diurnal variation with the solar zenith angle;
F2 is the seasonal variation;
F3 is the geomagnetic dependence;
F4 is the latitudinal dependence;
F5 is the solar activity dependence based on F10.7 index.
These variations include 12 coefficients which are determined by least squares fitting procedure.

4.4. Other empirical and physics-based ionosphere models

JPL Global Assimilative Ionosphere Model (JPL GAIM)

GAIM model is developed since 1999 in the University of Southern California and the Jet Propulsion Laboratory, USA (**http://iono.jpl.nasa.gov/gaim/intro.html**, [Mandrake et al., 2005]). This model has been developed since 1999 under the Multidisciplinary University Research Initiatives program sponsored by the U.S. Department of Defence.

Input parameters

- Line-of-sight TEC measurements made form ground-based GPS receivers and space-borne GPS receivers;
- Ionosonde measurements;
- Vertical TEC measured using satellite altimeter radar (such as TOPEX and Jason-1);
- Satellite UV (ultra-violet) limb scan.

Output parameters

3D electron density distribution as a function of time, ionospheric parameters, self-consistent ionospheric drivers (e.g. ionospheric convection).

Description of the model

It is an ionosphere forecast model, global, three-dimensional and time-dependent. It is based on the ionospheric physics, numerically solves for ion and electron densities through the hydrodynamic equations for individual ions.

Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) Model (https://spaceweather.usu.edu/htm/innovations/gaim-global-tec)

The Utah State University team at the Space Weather Center has developed a data assimilation model [Scherliess et al., 2006] of the Earth's upper atmosphere/ionosphere that is similar to the tropospheric weather models run by NOAA. This space weather model, which is called the Global Assimilation of Ionospheric Measurements (USU-GAIM), provides real-time specifications and forecasts for global distributions of upper atmosphere/ionosphere densities, temperatures, and winds https://spaceweather.usu.edu/htm/innovations/gaim-global-tec. Model was developed in the Center for Atmospheric & Space Sciences, Utah State University by R.W. Schunk, L. Scherliess, J.J. Sojka, D.C. Thompson, L. Zhu [Scherliess et al., 2006]. The physics-based model is the Ionosphere Forecast Model (IFM), which is global and covers the E-region, F-region, and topside from 90 to 1400 km. It takes account of five ion species (NO^+, O_2^+, N_2^+, O^+, H^+). The main output of the model is a 3-dimensional electron density distribution at user specified times. The system assimilates bottom-side electron profiles from a variable number of ionosondes, slant TEC from a variable number of ground GPS/TEC stations, and from four satellites. The ionospheric densities obtained from the IFM consist of a background ionospheric density profile on which perturbations are superimposed based on the available data sources and their errors.

Model Input

The user sets the start date (year, day of the year) and the duration of the run in days (currently 1 day up to 7 days). All input parameters and data required by the model are obtained automatically.

Model Output

The primary output from the USU GAIM 2.3 model is a time-dependent 3-dimensional global electron density distribution. The on-line visualization tool allows a view of the full GAIM model output as well as the output obtained from the IFM. VTEC obtained from the leveled, bias corrected, slant TEC values assimilated by the model and GPS stations coordinates are also provided.

Model Description

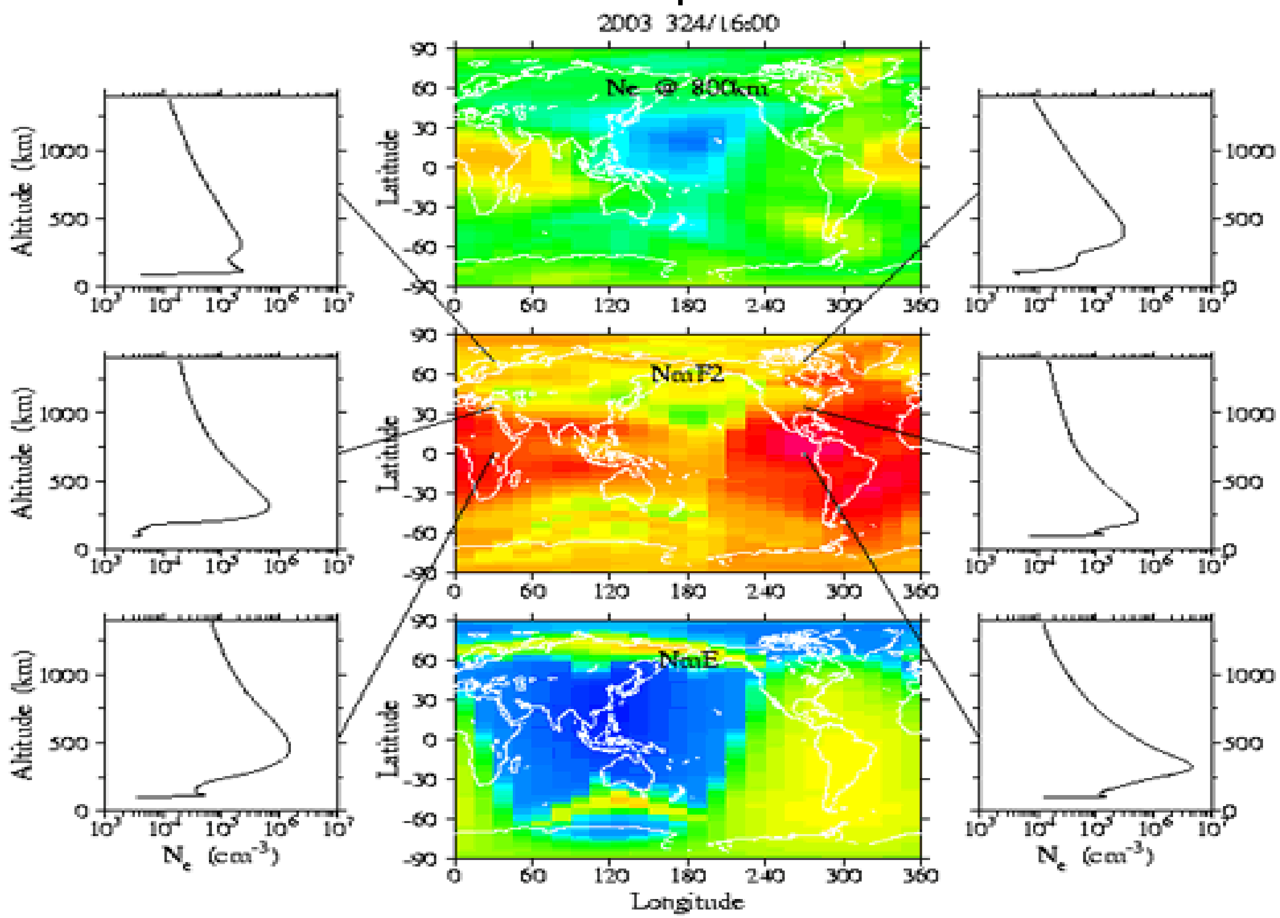


Figure 17. Utah State University Global Assimilation of Ionospheric Measurements (USU-GAIM) Model. Retrieved from https://spaceweather.usu.edu/htm/innovations/gaim-global-tec

Limitations of the model

The current version of the USU-GAIM model (see Figure 17) provides the 3-D ionospheric plasma density distribution over the globe. As a consequence the resolution of the model is rather coarse (15° longitude, 4.66° latitude).The version of the model assimilates GPS/TEC data between ±60° geographic latitude. The current version of the model cannot describe small-scale dynamic structures, such as spread-F and plasma bubbles. The model results are more reliable near data sources.

Space weather impact on the ionosphere is included in the model by using F10.7, average F10.7, daily Ap and eight 3-hour Kp indices. The IFM also uses empirical inputs for the neutral atmosphere and magnetosphere parameters needed by the model, e.g., neutral wind, electric field, auroral precipitation, solar EUV, and resonantly scattered radiation.

4.5. Scintillation services

The ionospheric dynamics is largely driven by coupling processes between the solar wind and the Earth's magnetic field and can be viewed in the ionosphere. These include ionospheric convection, energetic particles precipitations causing aurora and ionospheric irregularities causing rapid fluctuations of radio signal amplitude and phase, called scintillation, which can affect the performance of radio communication and navigation systems. This section is a review of existing services and models for ionospheric scintillation.

CHAIN (Canadian High Arctic Ionospheric Network. Scintillation Activity in the Polar Cap)

CHAIN (see Figure 18) consists of an array of ground-based radio instruments located in the Canadian High Arctic [Jayachndran et al, 2009].

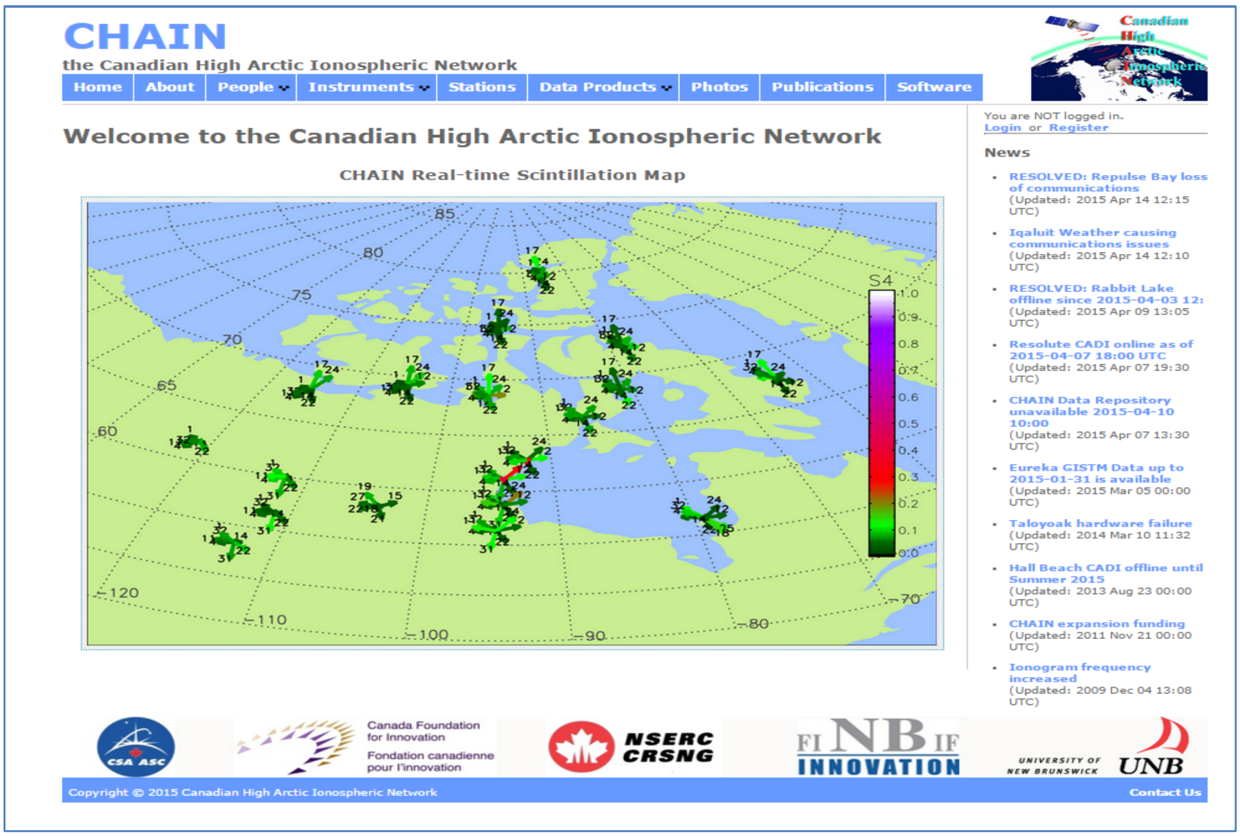


Figure 18. The Canadian High Arctic Ionospheric Network (CHAIN) http://chain.physics.unb.ca/chain/

The original array included 10 high data-rate Global Positioning System ionospheric scintillation and total electron content monitors; 6 Canadian Advanced Digital Ionosondes. Most of these instruments have been sited within the polar cap.

Presently, CHAIN is being augmented to the Expanded Canadian High Arctic Ionoapheric Network (ECHAIN) equipped with Septentrio PolaRxS multi-frequency receivers capable of tracking up to 30 satellites, including GPS, GLONASS and Galileo. The receivers measure phase and amplitude (at a 50-Hz rate) for each satellite being tracked on L1. TEC is computed from combined L1 and L2 pseudorange and carrier phase measurements. The S4 index is obtained as the stadard deviation of the received power normalized by its mean value, and the phase scintillation index σ_φ is the standard deviation of the detrended L1 phase.

On-line service of Australian Government. Bureau of Meteorology. Radio and Space Weather Service (http://www.ips.gov.au)

The on-line service of Australian Government Bureau of Meteorology, Radio and Space Weather Service provides among other services the scintillation monitoring (see Figures 19 and 20).

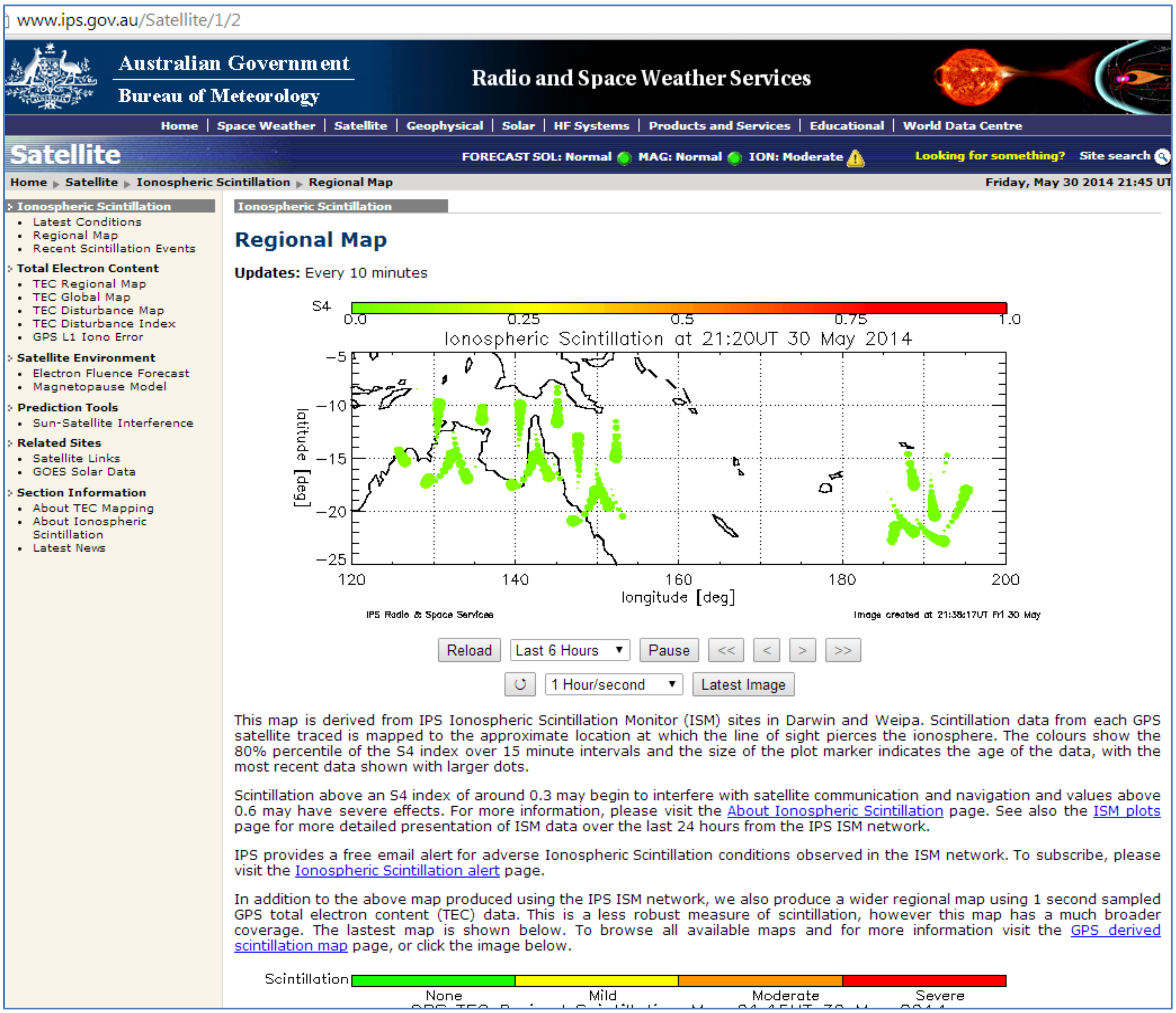


Figure 19. Regional map for Ionospheric Scintillation provided by the Australian Bureau of Meteorology. http://www.ips.gov.au/Satellite/1/2

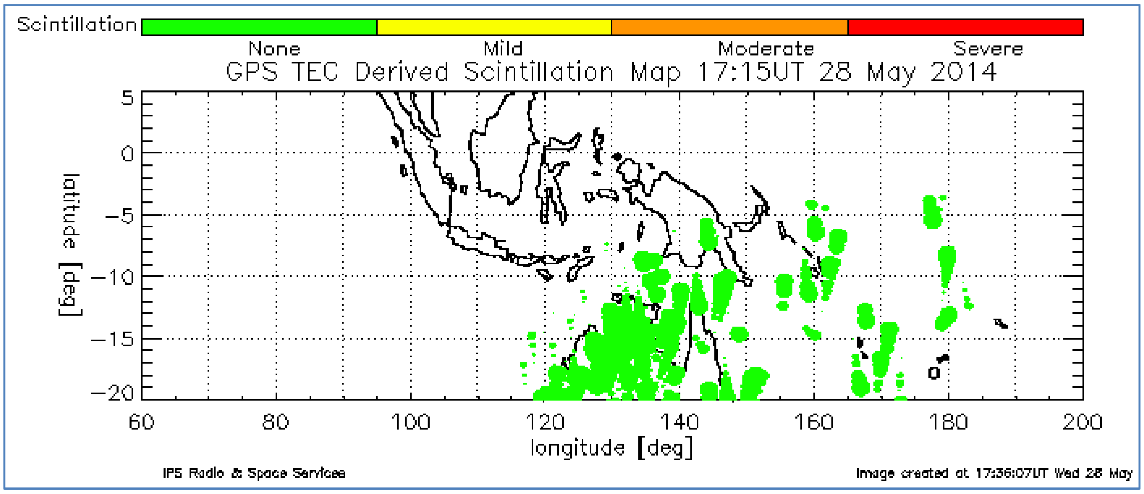


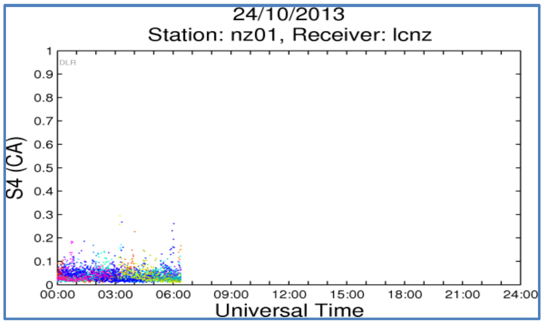
Figure 20.GPS TEC derived Scintillation map. http://www.ips.gov.au/Satellite/1/2

The regional scintillation map on Figure 19 is derived from IPS Ionospheric Scintillation Monitor (ISM) sites in Darwin and Weipa. Scintillation data from each GPS satellite traced is mapped to the approximate location at which the line of sight pierces the ionosphere. The colours show the 80% percentile of the S4 index over 15 minute intervals and the size of the plot marker indicates the age of the data, with the most recent data shown with larger dots. IPS provides a free email alert for adverse Ionospheric Scintillation conditions observed in the ISM network.

In addition to the above map produced using the IPS ISM network, this service also provides a wider regional map (see Figure 20) using 1 second sampled GPS TEC data. This wider region map has smaller accuracy for scintillation indices.

Scintillation service provided by SWACI

Among other products, SWACI (DLR, German Aerospace centre) provides indices for the ionosphere plasma irregularities, such as S4 (see Figure 21 for the screenshot) and σ_φ indices. Both indices are calculated over a one minute interval. The measurements are provided in near real time by DLR' Experimental and Verification Network (EVnet).



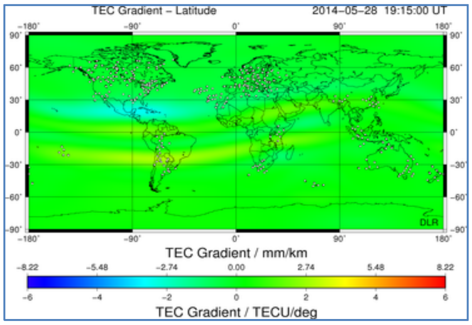


Figure 21. SWACI service, S4 index monitoring. **http://swaciweb.dlr.de/data-and-products/public/scintillation-index/?L=1**

4.6. Scintillation models

WBMOD (Wideband Ionospheric Scintillation model), ScintMod and NWRA scintillation Service http://spawx.nwra.com/ionoscint/wbmod.html

The WBMOD computer model (http://spawx.nwra.com/ionoscint/wbmod.html) is developed by researchers at NorthWest Research Associates, Inc. (NWRA) over the past two decades with support from the US Government. This model can be used to estimate the severity of scintillation effects on a user-specified system and scenario (location, date, time, geophysical conditions). WBMOD consists of an ionosphere model, which provides the global distribution and synoptic behavior of the electron-density irregularities that cause scintillation, and a propagation model that calculates the effects these irregularities will have on a given system (see Figure 22 and 23). SCINTMOD is the upgraded version of the WBMOD for equatorial and high-latitude region [Secan et al., 1995, Secan et al., 1997]. The improvements were made based on analysis of scintillation data over a 4-year period.

This model is a worldwide climatology model of the ionospheric plasma–density irregularities that cause scintillations, coupled to a model for the effect of these irregularities on a transionospheric radio signal. Two scintillation indices are calculate: S4, the standard deviation of intensity normalized by the mean, and σ_{Φ}, the standard deviation of phase.

The electron-density irregularities model, EDIM, is a collection of empirical models which describe geometry, orientation, strength, and motion of the irregularities as a function of location (latitude, longitude), date, time of day, solar activity level (sunspot number, SSN), and geomagnetic activity level (planetary K-index, Kp). These models were developed from analysis of large databases of scintillation measurements collected during the Wideband, HiLat, and Polar BEAR satellite experiments and from the USAF Phillips Laboratory equatorial scintillation monitoring network.

One of the eight parameters used within the model to characterize the electron-density irregularities, is the height-integrated electron-density irregularities strength, denoted CkL which is a measure of the total 'power' in the electron-density irregularities along a vertical path passing through the entire ionosphere. High-latitude CkL model includes variation with sunspot number, geomagnetic index (Kp), latitude, local time, longitude, and season. The new model provides the variation of the full probability distribution function of log(CkL). On Figure 23 the modeled value of CkL (right plot) and the observed values (left plot) are compared.

This high-latitude model includes geomagnetic activity index Kp. It should be noticed though that index Kp is calculated with use of mid-latitude magnetic observatories data and is not enough sensitive to high-latitude geomagnetic activity.

Output:

Estimates of intensity and phase scintillation levels and occurrence statistics for the user-specified scenario.

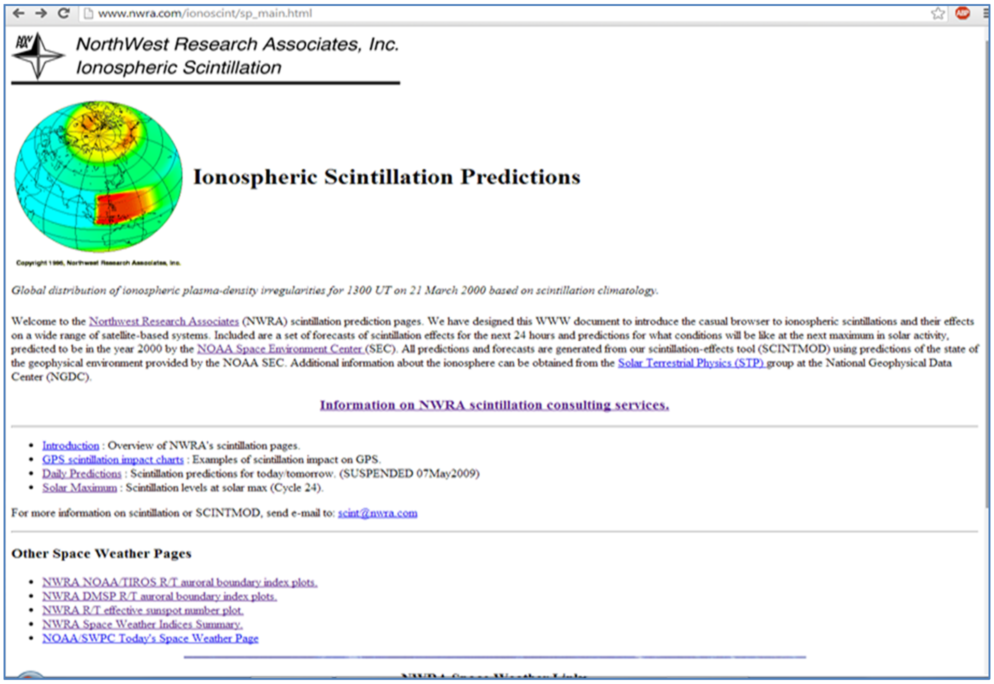


Figure 22. Ionospheric Scintillation Model worked out by at NorthWest Research Associates(NWRA) http://spawx.nwra.com/ionoscint/wbmod.html

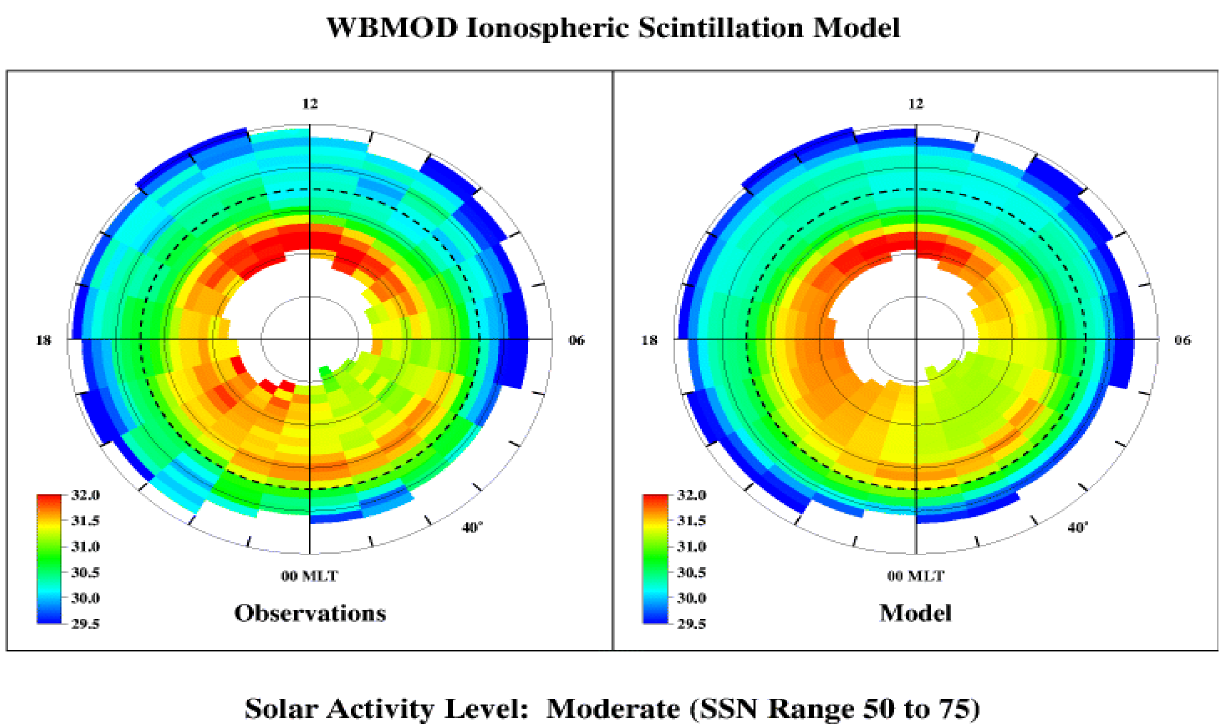


Figure 23. WBMOD Ionospheric scintillation model. Here is a comparison of observed (left plot) and modeled log(CkL) (right plot) at high latitudes.

Global Ionospheric Scintillation Model (GISM)

http://www.ieea.fr/en/softwares/references/gism-ionospheric-model.html

GISM is a climatology model, developed by IEEA (Informatique Electronique Electrotechnique Automatique), France. GISM has been accepted by International Telecommunications Union (ITU) as a reference code for scintillation evaluations. GISM model provides statistical characteristics of the transmitted signals, in particular the scintillation index, the fade durations in the equatorial region [Beniguel, 2011]. Maps of the scintillation index S4 and of the phase standard deviation may also be obtained (Figure 24).

Input parameters

Electron density is calculated using NeQuick model. Inputs of this model are the solar flux number, the year, the day of the year, and the local time. The magnetic parameters are computed based on a Schmidt quasi-normalized spherical harmonic model of the geomagnetic field. These are the declination, the inclination, the vertical intensity and the components of the field.

Scintillation outputs

It computes the ionospheric effects on a signal transmitted between two user defined points. The model provides intensity and phase scintillation indices (S4 and σ_φ), range and phase RMS errors, and angle of arrival fluctuations, coherence lengths, and spectrum of scintillation.

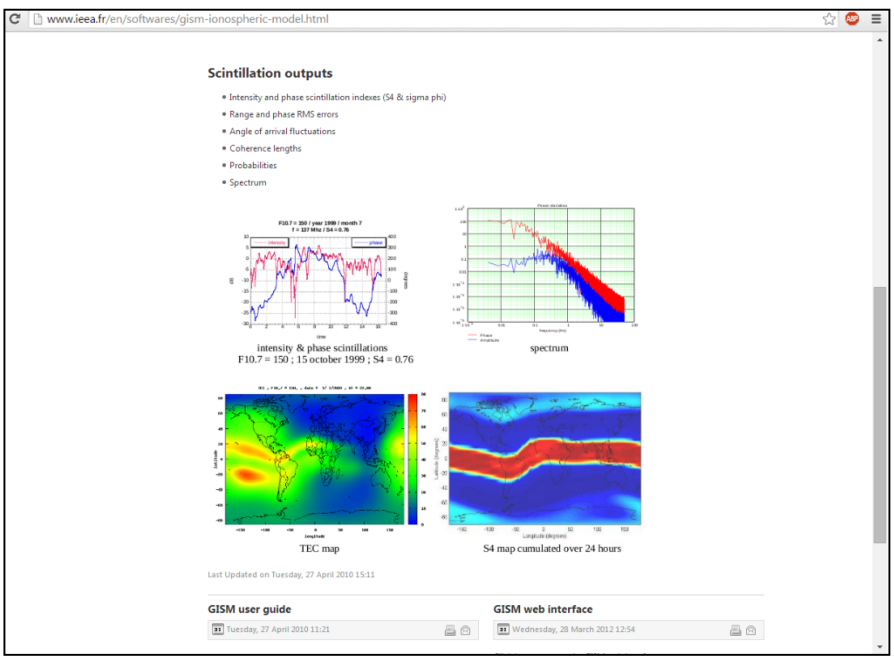


Figure 24. Screenshot of GISM model. http://www.ieea.fr/en/softwares/gism-ionospheric-model.html

4.7. Projects in progress

SWIPPA (Space Weather Impact on Precise Positioning Applications) project

SWIPPA is a pilot project supported by the German Aerospace Centre (DLR) and the European Space Agency (ESA) [Jakowski et al., 2005]. The project aims at establishing, operating, and evaluating a specific space-weather monitoring service than can possibly lead to current positioning applications based on GNSS. Their service aims to provide GNSS users with essential expert information delivered in the form of

- maps of TEC values;

- TEC spatial and temporal gradient;

- Alerts for ongoing/oncoming ionosphere disturbances due to space weather.

SWIPPA operational service is intended to help the GNSS users to mitigate space weather impact on precise positioning applications.

UPC (Technical University of Catalonia) ionospheric VTEC prediction model (test mode)

VTEC model is under developing by Technical University of Catalonia. The UPC Final/rapid IGS products are the input data for the prediction model. These products contain 13 global VTEC at a temporal resolution of 2 hours. Each VTEC map is a 2-dimensional with spatial grid points every 2.5/5 ^{o} in the latitude/longitude range assuming a thin shell layer model of the ionosphere at a height of 450 km. The scheme of this model is on Figure 25.

Input: VTEC maps;

Output: predicted VTEC maps;

Diagram of the model:

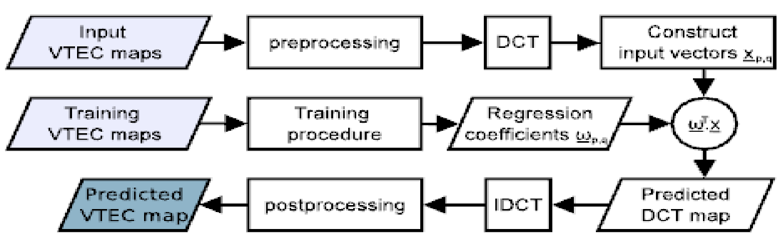


Figure 25. Diagram showing the main steps of the UPC prediction approach. DCT is the Discrete Cosine Transform, IDCT is the Inverse cosine transform, training procedure is based on a neural network [Garcia-Rigo et al., 2011]

Developers of this model consider an opportunity to include space weather effects in the model. But for the moment space weather effects are not included in the model, and the authors consider a possibility to include F10.7 Solar Flux, the sunspot number, Kp index of geomagnetic activity, and/or ionospheric parameters

AFFECTS (Advanced Forecast for Ensuring Communications through Space) project

To forecast ionospheric storms several hours ahead, the storm development from the sun via magnetosphere and thermosphere must be tracked continuously. This task is trying to be solved on the FP7 project AFFECTS (http://www.affects-fp7.eu) by the team of several partners including Germany, NOAA (USA), Norway, University of Tromso, DLR, Royal observatory of elgium, Ukrainen Space Research Institute. AFFECTS is planning to provide advanced early space weather warning to protect communication systems.

4.8. Proposed methods for forecasting of high-latitude GPS phase scintillation (NRCan)

- Analyses of GPS phase rate variations in response to geomagnetic field perturbations was made in NRCan and is described in (Ghoddousi-Fard et al., 2015), and (Nikitina et al., 2015). The geomagnetic hourly ranges were correlated with scintillation indices for the 2013 data for three locations in the auroral zone of Canada. It was shown that GPS phase rate responds to the geomagnetic field variations and could be used for developing proxy measures for scintillation occurrence.

- Climatology of GPS phase scintillation at high latitudes shows that the scintillation predominantly occurring in the ionospheric footprint of the cusp and the auroral zone. The GPS stations in Cambridge Bay and Taloyoak in Canada are used to construct time series of scintillations occurrence that is correlated with solar wind velocity. It is shown that there is a significant increase in phase scintillation just after the arrival of high-speed solar wind CIRs (corotating interaction regions) and ICMEs (interplanetary coronal mass ejections). A probabilistic forecasting method focusing on the scintillation in the cusp is proposed [Prikryl et al. 2013].

The summary of all the systems and models considered in chapter 4 are included in Tables 1-3.

Table 1. Summary of TEC systems and models

TEC	Monitoring and forecast possibility	Space weather parameters
Augmentation system WAAS (USA) http://www.faa.gov/about/office_org/headquarters_offices/ato/service_units/techops/navservices/gnss/waas	Correction service, Real time monitoring, no forecast	N/A
Augmentation systems EGNOS (ESA) http://www.essp-sas.eu/introducing_egnos	Correction service, Real time monitoring, no forecast	N/A
Monitoring services (real time < 5 min delay)		
CODE http://aiuws.unibe.ch/ionosphere/	Monitoring, 1-2 days forecast	N/A
GAIM (JPL, US) http://iono.jpl.nasa.gov/latest_rti_global.html	Real-time monitoring	N/A
SWACI (DLR) http://swaciweb.dlr.de/index.php?id=&L=1	Real time monitoring with local extrapolation, European and global, 1 hour forecast	N/A
UPC (Spain) [Garcia-Rigo et al., 2011]	Real time monitoring	N/A
EMR (Canada) [Ghoddousi-Fard et al., 2011]	Real time monitoring, local and global TEC map	N/A
NOAA SWPC (US) http://www.swpc.noaa.gov/	Real time monitoring, no forecast, does not cover Canada	N/A
NRT ROB (Belgium) http://gnss.be/	Real time monitoring, local TEC map	N/A
IPS (Australia) http://www.ips.gov.au	Real time monitoring	N/A
Climatology and Physics Based Models		
Klobuchar model [Klobuchar, 1991]	Ionosphere empirical model used for GPS positioning correction	N/A

IRI (international) www.irimodel.org	Ionosphere model based on climatology covered period 1958-2016	Sunspot number R12, solar radio flux F10.7
NeQuick (Austria, Italy) http://t-ict4d.ictp.it/nequick2/nequick-2-web-model	Ionosphere model based on climatology,	Input: solar activity indices, Zurich sunspot number R12, solar radio flux index F10.7
NTCM http://swaciweb.dlr.de	Ionosphere empirical model	Solar radio flux F10.7
GAIM (USU, US) https://spaceweather.usu.edu/htm/innovations/gaim-global-tec	Full physics time-dependent model including several empirical models	Solar radio flux F10.7, Ap and Kp indices

Table 2. Summary of scintillation monitoring services and models

Scintillation	Monitoring services and climatology models	Space weather parameters
CHAIN (Canada) http://chain.physics.unb.ca/chain/	Scintillation monitoring	N/A
WBMOD (USA) http://spawx.nwra.com/ionoscint/wbmod.html	Scintillation monitoring (output S4, σ_φ), Climatology. Forecast is based on the scintillation occurrence statistics for the user-specified scenario: location, SSN, Kp.	Sunspot number, Kp index
IPS (Australia) http://www.ips.gov.au	Real time monitoring and scintillation alert based on the probability of scintillations based on the current ionosphere monitoring	N/A
GISM (France) http://www.ieea.fr/en/softwares/references/gism-ionospheric-model.html	Scintillation climatology	Solar radio flux index F10.7
DLR/ESA SWACI (ESA) http://swaciweb.dlr.de	Scintillation monitoring	N/A

Table 3. Systems and projects under developing

Projects	
SWIPPA [Jakowski et al., 2005]	Forecast based on space weather parameters is discussed
UPC project [Garcia-Rigo et al., 2011]	Forecast based on space weather parameters is discussed
AFFECTS http://www.affects-fp7.eu	Forecast based on space weather parameters is discussed

Conclusion

The forecasting of ionosphere disturbances may assist users on reliability and availability of navigation and communication systems. This report reviewed the existing monitoring services and correction models of the ionosphere. Some research is included to estimate the potential of the ionosphere service and models to provide a forecast of the ionospheric conditions. The motivation for this survey and review was to investigate how to monitor and forecast the ionospheric disturbances caused by space weather variability.

Two characteristics for assessment of the ionosphere conditions are used for assessment of the GNSS performance. These are the total electron content (TEC) and radio wave phase and amplitude scintillations. The existing services include monitoring of the ionosphere and providing of global and local TEC maps and/or scintillation activity. Some of these services can provide as well short-term (from 1 hour to 1-2 days) forecast.

The correction models of the ionosphere are climatology models which are based on many years of ionosphere data. These models include diurnal and seasonal variation and can be used to get the ionosphere parameters for the moment defined by user.

Some of the models accounted for variation in solar activity. The long-term variation of solar activity is usually represented as 27-days variations due to the rotation of the Sun or 11 years variations due to varying solar activity. Some models include input parameters for solar activity, such as sun spot numbers (SSN or R12) or/and radio flux F 10.7 flux. Geomagnetic activity is usually represented by planetary geomagnetic indices Kp and Ap.

There are some attempts to work out full-physics ionosphere models which are still under development. In some models like USU GAIM model the full-physics approach is combined with empirical models.

Based on the review of the existing models we can conclude that

- some models include the long-term variation of the solar activity (like 27 –days variation and 11 years solar cycle variation);
- some empirical statistical models include the solar activity using Sunspot number and F10.7;
- the authors of some TEC models discuss the possibility of including the geomagnetic indices into ionospheric forecast;
- probabilistic models of scintillation could provide an estimation of the probability of scintillation in the ionosphere based on anticipated/forecasted ionospheric conditions;
- the existing TEC models that include diurnal and seasonal time variation cannot describe disturbances of the ionosphere and their impact on the GPS systems during space weather events because they are based on typical values assumed in climatology.

The problem of the assessment of space weather influence on GNSS performance is not solved, but there are some approaches which look promising and can be used in future models.

References

Beniguel, Ya., P. Hamel, 2011. A global ionosphere scintillation propagation model for equatorial regions. J. *Space Weather Space Clim., 1*, A04, doi: 10.1051/swsc/2011004.

Bilitza, D. (ed.), 1990. International Reference Ionosphere 1990, NSSDC 90-22, Greenbelt, Maryland.

Bilitza, D., K. Rawer, L. Bossy, and T. Gulyaeva, 1993. International Reference Ionosphere - Past, Present, Future: I. Electron Density, *Adv. Space Res.*, *13*, #3, 3-13.

Bilitza, D., K. Rawer, L. Bossy, and T. Gulyaeva, 1993. International Reference Ionosphere - Past, Present, Future: II. Plasma Temperatures, Ion Composition, and Ion Drift, *Adv. Space Res.*, *13*, #3, 15-23.

Bilitza, D., and Reinisch, B., 2008. International Reference Ionosphere 2007: Improvements and new parameters, *Adv. Space Res.*, *42*, #4, 599-609, doi:10.1016/j.asr.2007.07.048.

Garcia-Rigo, A., E. Monte, M. Hernandez-Pajarez, J. Juan, J. Sanz, A. Aragon-Angel, D. Salazar, 2011. Global prediction of the vertical total electron content of the ionosphere based on GPS data, *Radio Science*, *46*, doi :10.1029/2010RS004643.

Ghoddousi-Fard R., 2014. GPS ionospheric mapping at Natural Resources Canada. Poster presentation given at IGS Workshop 2014, June 23-27, 2014, Pasadena, California, USA.

Ghoddousi-Fard, R., P. Heroux, D. Danskin, D. Boteler, 2011. Developing a GPS TEC mapping over Canada. *Space weather*, *9*, S06D11, doi:10.1029/2010SW000621.

Ghoddousi-Fard, R., L. Nikitina, D. Danskin, P. Prikryl, 2015. Analysis of GPS phase rate variations in response to geomagnetic field perturbations over the Canadian auroral region, *Adv. Space Res*., *55*, 5, p.1372-1381.

Global positioning system wide area augmentation system (WAAS) performance standard, 2008. 1st Edition. 31 October 2008. http://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

Haines, G.V., Spherical cap harmonic analysis, 1985*. J. Geophys. Res*, *90*, 2583-2591, doi:10.1029/2002GL015067.

Hernández-Pajares, M., J. M. Juan, J. Sanz, R. Orus, A. Garcia-Rigo, J. Feltens, A. Komjathy, S. C. Schaer, A. Krankowski, 2009. The IGS VTEC maps: a reliable source of ionosphere information since 1998. *J. Geod.*, *83*, 263-275.

IGS(2015), NRCan Analysis Center Technical Report 2014. International GNSS Service Technical Report 2014, IGS Central Bureau, editors: Y. Jean and R. Dach, Astronomical Institute, University of Bern, May 2015.

IGS(2014), NRCan Analysis Center Report 2013. International GNSS Service Technical Report 2013, IGS Central Bureau, editors: R. Dach, and Y. Jean, Astronomical Institute, University of Bern, May 2014.

IGS(2013), NRCan Analysis Center Report for 2012. International GNSS Service Technical Report 2012, editors: R. Dach, and Y. Jean, Astronomical Institute, University of Bern, April 2013.

IGS(2012) NRCan Analysis Center Report for 2005-2011. International GNSS Service Technical Report 2011, editors: M. Meindel, R. Dach, and Y. Jean, Astronomical Institute, University of Bern, July 2012.

Jayachandran, P. T., R. B. Langley, J. W. MacDougall, S. C. Mushini, D. Pokhotelov, A. M. Hamza, I. R. Mann, D. K. Milling, Z. C. Kale, R. Chadwick, T. Kelly, D. W. Danskin, and C. S. Carrano, 2009. The Canadian high arctic ionospheric network (CHAIN), *Radio Sci.*, *44*, RS0A03, doi:10.1029/2008RS004046.

Jakowski, N., 1996. TEC Monitoring by using satellite positioning systems. *Modern ionospheric science*, (Eds. H.Kohl, R.Ruster, K.Schlegel), EGS, Katlenburg-Lindau, ProduServ GmbH Verlagsservice, Berlin, pp 371-390.

Jakowski, N., M.M. Hoque, C. Mayer, 2011. A new global TEC model for estimating transionospheric radio wave propagation errors. *J. Geod.*, *85* (12), 965-974. DOI: 10.1007/s00190-011-0455-1.

Jakowski, N., C. Mayer, K.D. Missling, H. Barkmann, C. Borries, M. Tegler, and V. Wilken, 2010. Products and services provided by the 'Space Weather Application Center – Ionosphere' (SWACI), COST ES0803 2nd Workshop, 22-23 March 2010, Paris.

Jakowski, N., S. Stankov, D. Klaehn, 2005. Operational space weather service for GNSS precise positioning, *Ann. Geophys.*, *23* (9), 3071-3079.

Klobuchar, J.A., 1991. Ionospheric effects on GPS. *GPS World*. April 1991.

Komjathty, A., A.J. Mannucci, L. Sparks, A. Coster, 2005. The ionosphere impact of the October 2003 storm event on WAAS. *GPS Solutions*, *9*, 41-50.

Liu, J., R. Chen, Z. Wang, and H. Zhang, 2011. Spherical cap harmonic model for mapping and predicting regional TEC. *GPS solutions*, *15*, 109-119, doi: 10.1007/s10291-010-1274-8.

Liu, J., R. Chen, J. An, Z. Wang, J. Hyyppa, 2013. Spherical cap harmonic analysis of the Arctic ionospheric TEC for one solar cycle. *J. Geophys. Res.: Space Physics*, *119*, 601-619, doi:10.1002/2013/JA019501.

Mandrake, L., B. Wilson, C. Wang, G. Hajj, A. Mannucci, and X. Pi (2005), A performance evaluation of the operational Jet Propulsion Laboratory/University of Southern California Global Assimilation Ionospheric Model (JPL/USC GAIM), *J. Geophys. Res.*, *110*, A12306, doi:10.1029/2005JA011170.

Mannucci, A. J., B. T. Tsurutani, M. A. Abdu, W. D. Gonzalez, A. Komjathy, E. Echer, B. A. Iijima, G. Crowley, and D. Anderson, 2008. Superposed epoch analysis of the dayside ionospheric response to four intense geomagnetic storms, *J. Geophys. Res.*, *113*, A00A02, doi:10.1029/2007JA012732.

Nava, B., P. Coïsson, S.M. Radicella, 2008. A new version of the NeQuick ionosphere electron density model. *JASTP*, *70*(15), 1856–1862.

Nikitina, L., D. Danskin, R. Ghoddousi-Fard, P. Prikryl, 2015. Analyses of the geomagnetic variations and GPS scintillation over the Canadian auroral zone. *Proceedings of Ionosphere effects symposium*, Alexandria, VA, USA, May 12-14, 2015.

Otsuki, S., M. Kamimuram, M. Ohashi, Y. Kubo, S. Sugimoto, 2011. Local models for ionospheric VTEC estimation based on GR models and spherical cap harmonic analysis. *Journal of Aeronautics, Astronautics and Aviation*, Series A, *43*, N1, pp.1-8

Prikryl, P., P.T. Jayachndran, S.C. Mushini, I.G. Richardson, 2012. Towards the probabilistic forecasting of high-latitude GPS phase scintillation. *Space Weather*, *10*, S08005, doi:10.1029/2012SW000800.

Prikryl, P., R. Ghoddousi-Fard, B.S.R. Kunduri, E.G. Thomas, A.J. Coster, P.T. Jayachandran, E. Spanswick, D.W. Danskin, 2013. GPS phase scintillation and proxy index at high latitudes during a moderate geomagnetic storm. *Ann. Geophys.*, *31*, 805-816, doi:10.5194/angeo-31-805-2013.

Radicella, S., 2010. The NeQuick model genesis, uses and evolution. *Annals Geophys*., *52*(3-4).

Secan, J.A., R.M. Bussey, E.J. Fremow, Sa. Basu, 1995. An improved model of equatorial scintillation, *Radio Science*, *30*, N3, 607-617.

Secan, J.A., R.M. Bussey, E.J. Fremow, Sa. Basu, 1997. High-latitude upgrade to the Wideband ionospheric scintillation model. *Radio Science*, *32*, 4, 1567-1574.

Service assessment. Intense space weather storms October 19 – November 07, 2003. U.S.Department of commerce. National Oceanic and Atmospheric Administration. National Weather Service. Silver Spring. Maryland, 2004.

Scherliess, L., R.W. Schunk, J.J. Sojka, D.C. Thompson, and L. Zhu, 2006. The USU GAIM Gauss-Markov Kalman Filter Model of the Ionosphere: Model Description and Validation, *J. Geophys. Res.*, *111*, A11315, 12p, doi:10.1029/2006JA011712