SPECTRE (www.noveltis.fr/spectre): a web Service for Ionospheric Products

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ABSTRACT

The dense GPS networks developed for geodesic applications appear to be very efficient ionospheric sensors because of interaction between plasma and electromagnetic waves. Indeed, the dual frequency receivers provide data from which the Slant Total Electron Content (STEC) can be easily extracted to compute Vertical Total Electron Content (VTEC) maps. The SPECTRE project, Service and Products for ionospheric Electron Content and Tropospheric Refractivity over Europe, is currently an operational service providing VTEC maps with time and space high resolution after 3 days time delay (http://www.noveltis.fr/spectre and http://ganymede.ipgp.jussieu.fr/spectre). This project is a part of SWENET, SpaceWeather European Network, initiated by the European Space Agency. TEC maps produced by SPECTRE are validated by comparing TEC estimations of several instruments like ionosondes, altimeter satellites and Global Ionosphere Maps (GIMs) supported by International GNSS Service (IGS). Moreover, we demonstrate that Regional Ionosphere Maps (RIMs) produced by SPECTRE provide a better resolution of small scale variations of the ionosphere than GIMs from IGS. Thus, The SPECTRE data products are useful for many applications which are discussed in term of interest for the scientific community with a special focus on spaceweather and transient ionospheric perturbations related to natural hazards (earthquakes, tsunamis). Finally, in the frame of the Galileo's advent, we present the resolution improvements of TEC maps by using synthetic orbits of Galileo satellites.

INTRODUCTION

Ionosphere is a plasma layer surrounding the Earth which disturbs satellite communications. Indeed, electromagnetic waves propagating through ionospheric layers are affected by time delays depending to their carrier frequencies and electron density. Such perturbations of propagation can be extracted from multi-frequencies ground to satellite communications and can be exploited to provide dedicated correction for mono-frequency systems or can be used for scientific applications. In this latter framework, networks of bi-frequencies GPS receivers have demonstrated their capabilities to monitor the state of the ionosphere providing maps of Vertical Total Electron Content (VTEC) [1]. Dense GPS networks and routine survey gave the opportunity to develop tomographic algorithms and distribution services of VTEC maps like the service SPECTRE, Service Products for ionospheric Electron Content and Troposphere Refractivity over Europe.

SERVICE DESCRIPTION

SPECTRE service computes VTEC maps with space and time resolution of 2.5°-by-2.5° and 30 seconds over Europe using GPS data of the European dense GPS network EUREF and distributes TEC products with a three day delay via the web interface http:/noveltis.fr/spectre. This service was set up with funding from European Space Agency (ESA), French space agency (CNES) and French ministry of Research.

Tomographic Algorithm

The GPS data produced by bi-frequencies receivers and used by SPECTRE algorithm are respectively for both frequencies f_1 (1575.42 MHz) and f_2 (1227.6 MHz) the pseudo-ranges P_1 and P_2, and the phase measurements L_1 and L_2.

By combining these data one can compute the slant path delay due to electron content of the ionosphere. The Slant Total Electron Content (STEC), expressed in TEC units, for a receiver-satellite couple at epoch t along ray i is given by the ionospheric combination:

$$d_i(t) = K\left(L_{gf}(t) - \left\langle L_{gf}(t) + P_{gf}(t)\right\rangle\right) \quad (1)$$

with,

$$L_{gf} = \lambda_1 L_1 - \lambda_2 L_2\,, \quad (2)$$

$$P_{gf} = P_1 - P_2\,, \quad (3)$$

$$K = \frac{8\pi^2 m_e \varepsilon_0}{e^2} \frac{f_1^{\ 2} f_2^{\ 2}}{\left(f_1^{\ 2} - f_2^{\ 2}\right)}, \quad (4)$$

where λ_1, λ_2 are the wavelength for f_1 and f_2, e is the charge of one electron, m_e is the mass of one electron and ε_0 is the vacuum permittivity. The coefficient K is derived from the second-order approximation of the refractive index of the ionosphere [3]. All non-dispersive effects on pseudo-range and phase measurements are avoided by the geometry-free combinations (2) and (3). The averaged sum of these combinations is subtracted to (2) in order to resolve phase ambiguity. Equation (1) is modelled by the sum of STEC and electronic biases affecting GPS satellites, Transmitter Group Delay (TGD), and GPS receivers, Inter-Frequencies Bias (IFB). These biases are assumed constant [2]. The Slant TEC is redressed to Vertical TEC using the thin shell assumption [1] with maximum of ionization at 350 km.

$$d_i(t) = STEC(t) + IFB + TGD \quad (5)$$

$$d_i(t) = \frac{VTEC(t)}{f_{ob}(t)} + IFB + TGD \quad (6)$$

where f_{ob} is the obliquity factor defined by the thin shell assumption. The intersection of ray i and the thin shell at 350 km give the position of the observation d_i that is usually call the Ionospheric Piercing Point (IPP). In order to assess VTEC maps over GPS network the IPP are interpolated by nearest method on a regular grid. Thus, system of equations (7) is formed and solved by extended Kalman algorithm [4]. Solution provides conjointly an estimation of VTEC on a regular grid and an estimation of the electronic biases IFB and TGD for each receiver and satellite by solving

$$d_{1\ldots N} = G.\begin{bmatrix} VTEC_{1\ldots P} \\ IFB_{1\ldots R} \\ TGD_{1\ldots S} \end{bmatrix} \quad (7)$$

where N is the number of GPS observations, P is the number of grid points, R is the number of GPS receivers, S is the number of GPS satellites, and G is the interpolation operator.

TEC Products and Distribution

SPECTRE service distributes several types of TEC products, daily raw STEC data and daily VTEC maps, over European area from -15° to 40° of longitudes and 30° to 70° of latitudes. The daily raw STEC data are sampled at 30 seconds and contain ionospheric combination d, positions of IPP, positions of satellites, list of receivers, obliquity factor f_{ob}, estimations and uncertainties of IFB and TGD. The daily VTEC maps have a resolution of 2.5°-by-2.5°, are sampled at 30 seconds, 15 minutes and 1 hour, and contain estimated VTEC at each grid point, relative uncertainty of VTEC, positions of grid points, lists of receivers and satellites, and matrix of the observation pairs between satellites and receivers.

SPECTRE is an operational service that has been opened since April, 01rst, 2004. Continuity of the distribution of TEC products is ensured by a mirror ftp server and a second wed interface (http://ganymede.ipgp.jussieu.fr/spectre).

EVUALUATION

Uncertainty of VTEC estimation provided in daily VTEC maps are extracted from the least means square solution of Kalman algorithm. Relative uncertainties of SPECTRE VTEC maps are below 0.4%. This value is very low and must not be used as the accuracy of the VTEC maps. The best method to assess pertinence and precision of VTEC maps is to compare with other VTEC maps like Global Ionosphere Maps (GIMs), ionosonde measurements and VTEC measurements of bi-frequencies satellite altimeters. Thus, we realized these comparisons for a time period of 7 month, from June 2004 to December 2004. We compare Regional Ionosphere Maps (RIMs) produced by SPECTRE and GIMs produced by Jet Propulsion Laboratory (JPL), Centre of Orbit Determination for Europe (CODE), University Polytechnica of Catalunya (UPC) and the combined solution of International GNSS Service (IGS) which are available on ftp server of IGS (ftp://igscb.jpl.nasa.gov/).

Altimeter Satellites

Bi-frequencies altimeter satellites have capability to monitor VTEC under their positions by combining measurements of each frequency. Therefore, these instruments can provide references of VTEC but only over sea surface type due to technical limitations. So, we compared VTEC estimation of SPECTRE and GIMs to VTEC measurements of altimeter satellites ENVISAT, Jason and Topex. VTEC measurements are data of bi-frequencies altimeters and are extracted from Geophysical Data Raw format A (GDR-A). Fig 1., Fig. 2. and Fig. 3 present histograms of residues between VTEC maps and VTEC measurements of altimeter satellites. Median, mean and standard deviation of residues were computed and are shown on these figures. In the following, mean of residues is call bias of estimation. So, we can note that CODE, JPL and SPECTRE present the smallest biases of estimation for, respectively, altimeter satellite ENVISAT, Jason and Topex. We recall that these satellites orbit at 800 km (ENVISAT) and 1,336 km (Jason,Topex) and GPS satellites orbit at 20,200 km. Therefore, biases of estimation should be positive because it represents electron content of the plasmasphere. This fact is not always respected. The occurrences of negative biases of estimation indicate that VTEC is under estimated by GIMs and/or VTEC is over estimated by altimeter satellites.

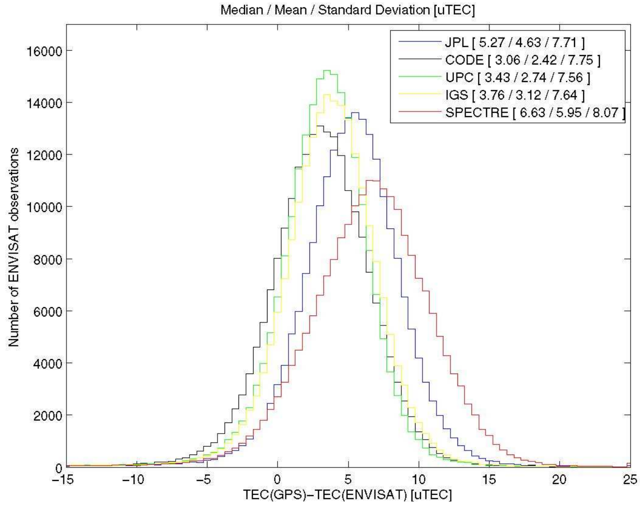

Fig. 1. Histogram of residues between VTEC maps of JPL, CODE, UPC, IGS, SPECTRE, and the altimeter satellite ENVISAT for time period from June 2004 to December 2004. Statistics are in the figure's title.

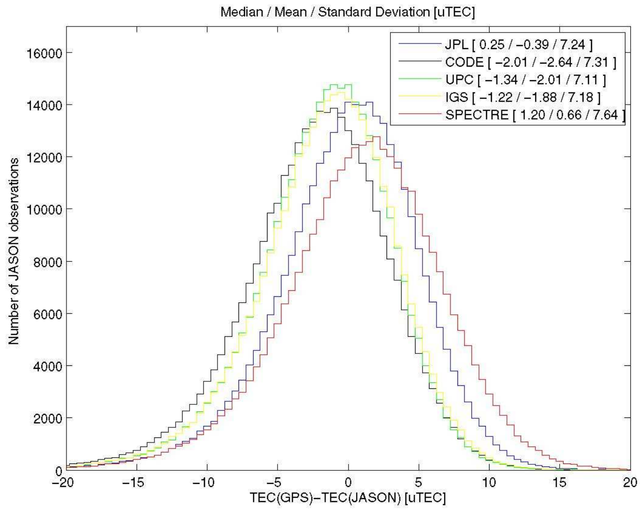

Fig. 2. Histogram of residues between VTEC maps of JPL, CODE, UPC, IGS, SPECTRE, and the altimeter satellite Jason for time period from June 2004 to December 2004. Statistics are in the figure's title.

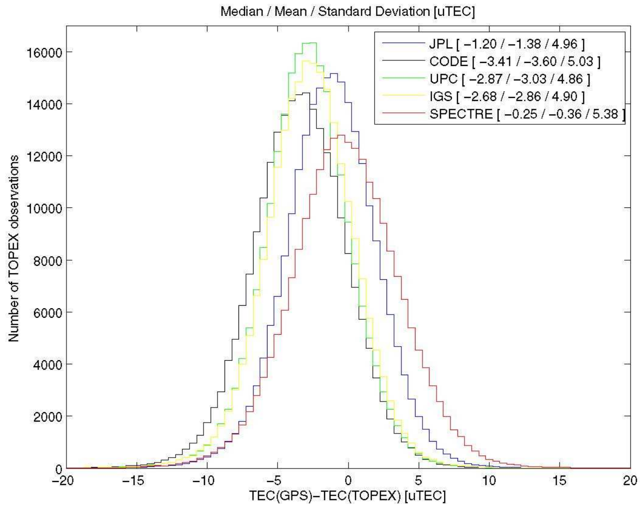

Fig. 3. Histogram of residues between VTEC maps of JPL, CODE, UPC, IGS, SPECTRE, and the altimeter satellite Topex for time period from June 2004 to December 2004. Statistics are in the figure's title.

By comparing Jason and Topex results we can note that difference between biases of estimation equal 1 TEC unit for each GIM and SPECTRE. Thus, the existence of instrumental biases for Jason and Topex is proved and was fisrt time demonstrated in CalVal reports [5]. Here, the most interesting result is the difference of biases of estimation between VTEC maps for each satellite. Results show that VTEC maps computed from GPS data under-estimate VTEC. Moreover, we can sort VTEC maps following increasing under-estimation: SPECTRE, JPL, IGS, UPC, CODE. This list is respected for each altimeter satellite. Therefore, it demonstrates that VTEC maps produced by SPECTRE present the higher VTEC values and seem to be the most pertinent VTEC estimations.

Ionosonde

Ionosondes do not measure VTEC but the bottom side electron density profiles of ionosphere. However, it is possible to estimate VTEC from ionosondes' measurements of altitude and electron density of F2 peak [6][7]. As proposed in [8] we convert F2 peak features to VTEC by

$$VTEC = 1.24\times 10^{13}\left(foF2\right)^{2}\tau \qquad (8)$$

where *foF2* is the electron density of F2 peak and τ is the slab thickness of ionosphere. For this study the slab thickness was set to 400 km. Fig. 4. maps the seven ionosondes that were used to realise comparisons. We can note that positions of ionosondes are stretched from 37° to 70° of latitude and therefore provide measurements at mid and high latitudes.

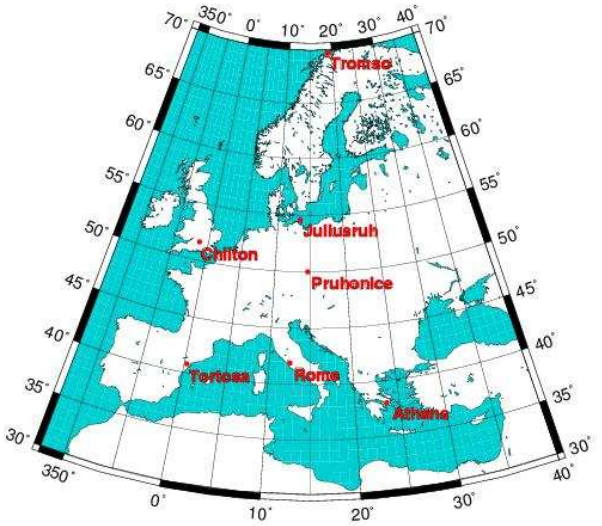

Fig. 4. Ionosondes that were used to evaluation of VTEC maps

Table 1. Averages of residues between VTEC estimations with GPS and ionosondes.

	ROME	ATHENS	TORTOSA	CHILTON	JULIUSRUH	PRUHONICE	TROMSO
JPL	-1.45	-0.66	-1.92	-1.25	-0.91	-0.79	-1.08
CODE	-3.36	-2.55	-4.01	-3.60	-3.42	-2.92	-3.58
UPC	-4.10	-3.54	-4.36	-2.66	-1.93	-2.28	-2.24
IGS	-3.21	-2.45	-3.67	-2.72	-2.28	-2.25	-2.41
SPECTRE	0.53	1.15	-0.02	-0.15	0.32	0.40	-1.06

Table 2. Standard deviations of residues between VTEC estimations with GPS and ionosondes.

	ROME	ATHENS	TORTOSA	CHILTON	JULIUSRUH	PRUHONICE	TROMSO
JPL	5.87	6.01	7.03	4.48	4.38	4.91	5.03
CODE	5.91	6.10	7.17	4.46	4.48	4.98	5.13
UPC	6.18	6.28	7.33	4.81	4.68	5.21	5.30
IGS	5.99	6.14	7.21	4.58	4.50	5.04	5.09
SPECTRE	5.44	5.49	6.66	4.45	4.32	4.98	4.83

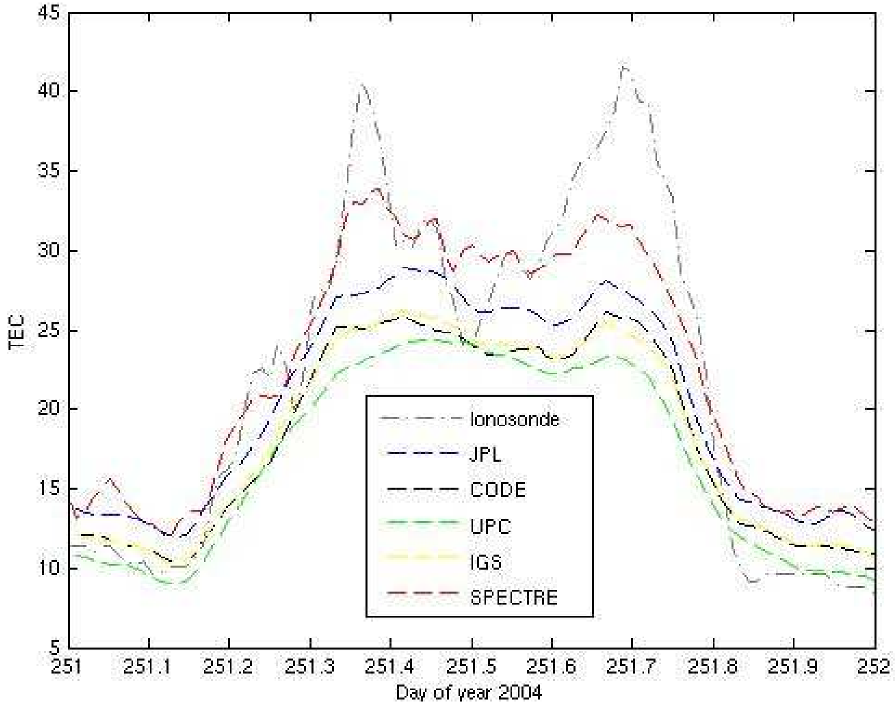

Fig. 5. VTEC estimation of ionosonde of Athens and VTEC estimations of JPL, CODE, UPC, IGS and SPECTRE for the day 251 of year 2004.

Table 1. and Table 2. present the average and standard deviation of residues between VTEC estimations, respectively with GPS and ionosondes. First, we can bserve that most of estimation biases are negative. It gives an indication about an over-estimation of VTEC with ionosondes and/or under-estimation of VTEC with GPS data, as shown by previous results. Second, VTEC estimations produced by SPECTRE present the smallest biases of estimation for each ionosonde, excepted ionosonde of Athens for which the smallest bias of estimation is for JPL results. In Table 2., SPECTRE gets lowest values of standard deviations of residues for the ionosondes of Rome, Athens and Tortosa. For all the others ionosondes, VTEC maps presents equivalent standard deviations of residuals for each ionosonde so that it is not possible to determine the most pertinent VTEC map compared to these ionosondes. Thus, one can argue that SPECTRE present the best results for ionosondes at lower latitudes, where dynamic of ionosphere is higher than at high latitudes. This seems to demonstrate that SPECTRE provides a better estimation of the variability of the ionosphere. This is illustrated on Fig. 5. Indeed, Fig. 5. shows VTEC estimations for GPS and ionosonde of Athens during the day 251 of year 2004. One notice that VTEC estimation of SPECTRE present the best fit of the “two peaks” feature of ionosonde’s VTEC estimation. The second best estimation is provided by JPL whereas estimations of CODE, UPC and IGS are the most smoothed.

Interpretation

The good results of SPECTRE products compared to the others can be explained by its high time and space resolution. In fact, SPECTRE provides a regional mapping sampled at 30 seconds with a space resolution of 2.5°-by-2.5° whereas GIMs provided by JPL, UPC, CODE and IGS are global maps with a space resolution equal to 5°-by-2.5° and sampled at 2 hours. Ionosonde data are sampled at 10 minutes so VTEC estimations have to be extracted from GIM with a dedicated routine of interpolation [9]. Moreover, tomographic algorithm using functions of global expansion like spherical harmonic expansion used by CODE induce a stronger damping of the amplitude of VTEC than algorithms using functions defined on local support like those used by JPL [1] and SPECTRE.
In conclusion, SPECTRE service provides VTEC estimations over Europe with accuracy inferior to few TEC units and proposes pertinent monitoring of the ionosphere's dynamic.

SCIENTIFIC APPLICATIONS

In this section we present two scientific exploitations of SPECTRE products: spaceweather monitoring and natural hazards mitigation.

Spaceweather

Magnetic storms are one of the most disturbing phenomena of the upper atmosphere of the Earth. Auroras are a spectacular and enjoyable effect of magnetic storms but it also exists consequences that could induce negative impacts on human activities [10]. Indeed, geomagnetically induced currents that can flow through power system and disrupt power grids. Such events can directly or indirectly cause permanent damage to network equipment such as high-voltage breakers, transformers, and generation plants because of extensive blackouts. Therefore, understanding of perturbations of ionosphere is a key point to mitigate effects of magnetic storms. Here we demonstrate the capabilities of SPECTRE VTEC maps to observe TEC fluctuations in European auroral area during magnetic storms. We compared perturbations of the geomagnetic field with variations of VTEC. Fig. 6. shows perturbations of the Dst index and of VTEC estimated by SPECTRE for the extreme magnetic storms of October 2003 and November 2004. We can heed the correlation between geomagnetic field and VTEC disturbances for the both storms. Moreover, during October, 14^{th}, 2003 we observe a perturbation of electron content fitting a moderate magnetic perturbation. So, we can argue that SPECTRE VTEC maps are still pertinent during magnetic storms and so, could be valuable to model behaviour of magnetic storms through assimilation data algorithms.

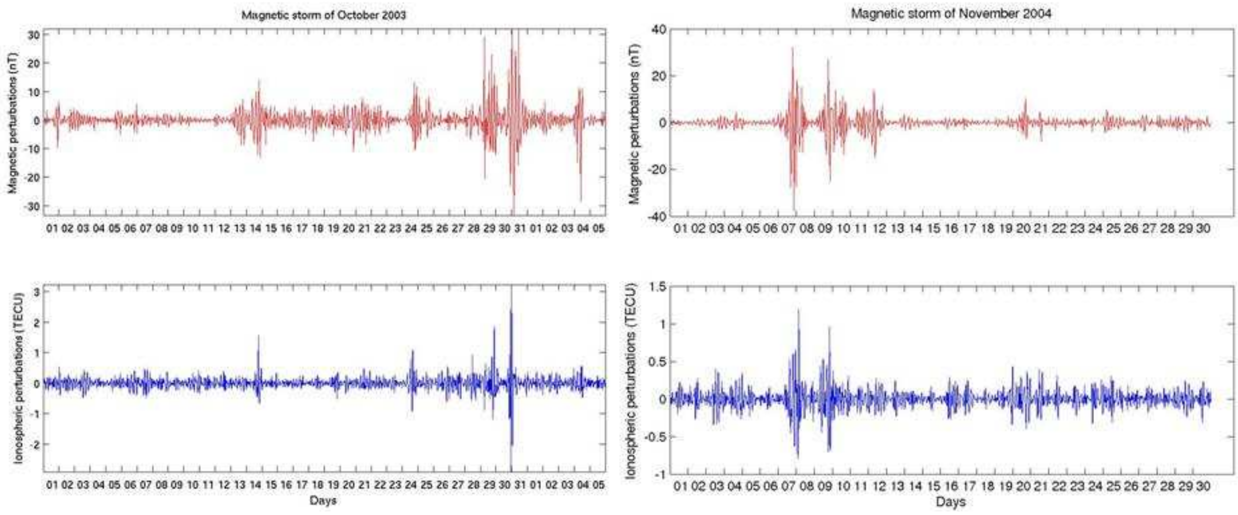

Figure 6: Dst index period low-pass filtered with 6h period cut-off (top) and mean VTEC in European auroral area (latitude > 60°N) filtered with previous filter for magnetic storms of October 2003 (left) and November 2004 (right).

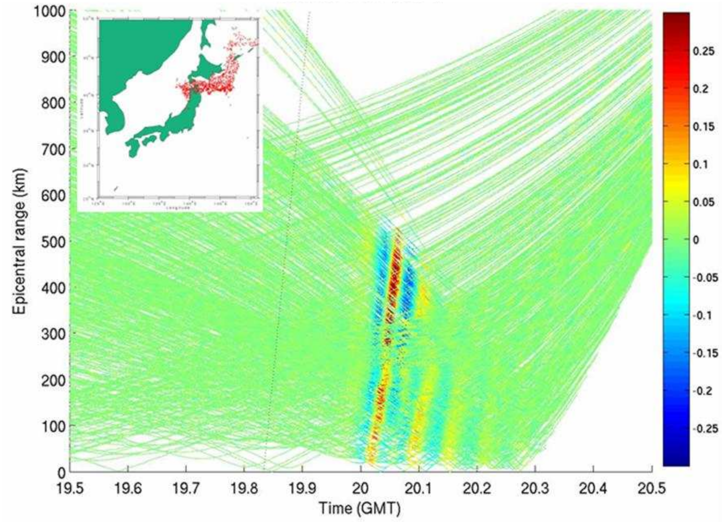

Fig. 7. Time-distance plot of post-seismic perturbation of the ionosphere recorded by GPS data of satellite PRN13 and GPS network of Japan after Tokachi-Oki earthquake, September, 25th, 2003. The map in the upper corner show corresponding ionospheric piercing points. Dot line on the plot represent theoretical propagation of Rayleigh waves at ground surface.

Ionospheric Seismology

Ionospheric perturbations induced by geophysical events like earthquakes and tsunamis have been observed with GPS data for a ten of years [11] but recent events have recall the need to explore all possibilities to improve natural hazards mitigation. Since, electron density disturbances have been modelled in case of earthquakes and tsunamis origins [12][13]. Here, we demonstrate that SPECTRE service is a useful tool for ionospheric seismology applications. Indeed, daily raw STEC data provided by SPECTRE can be filtered in order to study disturbances of ionosphere induced by acoustic and gravity waves that propagate in the atmosphere. Fig. 7. represents the post-seismic perturbation of the ionosphere after the Tokachi-Oki earthquake, September, 25th, 2003. This detection was realized with SPECTRE algorithm using 1 second sampling rate GPS data recorded by the GPS network of Japan. These ionospheric perturbations are coherent with expected disturbances in both time and space. Moreover, SPECTRE algorithm proved its efficiency to monitor such perturbations over Japan after several seismic events but also over California after the Denali earthquake, November, 3rd, 2002 and over Indian Ocean after the Great Sumatra earthquake, December, 26th, 2004 [14][15]. By the way, we showed that STEC provided by SPECTRE can detect post-seimic perturbations of the ionosphere with amplitude of few 10^{-3} TEC units. Moreover, in the frame of these studies, we demonstrated that SPECTRE algorithm can be used for regional applications with all existing dense GPS networks. It was also proved that SPECTRE algorithm can use 1 second as well as 30 seconds sampling rate GPS data.

GALILEO SUPPORT

The development of the GALILEO system will contribute to enhance capabilities of GNSS networks to monitor atmosphere content like water vapour and electron content. In the framework of ionospheric monitoring, we computed the positions of ionospheric piercing points induced by the incoming GALILEO system. We used a simulation of ephemerid of GALILEO satellites realized by French space agency (CNES) for September, 25th, 2003. Corresponding ionospheric piercing points were computed by assuming that current European GPS networks will be able to record GALILEO signals. Fig. 8. shows ionospheric piercing points for European GPS network and, respectively, GPS constellation and GPS+GALILEO constellations. First, we can say that adding a new equivalent constellation, in term of number of satellite, double the number of observations. Second, we can pay attention to the fact that GALILEO constellation will be useful by completing the GPS constellation. Indeed, the position of ionospheric piercing points from GALILEO system are located at different positions than GPS ones. Therefore, it will provide a very interesting enhancement of the density of measurements and a better coverage of map boundaries. In conclusion, it should be possible to improve space resolution of VTEC maps to 0.5°-by-0.5° and to provide better VTEC estimations over area of special interest like, for examples, Mediterranean Sea and coasts of Atlantic Ocean.

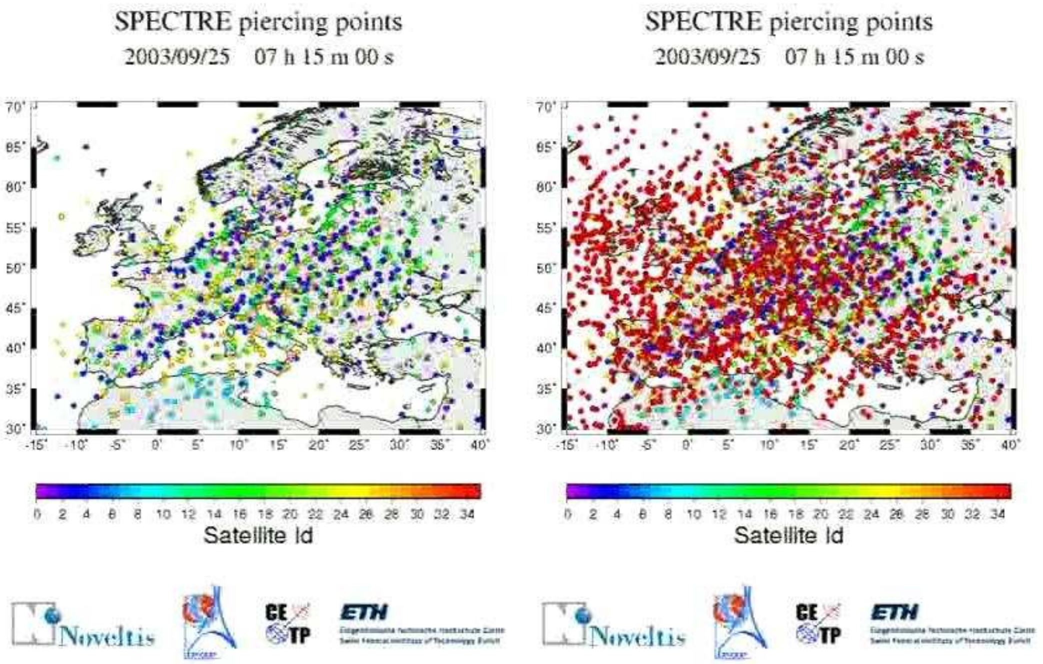

Fig. 8. Ionospheric piercing points for European GNSS network and GPS constellation (left) and GPS+GALILEO constellations (right)

CONCLUSION AND PROSPECTS

In conclusion, we recall that the SPECTRE service is an operational service using European GPS dense networks for ionopheric monitoring. It produces daily STEC raw data at 30 seconds and daily VTEC maps at 30 seconds, 15 minutes and 1 hour with a 2.5°-by-2.5° space resolution. The quality of the regional VTEC maps estimation was evaluated by comparing to global VTEC maps estimation from JPL, UPC, CODE and IGS, VTEC measurements of altimeter satellites ENVISAT, Jason and Topex, and VTEC estimations of seven ionosondes. We demonstrated that SPECTRE VTEC maps provide a more pertinent estimation of VTEC than these GIMs in term of ionosphere dynamic, so that we proved the interest of developing RIMs over dense GPS networks.
Then, we presented two examples of scientific applications of SPECTRE products: spaceweather and ionospheric seismology, and we showed that SPECTRE is a powerful tool for these research topics. In addition, we can list other applications for which SPECTRE products would be valuable. Indeed, pertinent ionospheric correction is useful to spaceborne SAR measurements in the frame of existing instruments as well as design studies. VTEC maps can be used to correct mono-frequency altimeter satellite but can also improve bi-frequencies altimeter satellite corrections in coastal area and for continental hydrology.
The number of potential users and applications will be increased by several improvements of SPECTRE service. First, SPECTRE service has to be operationally extended to Californian and Japanese regions by using the dense GPS networks of these areas. Second, SPECTRE algorithm has to evolve towards real time processing. For European region, it is possible thanks to the recent development of real time GPS dense networks and it will receive our best efforts in order to propose nowcasting TEC products. Another improvement of SPECTRE service, which is actually under development [16], is to compute 3D estimation of the electron density in order to reach fields of applications requiring a precise ray tracing of electromagnetic waves in the ionosphere like HF communications and Over-The-Horizon radars.
Performances of SPECTRE service products are encouraging us to actively develop these improvements and to be aware of futures possibilities of upgrading like those expected with the advent of GALILEO system.

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