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Synthetic events description, generation and characterization report

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Table of Contents

1 INTRODUCTION

The ionosphere is a highly variable and hardly predictable environment. Phenomena of different geographical and temporal characteristics may affect the performances of ionospheric monitoring methods based on real time GPS measurement data. Specifically, this is a problem to generate case scenarios for validating ionospheric models for SBAS systems (like EGNOS). Indeed, given that the performance thresholds for availability and integrity must be guaranteed, these scenarios shall be representative of both quiet and disturbed ionospheric conditions over sufficiently long periods.

The approach for the European SBAS, EGNOS, foresees the following scheme: first the specification of ionospheric conditions using the Along Arc TEC Rate (AATR) ionospheric indicator presented [**Error! Reference source not found.** and RD-4] and, based on this specification, the generation of realistic ionospheric reference scenarios in order to support algorithm development and qualification. These scenarios, generated from real data shall be representative of both quiet and disturbed ionospheric conditions over sufficiently long periods.

This report is devoted to the generation of synthetic ionospheric events which has been done according to the task3 of the ICASES-2 project. These ionospheric events have been simulated taking into account actual GPS geometry (days 225-228 in 2012) and modelling some of the largest ionospheric gradients occurred during 2013.

1.1 Applicable and Reference Documents

1.1.1 Main Reference Documents

RD-1 ICASES FICR “Final report on EGNOS Default Ionospheric Conditions. Volume 1: Selection and Justification of Indicators and analysis against past EGNOS performance”, Iss. 1, Rev. 2. 10/01/2013

RD-2 ICASES FICR “Final report on EGNOS Default Ionospheric Conditions. Volume 2: Selection and Justification of Indicators and analysis against past EGNOS performance”, Iss. 1, Rev. 2. 10/01/2013

RD-3 ICASES2 SEGR “Synthetic event generator implementation and validation report”. 18/04/201

RD-4 J.Sanz et al. “Novel ionospheric activity indicator specifically tailored for GNSS users”, ION-GNSS+ 2014, Tampa, Sep., 2014

1.2 Document Overview

The document is organised according to the following sections:

1. A brief introduction explaining the goal of the study.
2. A general view about the model that we used for generating the synthetic ionospheric events.
3. A section about how the model parameters were determined
4. An example of large ionospheric gradients occurred during the storm on day 324 in 2014.
5. Another example of large ionospheric gradients occurred during the Halloween ionospheric storm.
6. In this section we describe the 4 ionospheric scenarios thar we have simulated during this task.
7. Summary of the main conclusions.

1.2.1 Acronyms and Terms

AD	Applicable Document
CPF	Central Processing Facility
AATR	Along Arc TEC (vertical) Rate.
CPF	Central processing Facility
DoY	Day-of-Year
EC	Electron Content
ECAC	European Civil Aviation Conference
EGNOS	European Geostationary Navigation Overlay Service
EUV	Extreme-ultraviolet
F-PPP	Fast Precise Point Positioning
gAGE	Research Group of Astronomy and Geomatics
GIM	Global Ionospheric Map
GNSS	Global Navigation Satellite System
GPS	Global Positing System
IGP	Ionospheric Grid Point
IGS	International GNSS Service
IPP	Ionospheric Pierce Point
LT	Local Time
PPP	Preciese Point Positioning
RINEX	Receiver Independent Exchange Format
RD	Reference Document
RMS	Root Mean Square
SIS	Signal-In-Space
STEC	Slant TEC
SOW	Statement Of Work
ST	Solar Terminator
SW	Software
TBC	To Be Confirmed
TBD	To Be Determined
TBW	To Be Written
TEC	Total Electron Content
UPC	Technical University of Catalonia
VTEC	Vertical TEC

1. GENERATION OF IONOSPHERIC SYNTHETIC EVENTS FOR EGNOS

This report describes the main trends of a tool for generating synthetic ionospheric threats for EGNOS, specifically targeted to reproduce ionospheric storms and super-storms, the events causing the largest values of the AATR index. After a general description of the underlying model used to simulate the effects on STEC measurements from an ionospheric storm, the strategy to find the most suitable values of the model parameters to reproduce a particular ionospheric event is described. Two examples based on real observations of the STEC taken during two ionospheric super-storms are presented to illustrate the degree of realism achieved by the simulations by comparing real and simulated measurements of the STEC and the AATR indicator. Finally, the different scenarios generated for EGNOS, including different kinds of ionospheric synthetic events are described in detail.

2. MODEL DESCRIPTION

The underlying model used to simulate ionospheric events has several elements that provide a description of the spatial distribution, the motion and the temporal evolution of the VTEC excess (referred to nominal VTEC values) caused by ionospheric events of different severity.

- **Spatial distribution:** the following functionality has been considered to describe the two-dimensional (longitude and latitude) spatial variation of the TEC excess (E_{TEC}) caused by an ionospheric perturbation

$$E_{TEC}(x,y) = A_{max} F_D(x) F_W(y) \quad (1)$$

where $F_D(x)$ describes the TEC-excess variation in the direction of the perturbation motion, $F_W(y)$ gives the variation of the TEC-excess in the direction perpendicular to motion, and A_{max} is the amplitude or maximum TEC-excess of the perturbation. The variables *x* and *y* represent the spatial coordinates referred to the point where the TEC excess is maximum in the directions parallel and perpendicular to motion of the perturbation, respectively. Hence,

$$A_{max} = E_{TEC}(0,0) \quad (2)$$

The particular choice for the functions $F_D(x)$ and $F_W(y)$ was introduced in the previous report [SEGR_Report_gAGE_UPC] and corresponds to different combinations of three basic models which hereafter will be referred as a two-dimensional Gaussian (GAUS), a constant front with exponential decay (EXPO) and a sinusoidal oscillation (OSCN). In the case of model OSCN, the parameter A_{max} corresponds to the maximum TEC value achieved during the oscillation. The specific functions employed by these models to generate the different scenarios for EGNOS will be described in more detail in Section 6.

Finally, to quantify the effects caused by a perturbation in the ground STEC measurements, a single layer model has been assumed and the altitude of the spherical layer, where the perturbation is assumed to be placed, has been set to $H_p = 350$ km.

  - *Summary of spatial parameters*: the amplitude of the perturbation A_{max} is a common parameter for the three models considered. Another common parameter is the wideness of the perturbation, S_W, in the direction orthogonal to its motion. For models GAUS and EXPO there is one more parameter to describe the deepness of the perturbation, S_D, in the direction parallel to the perturbation motion. A single couple of values (S_W, S_D) are sufficient if the perturbation is assumed to be symmetric in those two directions. However, an asymmetric perturbation can also be generated by considering different values of the wideness and/or the deepness parameters at either side of the perturbation centre. For example, if the back-side and the front-side of the perturbation in the direction of motion are required to have a different shape, two values, S_D and S'_D respectively, of the deepness parameters can be considered. Finally, for model OSCN, the oscillation is assumed in the direction of motion of the perturbation and there are two parameters that describe the amplitude and period of the oscillation, C_p and T_p, respectively.

- **Motion:** The model assumes that the ionospheric perturbation is moving over a sphere of fixed altitude H_p with a constant speed of modulus V_p and direction of motion given by an azimuth angle α_p measured from the North direction and with positive orientation from North to East. In this way, once the longitude and latitude of the perturbation center is known at a given epoch, the position of the perturbation at any other epoch can be calculated forward and backward in time. In general, the perturbation center is assumed to coincide with the position of the maximum value of the TEC excess. In the case of model OSCN the perturbation center can be chosen arbitrarily.

  - *Summary of motion parameters*: apart from the parameters that describe the velocity vector of the perturbation, V_p and α_p, the longitude and latitude of the perturbation center at a given epoch, (λ_c, φ_c, t_c) respectively, are required in order to set the boundary conditions to calculate the trajectory of the synthetic perturbation.

- **Temporal evolution:** In order to simulate the time evolution of an ionospheric perturbation, the spatial distribution described by the functionality $E_{TEC}(x, y)$ is filtered by a Gaussian function depending on time, with a central value given by the epoch, t_m, when the perturbation is assumed to have its maximum contribution to the TEC. From this epoch forward and backward in time the magnitude of the TEC-excess provided by the perturbation is assumed to decay with a characteristic time scale S_T given by the standard deviation of the Gaussian filtering function. This time scale is used to control the time interval of the day during which the perturbation is active. The perturbation is assumed to develop and decay during a single day.

  - *Summary of temporal parameters*: the epoch of maximum development of the perturbation, t_m, and the time-scale of growth and decay around that maximum, S_T.

3. DETERMINATION OF MODEL PARAMETERS

In order to show that the model described in Section 2 is able to reproduce the particularly high values of the STEC and the AATR index observed during a real ionospheric storm, a set of realistic values of the model parameters must be chosen. The strategy followed to find a suitable set of values for those parameters is described in this section, and it is based in a two-step approach.

The first step is aimed at fixing the majority of the parameters by means of selected observations of the STEC during a given ionospheric event for a single PRN satellite in view from a small network of ground stations. The procedure followed in this step was introduced in ICASES-1 and it has also been described in section 4 of the previous report [RD-3]. This method allows the determination of the STEC gradient, propagation velocity and amplitude of the ionospheric perturbation, from which the values of the model parameters V_p, α_p, A_{max}, and S_D can be established. Finally, the parameters (λ_c, φ_c, t_c) can be obtained from the longitude and latitude of the IPP corresponding to the epoch of the maximum STEC measured by a given ground receiver from the small network used in this step. The adequacy of the parameters can be verified comparing the real measurements from the small network of ground receivers and the results of performing a simulation that assumes a constant shape of the perturbation at any epoch and a large value of S_W.

The second step is targeted at the determination of the remaining parameters not fixed in the previous step. Specifically, these parameters are t_m, S_T and S_W. The strategy searches for a particular realization of the simulated perturbation giving rise to values of the AATR index similarly large as the real ones calculated for an individual ground station using all the satellites in view during a full day. The AATR index from observations may be used to estimate the time interval during which an ionospheric storm is active as well as the period when the storm had a maximum impact in the measured STEC. During those periods one should expect very large values of the AATR index (significantly larger than 0.15, see previous report [RD-3]). In this way, it is possible to find suitable values for the parameters t_m and S_T. Moreover, the value of the wideness parameter S_W can also be estimated using the AATR with a similar strategy, although it must also be taken into account another relevant restriction. If S_W is too large, then the simulated perturbation might affect a larger number of satellites than in the real case, while if it is too small the opposite situation might occur. At this respect, the STEC measurements from the real case and from the simulation must be checked for all satellites in view from the ground station in order to ensure that the subset of satellites affected by the perturbation while it is active is essentially the same.

4. REPRODUCING THE IONOSPHERIC STORM OF DAY 324 OF 2003

In this section we describe how to generate a synthetic ionospheric event with similar properties to the ionospheric super-storm observed during day 324 of 2003 by the USNO network of receivers. The similarity is searched not only in the magnitude of the STEC and the AATR but also in the temporal evolution of such quantities during the day of the observations.

A study of the real ionospheric event considered in this section was presented in a previous report [SEGR_Report_gAGE_UPC]. The model EXPO has been selected for this case after the particular shape of the observed STEC that was shown in Figure 13 from that report (see also Figure 1 below). For this model, the TEC excess perpendicular to the direction of motion of the perturbation in equation (1) is represented by a Gaussian function

$$F_W(y) = \exp\{-y^2/S_W^2\} \qquad (3)$$

while in the direction of motion the particular functionality is given by

$$F_D(x) = \begin{cases} exp\{x/S_D\} & , \quad x < 0 \\ exp\{-x^2/S'^2_D\} & , \quad x \geq 0 \end{cases} \qquad (4)$$

The determination of the set of parameters corresponding to the first step described in Section 3 was done by means of the tool developed in ICASES-1. The results were presented in Figure 13 of the previous report [RD-3], from which the propagation velocity of the super-storm was characterized (values of V_p and α_p) and also its STEC gradient, which in combination with the STEC measurements allowed a first guess for the values of the amplitude and deepness parameters (A_{max} and S_D, respectively). The value of S'_D was taken one order of magnitude greater than S_D to reproduce a perturbation characterized by a front of large spatial extension, in agreement with the characteristics of the real perturbation.

Figure 1 shows the results of a simulation where the STEC from a synthetic event is compared with real observations for one single satellite in view from the USNO station. The epoch t_c was set to 72 600 s (just before the beginning of the rapid decline of the STEC measurements seen in Figure 1). From this epoch, the boundary condition for the trajectory of the synthetic perturbation in the longitude-latitude plane was derived. Note that the synthetic STEC results are generated using a model that does not include the nominal background that should be observed before or after the period of time affected by the super-storm. In other words, they correspond to the TEC excess caused by an ionospheric event. For this reason, the synthetic STEC always decays to exactly zero once the receiver-satellite line of sight does not cross the region of influence of the synthetic event (see Figure 1).

On the other hand, the simulated results in Figure 1 were calculated without a specific restriction for the time scale of evolution of the perturbation, S_T, and the wideness parameter, S_W. The final values of those two parameters were fixed in a second step after the examination of the behavior of the AATR index during the day 324. Figure 2 presents the AATR calculated from a synthetic event simulated after a guided choice for the values of S_T and S_W following the general strategy introduced in Section 3. The results can be compared with the values derived by the USNO station for the real super-storm. The synthetic perturbation reproduces large values of the AATR, not far from those observed and during the same period of time affected by the real ionospheric super-storm. The final set of parameters used to generate the synthetic ionospheric event is presented in Table 1.

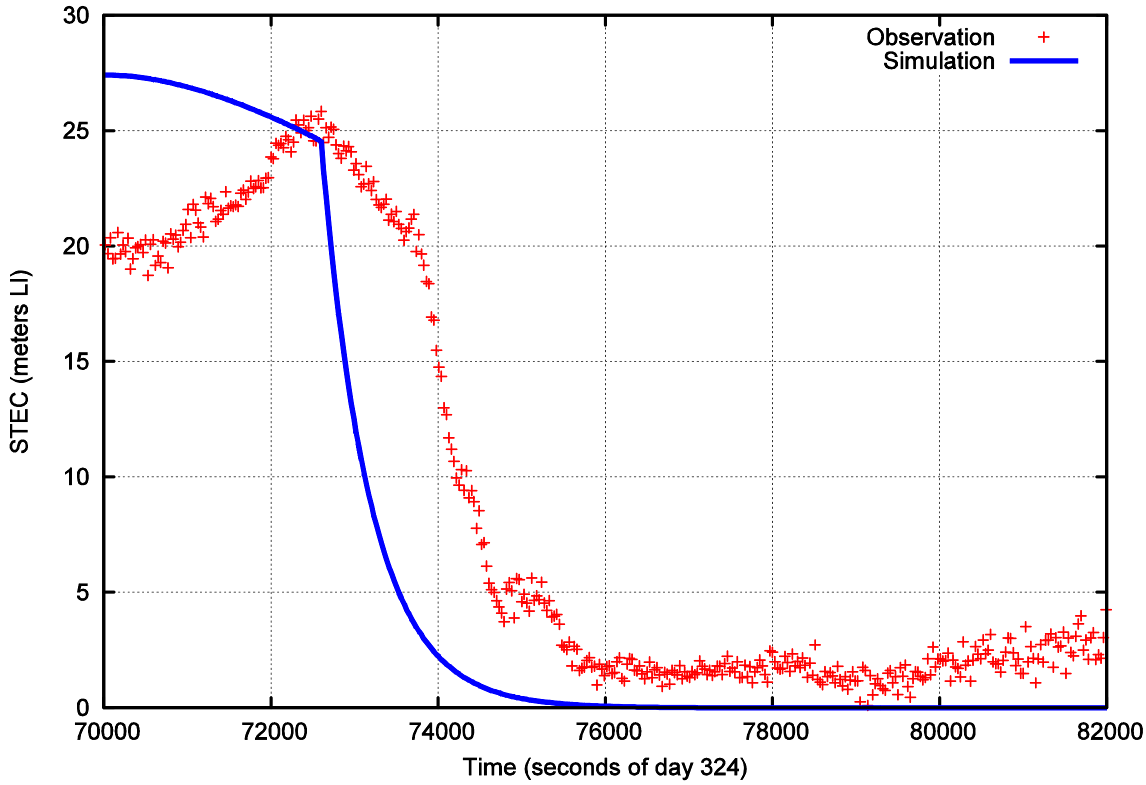

Figure 1. STEC measurements of PRN 11 from USNO receiver during day 324 of 2003 (red crosses) compared with the results of the simulated synthetic event described in the text (blue curve).

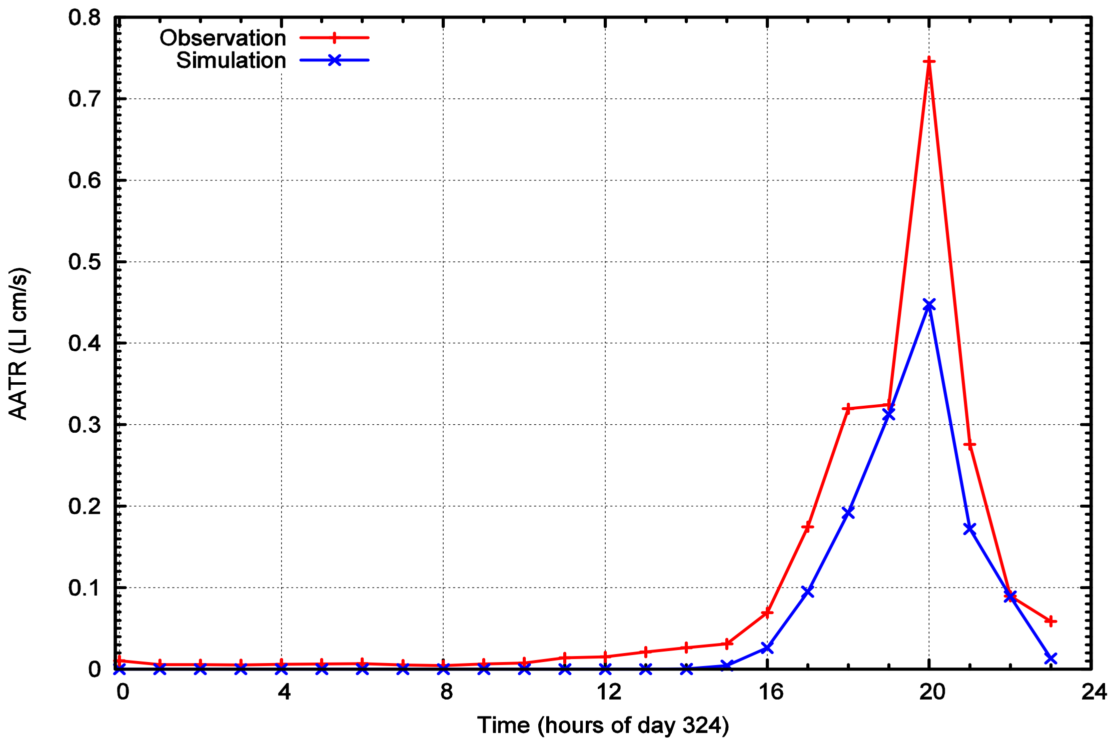

Figure 2. Comparison of the AATR values calculated for the USNO station during the day 324 of year 2003 from observations (red) and from the synthetic event described in the text (blue).

Synthetic event:	Model Parameters	Values
Epoch of maximum	Year , DOY , SOD	2003 , 324 , 72600 s
Time scale	S_T	7200 s
Boundary condition	λ_c , φ_c , t_c	-75°.07, 36°.83, 72600 s
Propagation velocity	V_p	100 m/s
Azimuth of propagation	α_p	225°
Maximum VTEC	A_{max}	185 TECU
Wideness, Deepness	S_W , S_D , S'_D	1000 km , 90 km , 900 km

Table 1. Summary of parameters for synthetic event during day 324 of 2003-

5. REPRODUCING THE IONOSPHERIC STORM OF DAY 303 OF 2003

In this example, a synthetic ionospheric event has been simulated with the purpose of reproducing similar values of the STEC and the AATR index as those measured during the ionospheric storm that occurred in day 303 of 2003. This ionospheric storm was analyzed in detail in the previous report [RD-3] and the model GAUS has been chosen for this case after the particular shape shown by the observed STEC (see in Figure 14 from that report and Figure 3 below). For the GAUS model the functions $F_D(x)$ and $F_W(y)$ in equation (1) are assumed to be symmetric Gaussian functions with standard deviations equal to S_D and S_W, respectively.

The determination of the set of parameters from the first step described in Section 3 was performed from the examination of the STEC values measured for satellite PRN 9 by the NANO network (the same that had been used to analyse this ionospheric event in the report [RD-3]). Figure 3 shows the results of a simulation where the synthetic TEC excess is compared with real observations of that satellite. For this simulation, the wideness parameter, S_W, and the time scale of evolution of the perturbation, S_T, were assumed to have artificially high values since the interest was focused only in reproducing similar STEC values as those measured from a single satellite and during a restricted time interval of the day. To determine, the rest of parameters, the same method as explained in Section 4 was used. In particular, the epoch t_c was set to coincide with the epoch of maximum STEC observed by the DRAO receiver from the NANO network.

In the second step, the values of the AATR index during the day 303 (see Figure 4) were used to decide the final values of the parameters S_T and S_W. In particular, an upper limit for the wideness of the synthetic perturbation was inferred (S_W less than about 3 000 km) by requiring that the simulated STEC do not significantly exceeds the real STEC measurements between 0 and 19 hours of the day when the real values of the AATR index are within nominal limits. Taking S_W greater than 3000 km gives rise to artificially high values of the AATR during the period of the day when the real ionospheric storm did not affect the STEC measurements from the NANO network of receivers. On the other hand, from Figure 4 one can see that the period of the day showing large values of the AATR indicator spans about 4-5 hours, while the maximum AATR occurs for the period between 22:00 and 23:00 local time (recall that the AATR is an hourly indicator). The parameters t_m and S_T were chosen taking into account the previous restrictions. In Figure 4 the AATR calculated from the synthetic event simulated after the final choice of t_m, S_T and S_W can be compared with the real results for the DRAO station. One can see that the synthetic perturbation reproduces similarly large values of the AATR and for the same period of time affected by the real ionospheric super-storm. The final values of the parameters used for the generation of the synthetic event are shown in Table 2.

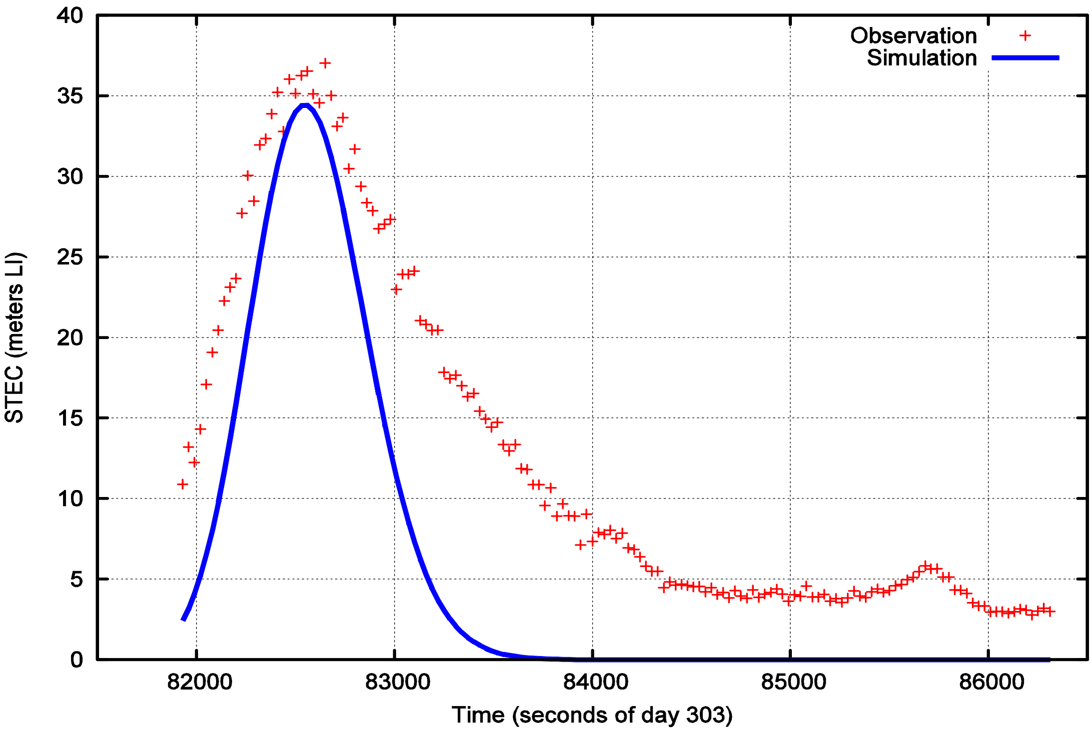

Figure 3. STEC measurements of PRN 09 from DRAO receiver during day 303 of 2003 (red crosses) compared with the results of the simulated synthetic event described in the text (blue curve).

Synthetic event:	Model Parameters	Values
Epoch of maximum	Year , DOY , SOD	2003 , 303 , 81000 s
Time scale	S_T	9000 s
Boundary condition	λ_c , φ_c , t_c	-130°.89, 53°.73, 82560 s
Propagation velocity	V_p	100 m/s
Azimuth of propagation	α_p	240°
Maximum VTEC	A_{max}	135 TECU
Wideness, Deepness	S_W , S_D	3000 km , 110 km

Table 2. Summary of parameters for synthetic event during day 303 of 2003

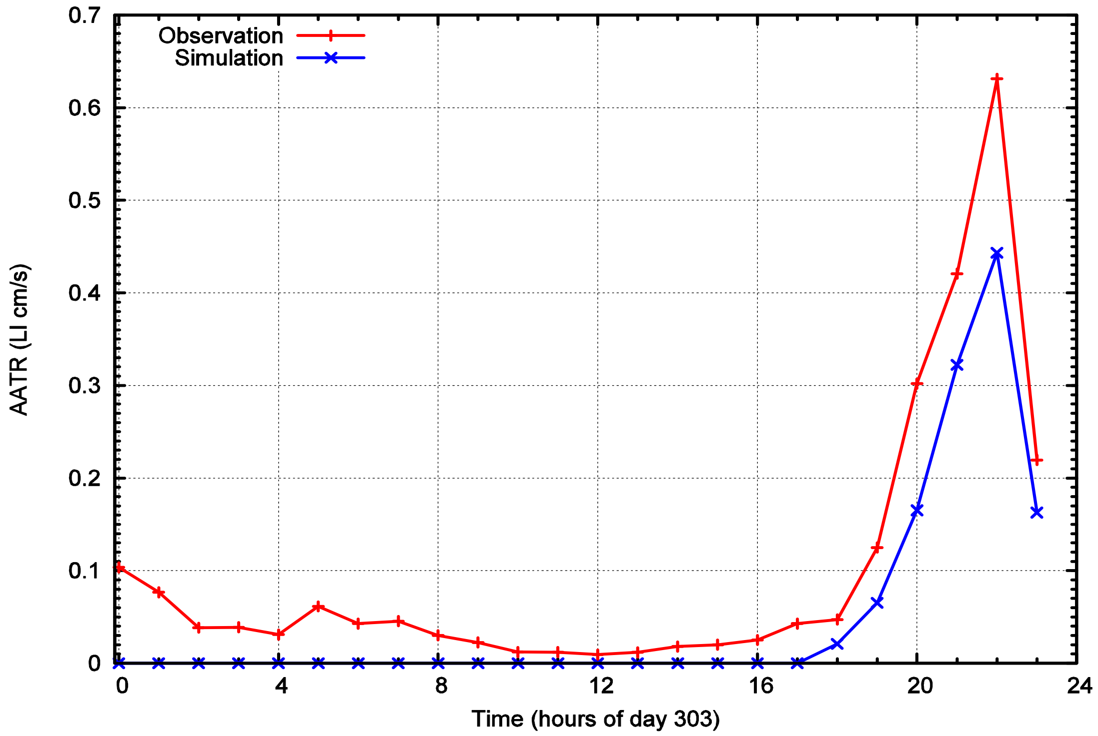

Figure 4. Comparison of the AATR values calculated for the DRAO station during the day 303 of year 2003 using real measurements (red) and the synthetic event described in the text (blue).

6. PROPOSED SCENARIOS INCLUDING SYNTHETIC EVENTS

The general characteristics of the scenarios are described next. Then, in different subsections the particularities of each scenario are described in detail and some images and plots are used to illustrate their specific properties.

Four scenarios each of them composed of 4 days of data have been generated. In all the scenarios, the first day (day 1) corresponds to a quiet period with nominal measurements. The remaining days (hereafter referred as non-nominal days) correspond to disturbed periods that are affected by different ionospheric synthetic events of increasing severity (increasing STEC and AATR values) from day 2 to 4, the last day including events that can be similar to the super-storms observed during the days of 2003 analyzed in the previous sections. Each non-nominal day from a given scenario includes four synthetic events (except scenario 4 which has 3 events per day as will be explained later on) having identical characteristics but a different direction of propagation, covering a different time interval of the day and a different spatial location within the ECAC region. In general, the different events in a single day have neither temporal nor spatial coincidence. The following tables T3 and T4 summarize the spatial location at the time of maximum TEC excess and the directions of propagation considered for the events in a single day of the four scenarios. The values shown in the tables set up the parameters that determine the motion and temporal evolution of the ionospheric event: λ_c longitude, φ_c latitude, and t_c (taken equal to t_m for all scenarios) time of maximum TEC excess generated by the event. Other common parameters of the scenarios are also presented in these tables.

Event	λ_c	φ_c	t_m	S_T	α	V_p (m/s)	Location	Propagation
1	-22°	35°	17:00	2 h	45°	100	SE	SE to NW
2	0°	60°	20:00	2 h	135°	100	N	NE to SW
3	23°	60°	4:00	2 h	180°	100	NW	N to S
4	28°	36°	12:00	2 h	315°	100	SW	SW to NE

Table 3 Summary of parameters used in the scenarios 1, 2 and 3 and determining the position, time, velocity of propagation and duration of the 4 events in a single day.

Event	λ_c	φ_c	t_m	S_T	α	Location	Propagation
1	0°	60°	19:00	4 h	135°	N	NE to SW
2	23°	60°	5:00	4 h	180°	NW	N to S
3	28°	36°	12:00	4 h	315°	SW	SW to NE

Table 4. Summary of parameters used in the scenario 4 and determining the position, time, direction of propagation and duration of the 3 events in a single day.

Scenarios 1, 2 and 3 consider different models of an ionospheric perturbation to generate the synthetic events. However, as can be seen from Table 3 all the events in these 3 scenarios have the same propagation velocity (fixed to 100 m/s) and the same timescale for the duration of the ionospheric event (set to 2 hours). Such values are similar to the ones observed for the ionospheric super-storms analyzed in previous sections. On the other hand, in scenario 4 the synthetic events have propagation velocities that change from day to day and are different from the value used in the other 3 scenarios (the particular values will be specified in Section 6.4). Moreover, as shown in Table 4, the duration of the events in scenario 4 is two times longer than in the rest of scenarios. For this reason and to avoid excessive spatial and temporal superposition of the events in a single day, the number of events in scenario 4 has been reduced from four to three.

Finally, in order to generate realistic values for the VTEC maps and for the STEC measurements from ground stations, the TEC excess from the synthetic ionospheric events has been superimposed over real measurements taken under undisturbed conditions. Specifically, a set of nominal data has been used corresponding to real STEC measurements collected during the period from August 12 to 15 of 2012 (four days). This was a quiet period of ionospheric activity (values of the D_{st} index greater than -20 nT). Then, for each scenario, the first day corresponds to the nominal data from August 12, and during the other 3 days the events shown in tables T3 and T4 are superimposed over the nominal data from August 13 to 15, respectively. Additionally, note that the temporal evolution of the events described in tables T3 and T4 has been designed to minimize its impact during the beginning and the end of the day. Consequently, the STEC measurements will be close to the original nominal data during approximately the first and last 2 hours of the non-nominal days.

6.1 Description of Scenario 1

The model GAUS is used in this scenario to generate the events. This model is based in the study presented in Section 5 and uses the same functionality for the TEC excess, but different sets of values of the model parameters are considered. The parameters used to regulate the severity of the synthetic events in this scenario are the amplitude, the deepness and the wideness of the ionospheric perturbation (A_{max}, S_D and S_W, respectively). Increasing severity (or equivalently, larger STEC and AATR values) are obtained for the different days by simultaneously increasing A_{max} and S_W while decreasing S_D. The following table describes the values used for the non-nominal days of this scenario.

Day	A_{max} (TECU)	S_W (km)	S_D (km)
2	50	1000	200
3	100	2000	150
4	150	3000	100

Table 5. Parameters used for the events in different days of the scenario 1.

An example of the AATR values calculated for the events of this scenario can be seen in the following Figure 5 to Figure 7. The stations used in these calculations have been chosen from locations near the events at the time of its maximum. In particular, LPAL in Canary Islands for event 1, FOYL in Ireland for event 2, SVTL in Russian Federation for event 3 and TUBI in Turkey for event 4. Examples of color-maps of the VTEC from different days of the scenario are presented in Figure 8 to Figure 10 .

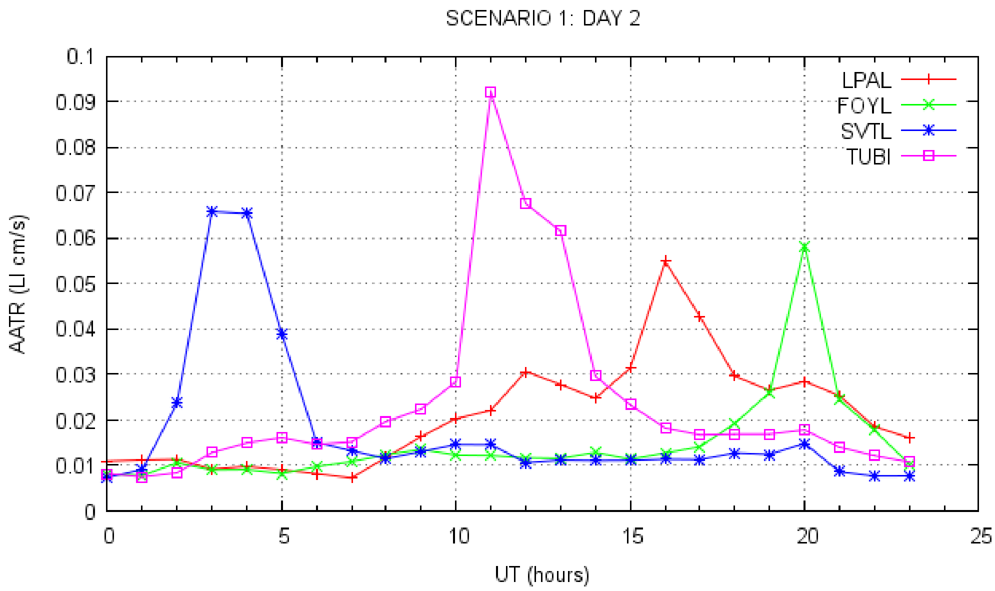

Figure 5. The AATR calculated for selected stations located in the proximity of the four events (when they had maximum severity) in day 2 of scenario 1.

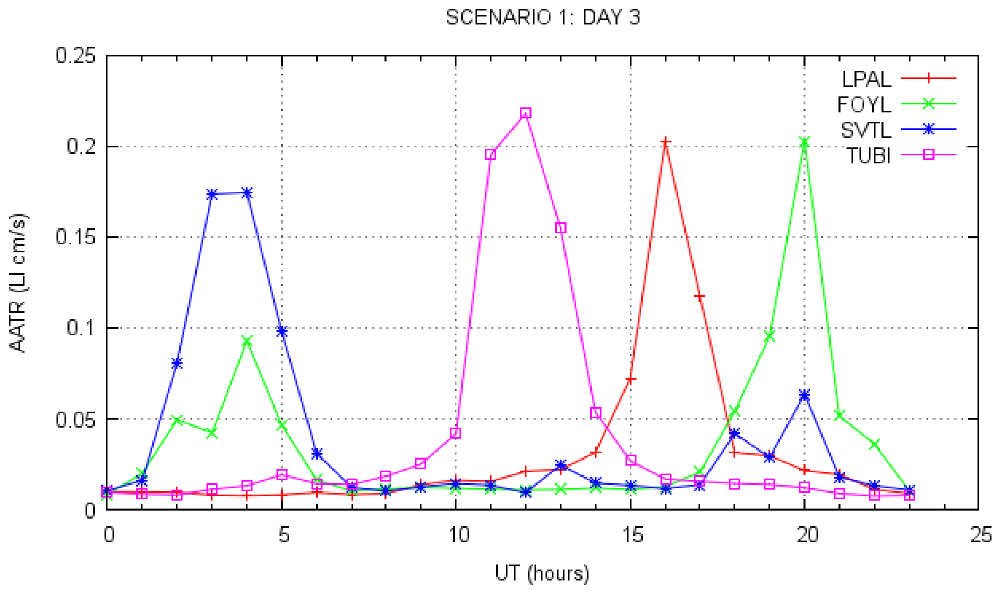

Figure 6. Same as previous figure but for day 3 of scenario 1.

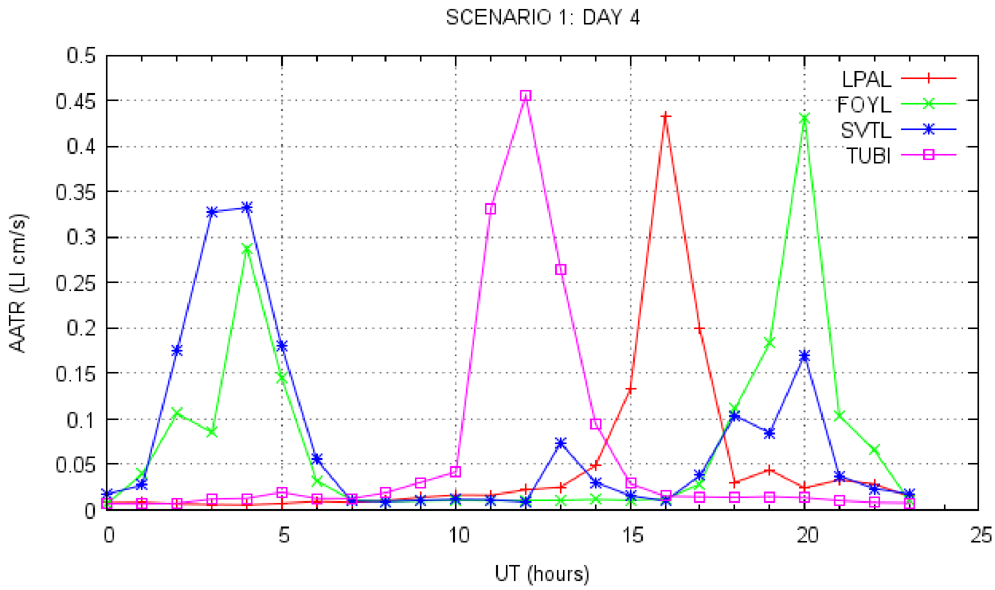

Figure 7. Same as previous figure but for day 4 of scenario 1.

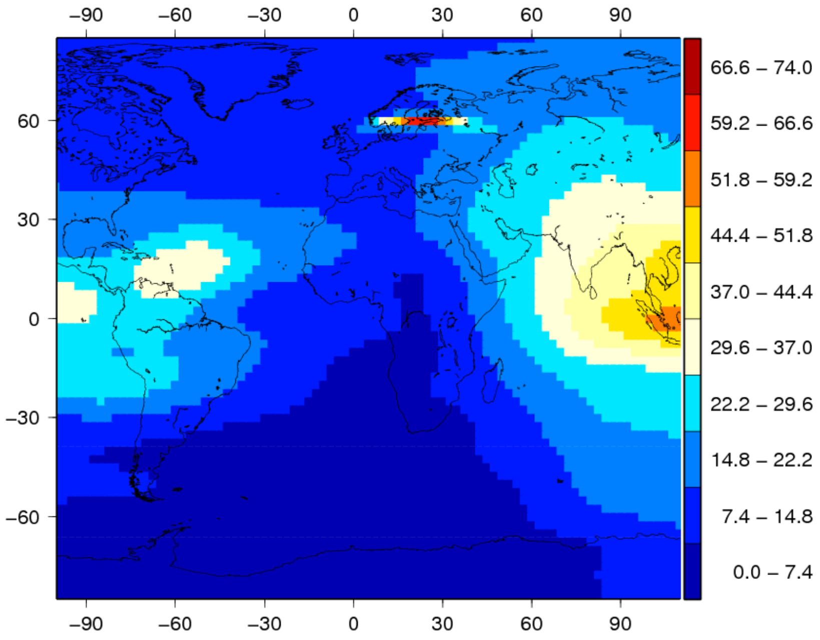

Figure 8. VTEC colour map showing event 3 during day 2 of scenario 1 at the time of its maximum intensity occurring at 4:00 UT. The color scale is in TECU.

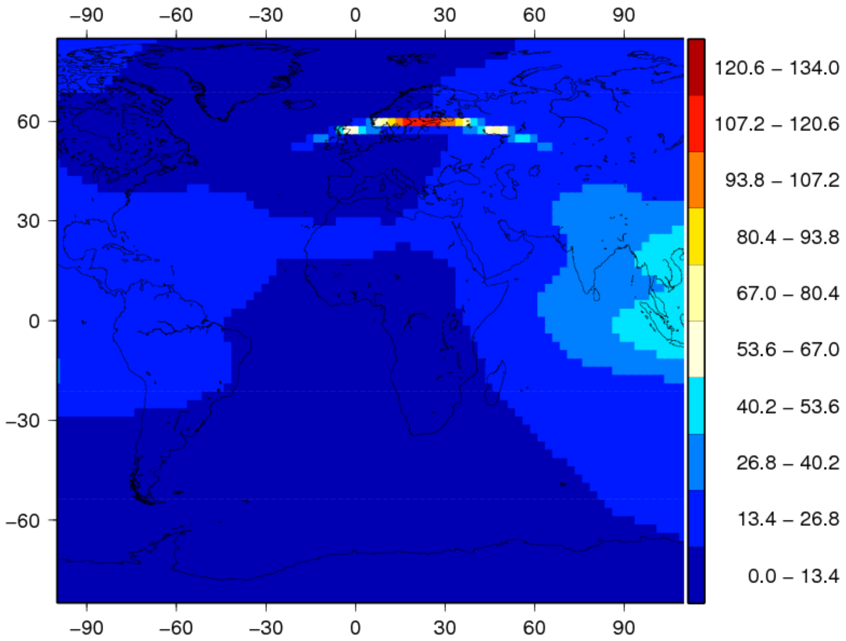

Figure 9. Same as previous figure but for day 3 in scenario 1.

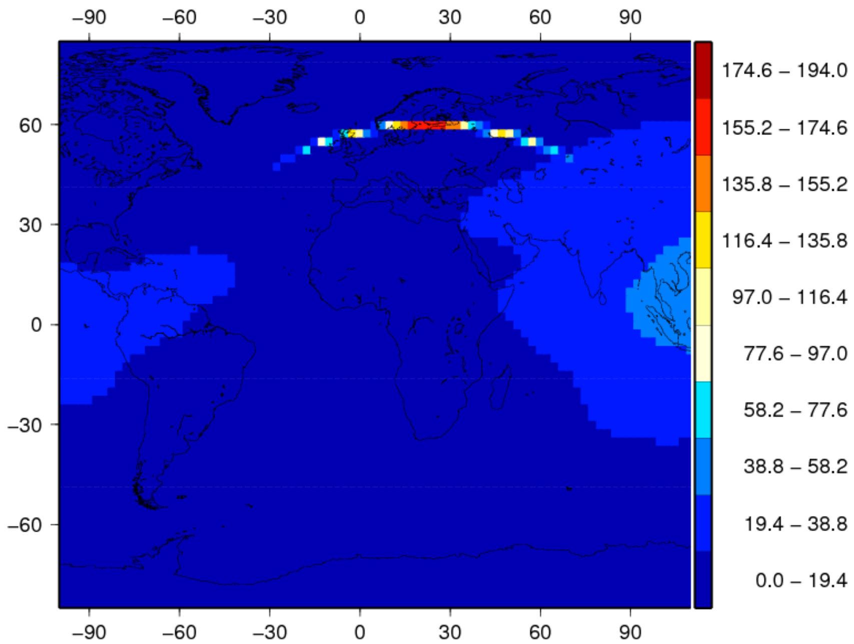

Figure 10. Same as previous figure but for day 4 in scenario 1.

6.2 Description of Scenario 2

The model EXPO is used in this scenario to generate the events. This model is based in the study presented in Section 4, using equations (3) and (4) for the spatial distribution of the TEC excess, although different sets of values of the model parameters are considered. The parameters regulating the severity of the synthetic events in this scenario are the same as in scenario 1, namely, the amplitude, the deepness and the wideness of the ionospheric perturbation (A_{max}, S_D and S_W, respectively). Increasing severity (or equivalently, larger STEC and AATR values) are obtained for the different days by simultaneously increasing A_{max} and S_W while decreasing S_D. The parameter S'_D is used to determine the size of the event in its front-side. Larger values of S'_D mean greater spatial extension of the event, implying that a larger region is affected by the perturbation. The following table describes the set of values used for the non-nominal days of this scenario.

Day	A_{max} (TECU)	S_W (km)	S_D (km)	S'_D (km)
2	60	1000	200	500
3	130	2000	140	1000
4	200	3000	90	1500

Table 6. Parameters used for the events in different days of the scenario 2.

An example of the AATR values calculated for the events of this scenario can be seen in Figure 11 to Figure 13 for the same stations that were used in the previous scenario. Colour maps of the VTEC from different days of the scenario are presented in to Figure 14 to Figure 16.

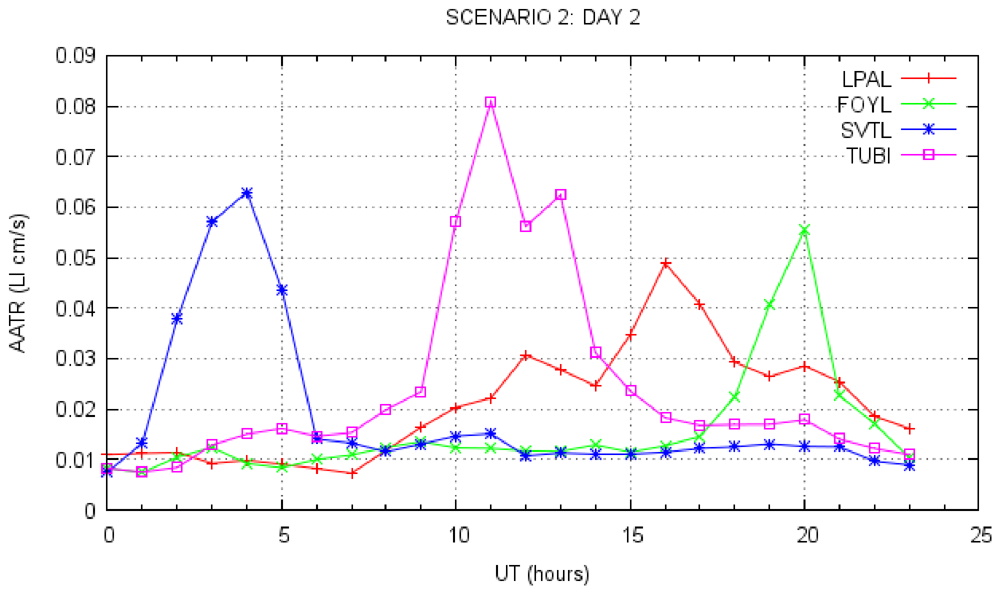

Figure 11. The AATR calculated for selected stations located in the proximity of the four events (when they had maximum severity) in day 2 of scenario 2.

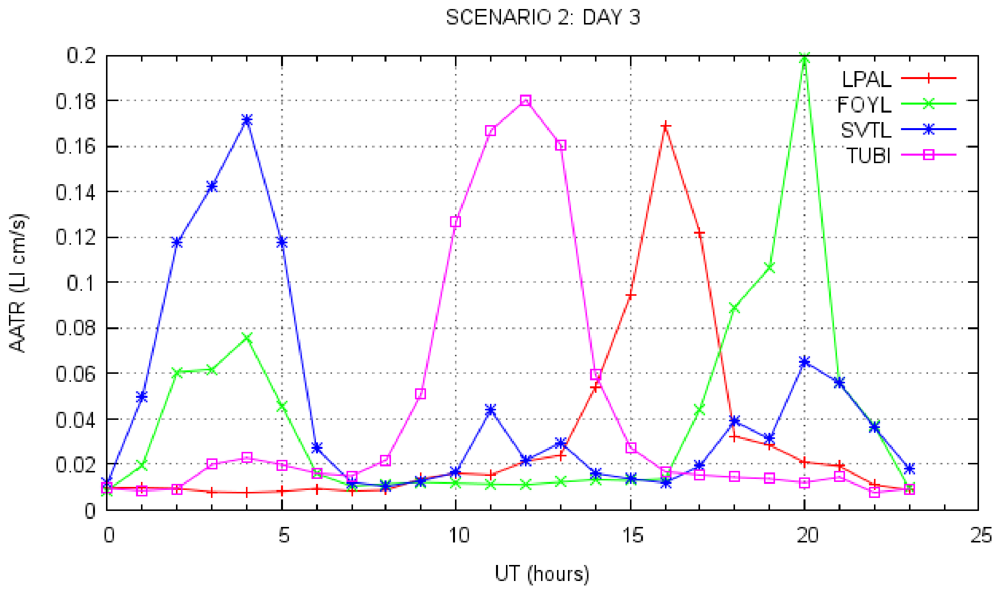

Figure 12. Same as previous figure but for day 3 of scenario 2.

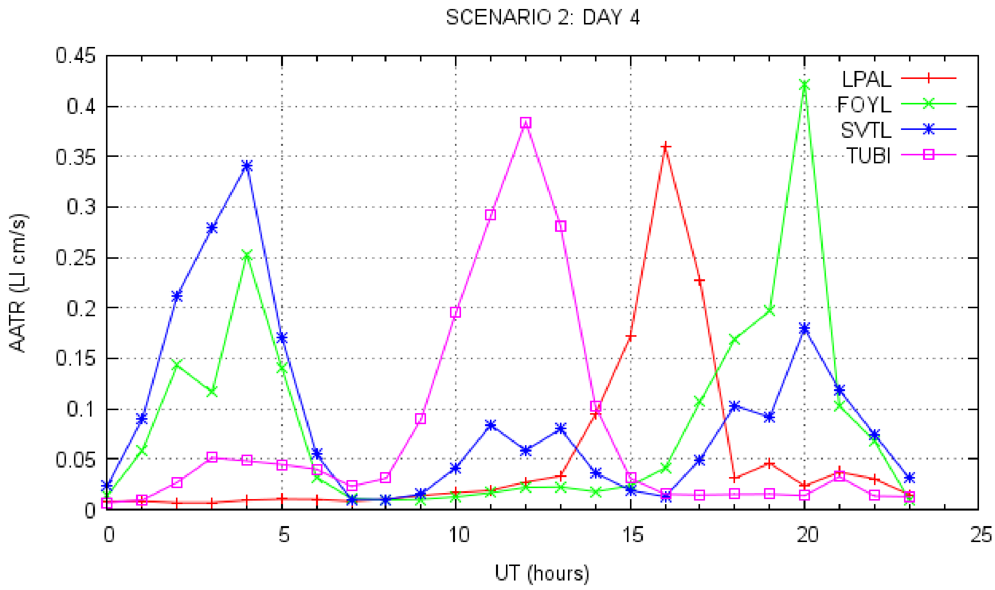

Figure 13. Same as previous figure but for day 4 of scenario 2.

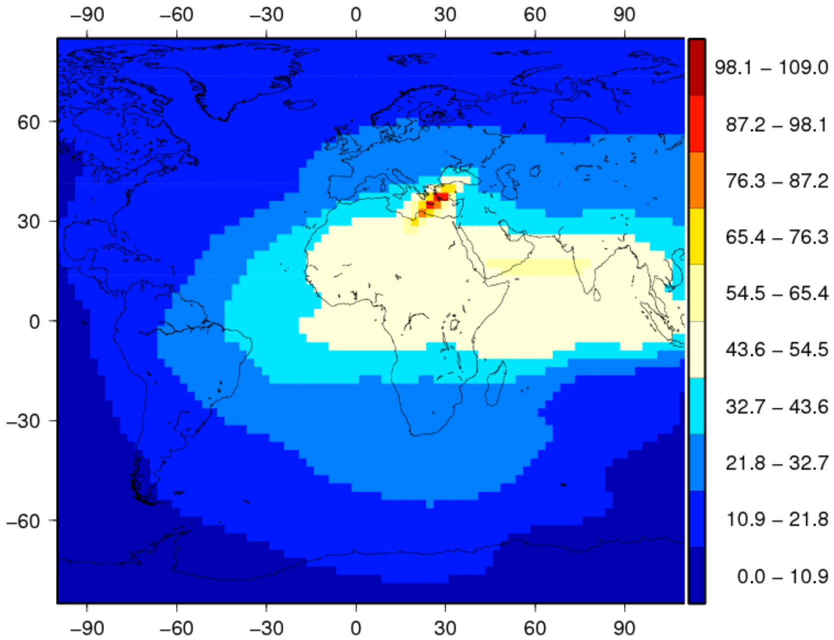

Figure 14. VTEC colour map showing event 4 during day 2 of scenario 2 at the time of its maximum intensity occurring at 12:00 UT. The color scale is in TECU.

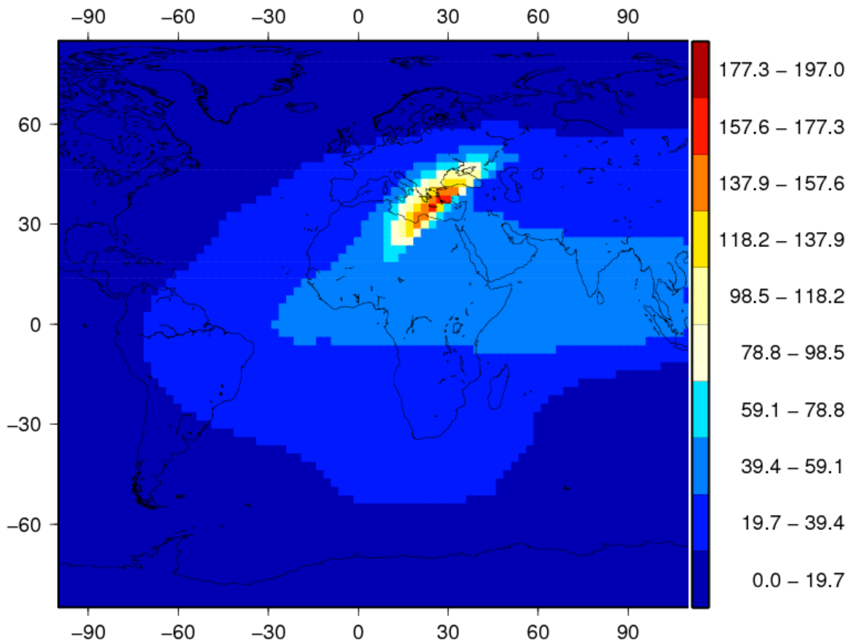

Figure 15. Same as previous figure but for day 3 in scenario 2.

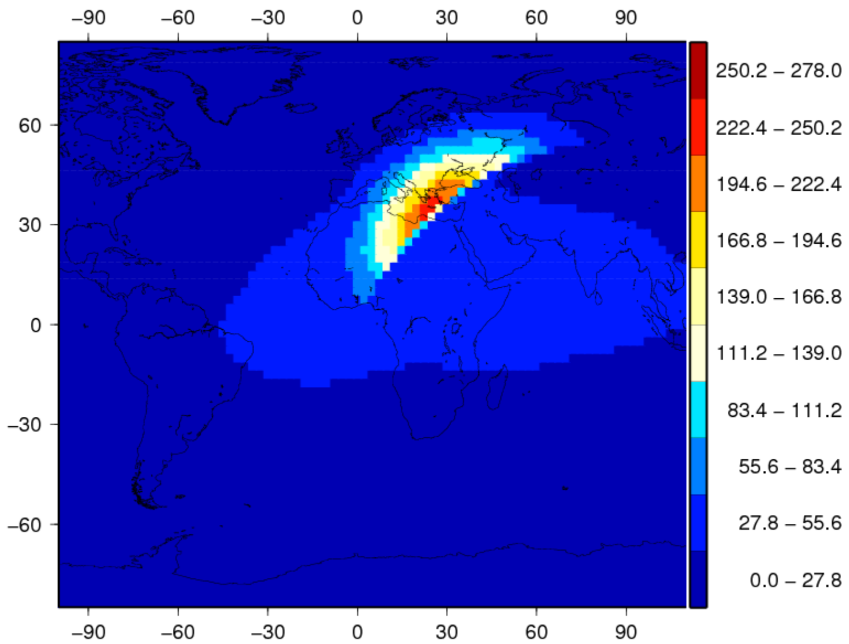

Figure 16. Same as previous figure but for day 4 in scenario 2.

6.3 Description of Scenario 3

In this scenario, the events are generated using a superposition of the GAUS and OSCN models. The particular function used to calculate the TEC excess for the events in this scenario is the following:

$$E_{TEC}(x,y) = \exp\{-y^2/S_W^2 - x^2/S_D^2\}\left[A_{max} + C_p(\cos k_p x - 1)\right] \quad (5)$$

As can be seen from equation (5), the shape in the direction orthogonal to the motion of the synthetic perturbation is a Gaussian function as in previous models. However, in the direction of motion the perturbation is the sum of a Gaussian function and a cosine representing an stationary wave of amplitude C_p and period T_p, while the wavenumber k_p is determined in the usual way from the period and the velocity of the perturbation as $k_p = 2\pi/(V_p \cdot T_p)$.

According to equation (5), the ionospheric synthetic events generated in this scenario will be characterized by oscillatory values of the VTEC, and the oscillations will grow and decay in the space following a Gaussian function resembling the evolution of a damped oscillator. The restriction $A_{max} \geq 2C_p$ must be applied to the maximum TEC and the amplitude of the perturbation to prevent negative values of the TEC excess in equation (5), but this does not impose severe limitations to the events that can be generated with this equation since the amplitude of STEC oscillations in real measurements hardly exceed 20 TECU, and in many cases, they are smaller than 10 TECU.

The interest of this scenario is the possibility of achieving large AATR values without using large TEC excess. In other words, the frequency of oscillation is used to generate a large AATR while the magnitude of the TEC excess caused by the event is kept in the lower range of values considered in scenarios 1 and 2. To this end, the parameters A_{max}, S_W and S_D, are fixed in this scenario to similar values as were used for the less severe events in day 2 of scenarios 1 and 2 (see Table 7). A slightly larger value of the deepness parameter has been taken to ensure that several periods of oscillation are reproduced by the TEC excess. Increasing severity for the events in scenario 3 is achieved for the non-nominal days by reducing the values of the period T_p of oscillation within the typical limits that reproduce realistic perturbations. The amplitude of the oscillations C_p is reduced as the period is increased in order to don't increase so much the AATR values. Table 8 gives the particular values that have been used for the non-nominal days of this scenario.

A_{max} (TECU)	S_W (km)	S_D (km)
50	2000	300

Table 7**.** Fixed parameters used for the events in scenario 3 (see also Table 3).

Day	C_p (TECU)	T_p (sec)
2	15	3600
3	10	1000
4	7,5	500

Table 8**.** Parameters used for the events in different days of the scenario 3.

An example of the AATR values that can be obtained in this scenario is shown in Figure 17 to Figure 19 . Also, color maps of the VTEC generated by events from different days of the scenario are presented in Figure 20 to Figure 22.

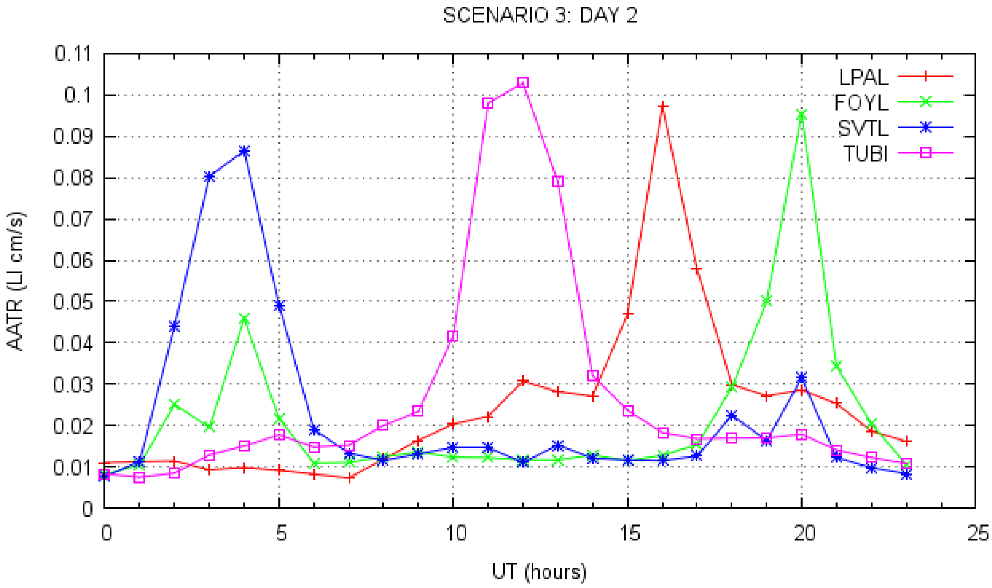

Figure 17. The AATR calculated for selected stations located in the proximity of the four events (when they had maximum severity) in day 2 of scenario 3.

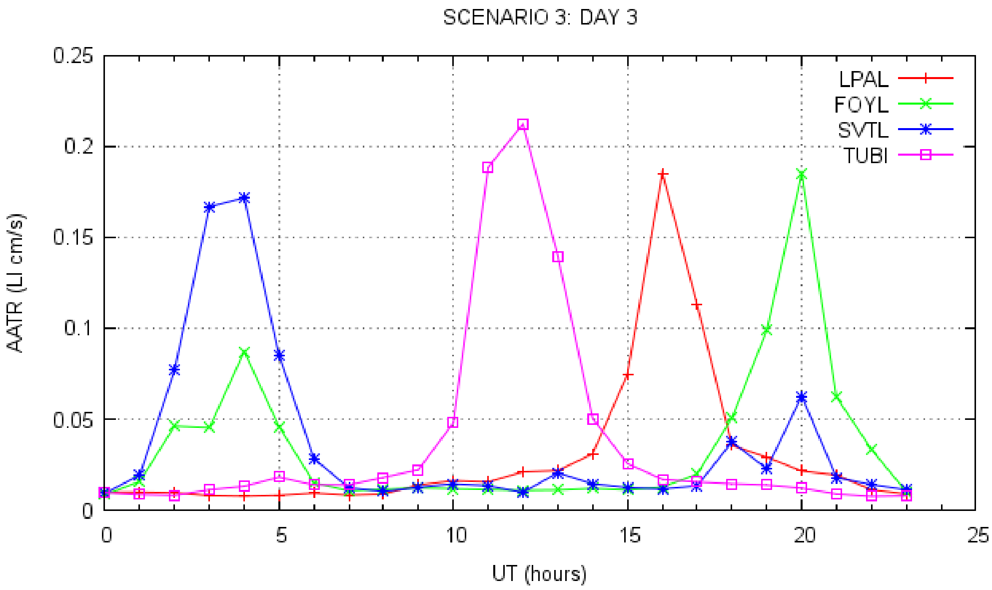

Figure 18. Same as previous figure but for day 3 of scenario 3.

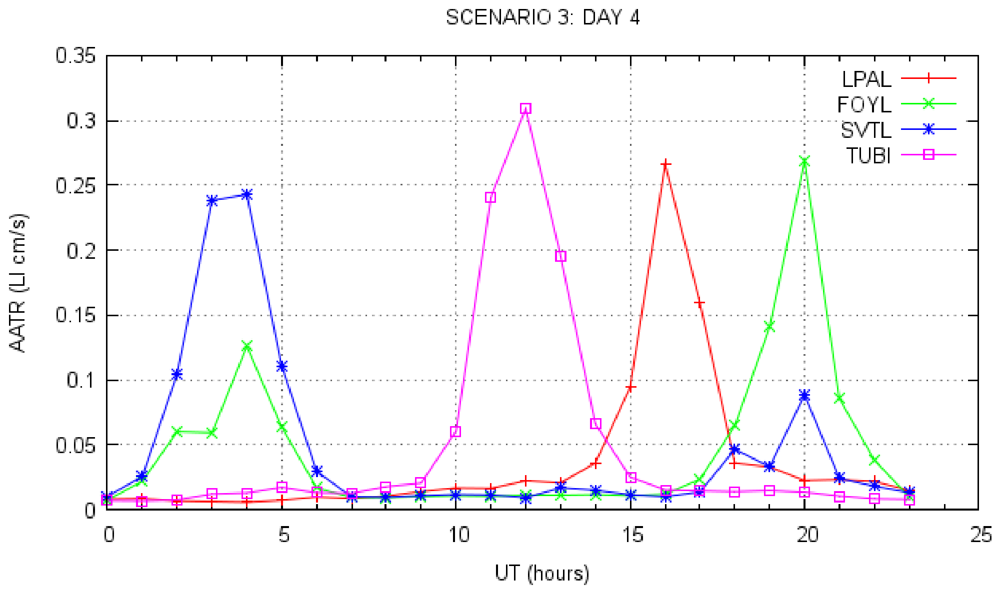

Figure 19. Same as previous figure but for day 4 of scenario 3.

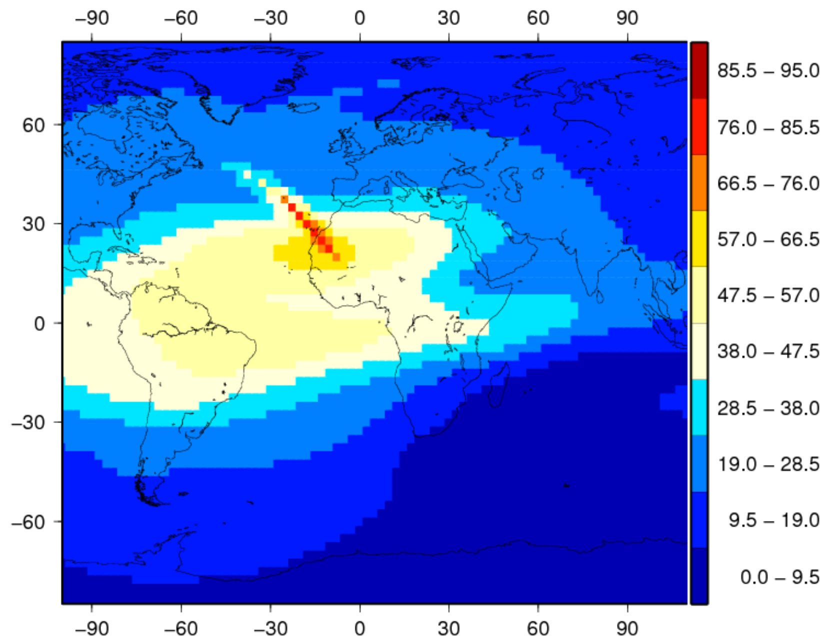

Figure 20. VTEC colour map showing event 1 during day 2 of scenario 3 at the time of its maximum intensity occurring at 17:00 UT. The color scale is in TECU.

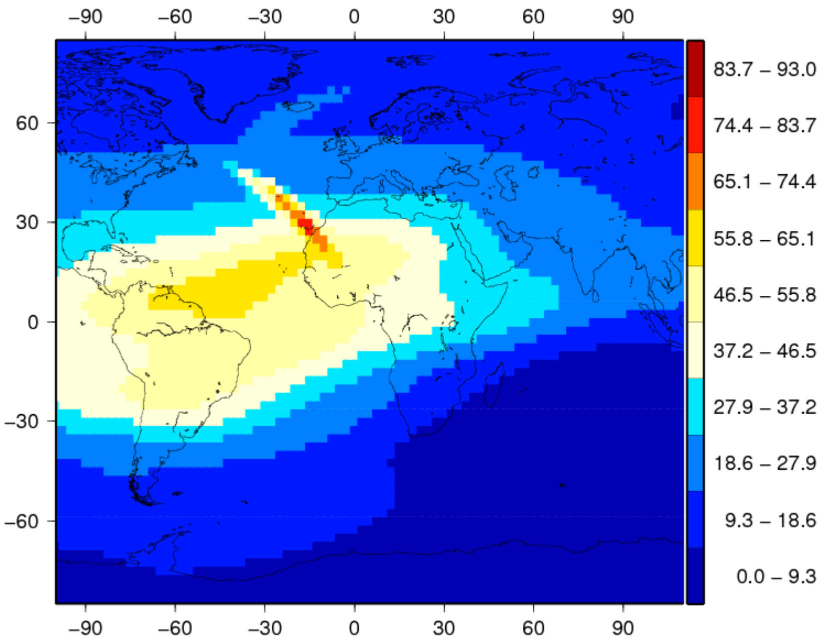

Figure 21. Same as previous figure but for day 3 in scenario 3.

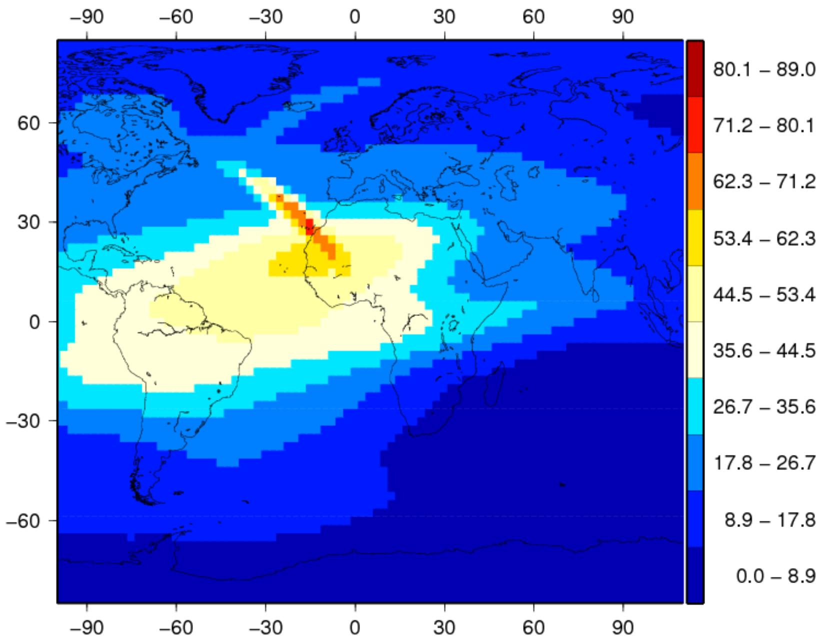

Figure 22. Same as previous figure but for day 4 in scenario 3.

6.4 Description of Scenario 4

The model EXPO is used for generating the synthetic events in this scenario which has been designed to include events that combine low and high propagation velocities with a longer duration of the perturbation with regard to the other 3 previous scenarios. The amplitude, wideness and deepness in this scenario have been fixed to the lowest values considered in scenario 2 (that used the same model EXPO) and they are reproduced in Table 9.

Day	V_p (m/s)	A_{max} (TECU)	S_W (km)	S_D (km)	S'_D (km)
2	50	60	1000	200	500
3	150	60	1000	200	500
4	450	60	1000	200	500

Table 9. Parameters used for the events in different days of scenario 4 (see also Table 4).

The severity of the synthetic events in the successive days of scenario 4 is regulated by the velocity of propagation of the events. Increasing severity is obtained by augmenting the magnitude of the parameter V_p between consecutive days of the scenario. The extreme values considered are consistent with observations of real ionospheric events. Finally, as it has been commented before, due to the longer duration considered for the events in this scenario (four hours instead of two hours used in the other scenarios), the number of events per day has been reduced from 4 to 3 to minimize the spatial and temporal coincidence of the events over the ECAC region during the periods of greatest intensity of the events. In general, this scenario reproduces a kind of events having not very large STEC values but still leading to significant AATR values that may last during a long period of time. Figure 23 shows a comparison of the STEC measurements reproduced by this and the other three scenarios during the day 4 (when the events have the largest severity) for the ground station SVTL and GPS satellite PRN 7.

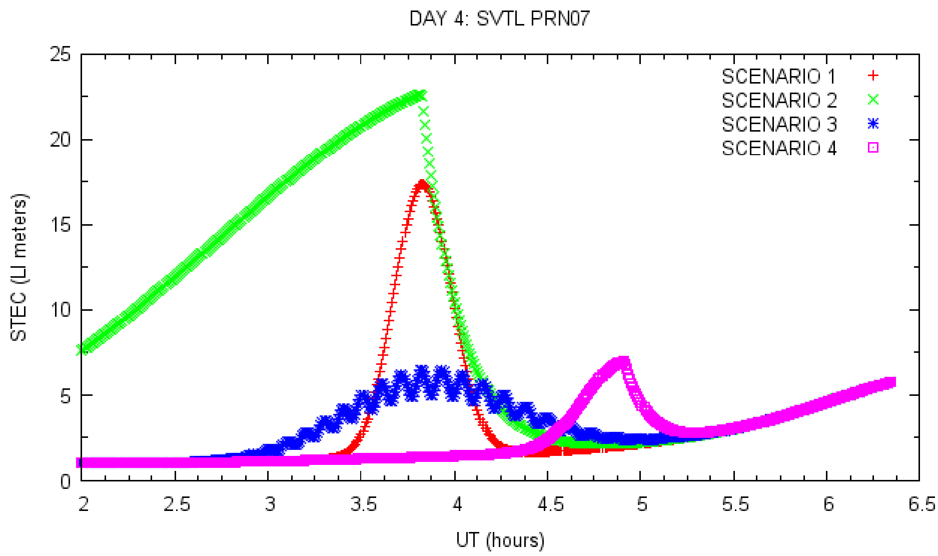

Figure 23. Comparison of the STEC measurements generated from different scenarios for the particular case of the station SVTL and the GPS satellite PRN 7.

Figure 24 to Figure 26 show some examples of the values achieved by the AATR in this scenario. The results for the LPAL station have also been represented just to illustrate the differences with the other three previous scenarios, but note that the event near that station has been eliminated from this scenario, which has 3 events per day instead of 4 for the reasons that were explained above. Figure 27 to Figure 29 show examples of color maps of the VTEC obtained during the different days of the scenario.

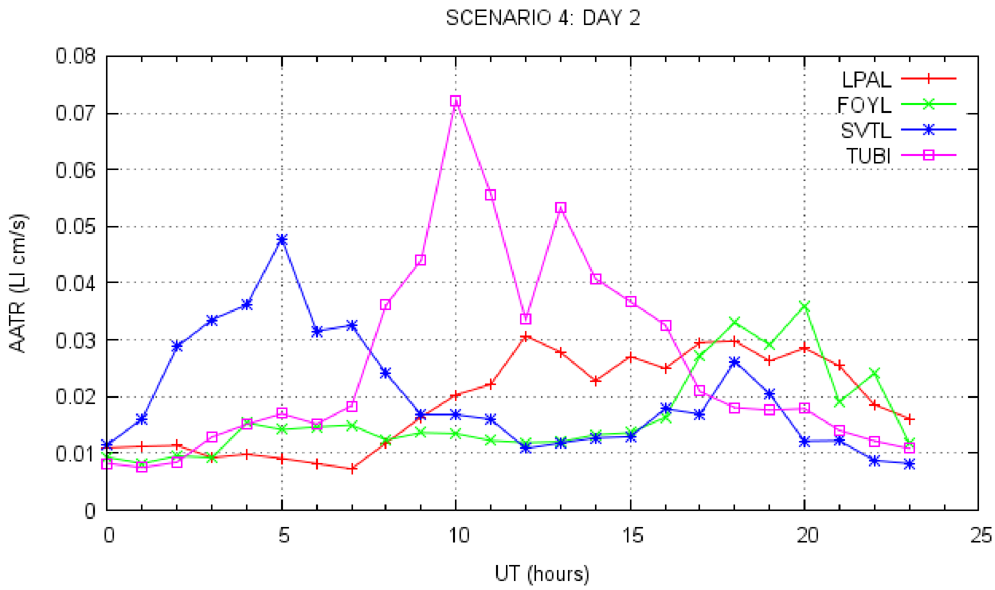

Figure 24. The AATR calculated for selected stations located in the proximity of the three events (when they had maximum severity) in day 2 of scenario 4.

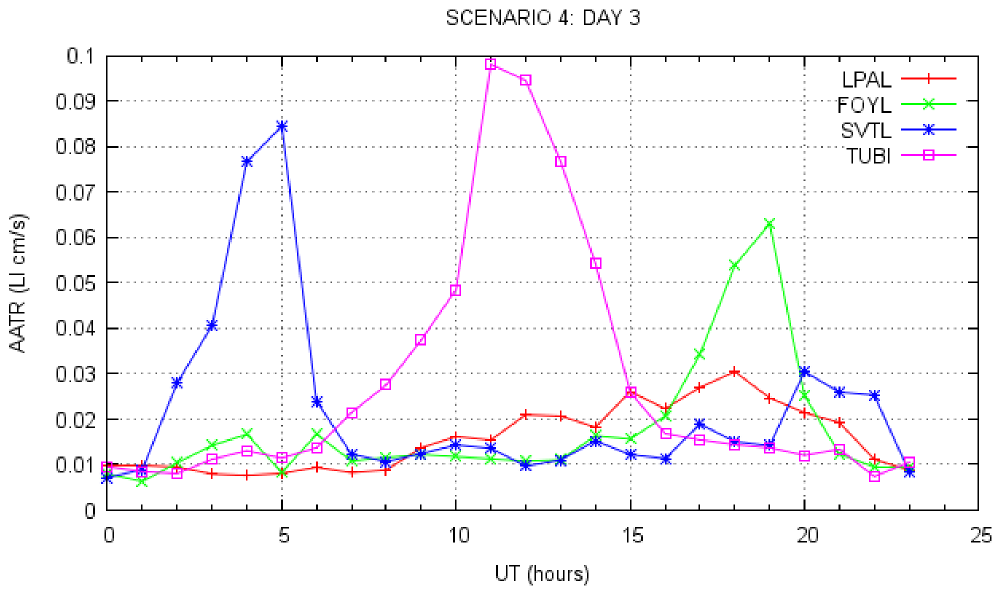

Figure 25. Same as previous figure but for day 3 of scenario 4.

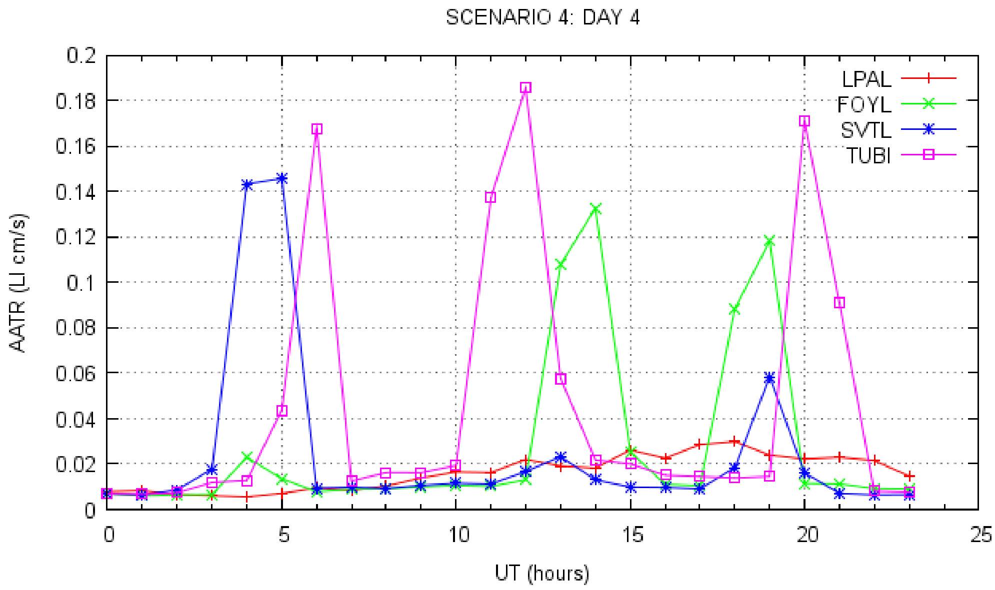

Figure 26. Same as previous figure but for day 4 of scenario 4.

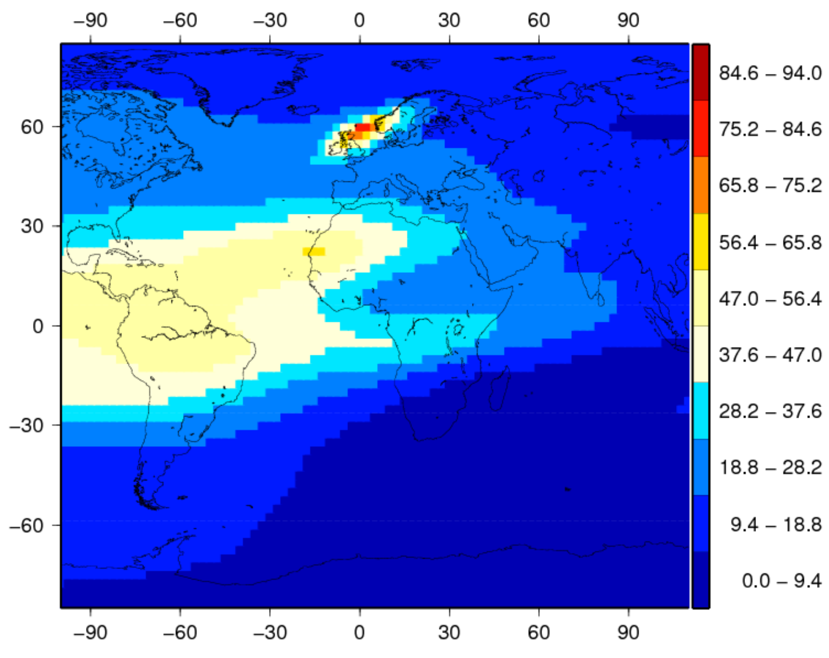

Figure 27. VTEC colour map showing event 1 during day 2 of scenario 4 at the time of its maximum intensity occurring at 19:00 UT. The color scale is in TECU.

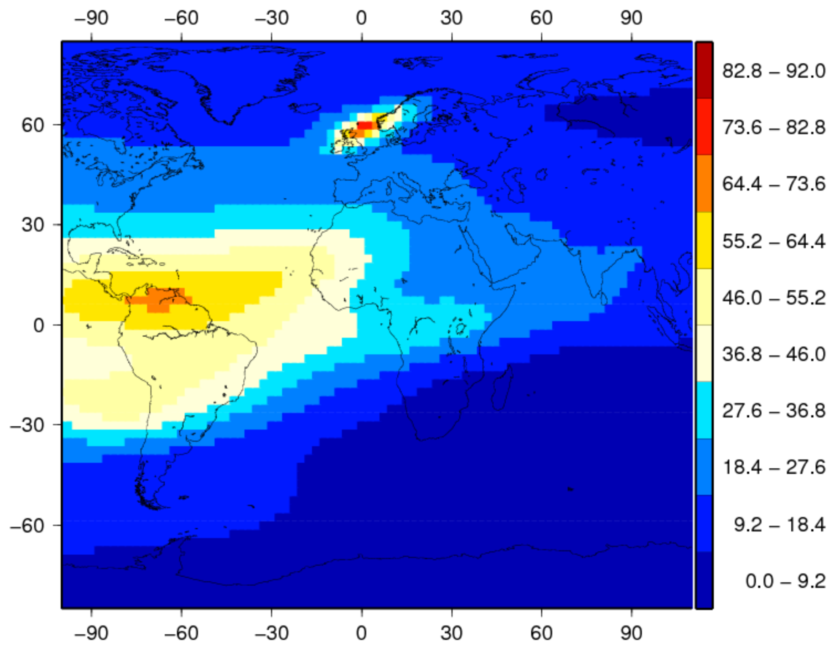

Figure 28. Same as previous figure but for day 3 in scenario 4.

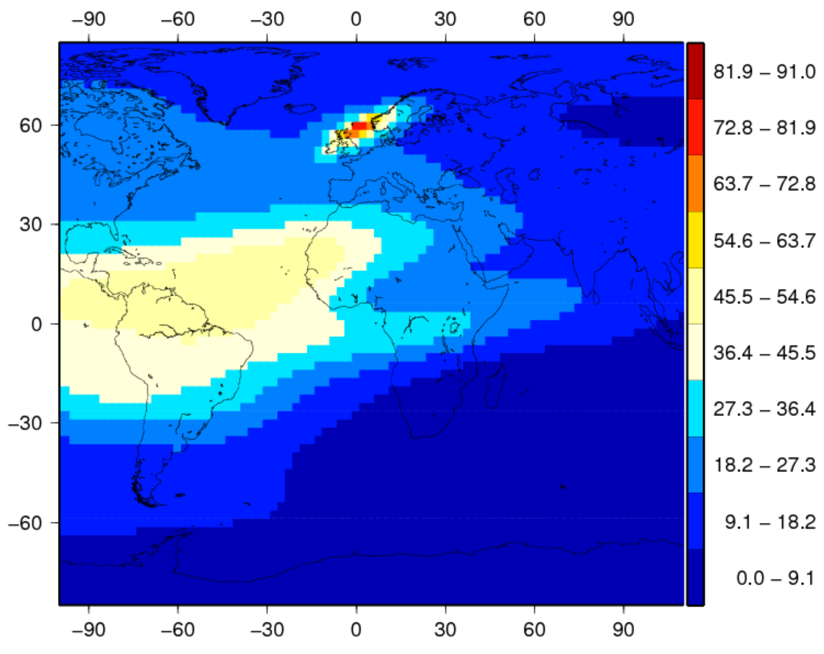

Figure 29. Same as previous figure but for day 4 in scenario 4.

7. SUMMARY AND CONCLUSIONS

In this report we have presented the work done into the task3 of ICASE2 project. In this sense we have generated a set of 4 scenarios, simulating different ionospheric effects at different intensity levels characterized by the AATR index.

Every scenario consists of 4 days starting on a day with nominal/quiet ionospheric conditions and, in the following days, ionospheric activity increases from moderate (2nd day) to severe (4th day).

The geometry of all the generated scenarios corresponds to the actual geometry during the days 225--228 in 2012. The ionospheric perturbations have been generated taking into account actual ionospheric disturbances that have been found during the ICASES-1 or ICASES-2 projects. In this sense the simulated perturbations are:

1.- A gaussian enhancement of TEC which propagates at 100m/s in several directions and several amplitudes.

2.- An exponential decay of TEC which propagates at 100m/s in several directions and several amplitudes.

3.- An oscillating variation of TEC which propagates at 100m/s in several directions with several amplitudes

4.- An exponential decay of TEC which propagates at several velocities in several directions.

In general, with these simulations, we achieve AATR values from close to 0.1 LI cm/s, during the 2nd day, to more than 0.4 LI cm/s during the last day of some scenarios.

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