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Warning and Mitigation Technologies for Travelling Ionospheric Disturbances Effects

TechTIDE

D2.1

Report on the design and specifications of the TID algorithms and products

Version 2.3

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Abstract

This deliverable presents the design of the basic TID detection codes followed by the upgrades resulted from the analysis of the users' requirements, and provides the specification of the value-added products resulted from the basic codes.

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Executive Summary

TechTIDE project, funded by the European Commission Horizon 2020 research and innovation program [AD-1], will establish a pre-operational system to demonstrate reliability of a set of TID (Travelling Ionospheric Disturbances) detection methodologies to issue warnings of the occurrence of TIDs over the region extended from Europe to South Africa. TechTIDE warning system will estimate the parameters that specify the TID characteristics and the inferred perturbation, with all additional geophysical information to the users to help them assess the risks and to develop mitigation techniques, tailored to their application. This document is TechTIDE D2.1 "*Report on the design and specifications of the TID algorithms and products*" and it is an output of TechTIDE Task 2.1 (Specifications for the TID algorithms and the resulting products) of the WP2 (TID identification methodologies) which has the final goal to release the basic algorithms for the TID identification and the value-added products for implementation in the TechTIDE warning system. The document presents the design of adjusted and upgraded TID detection codes, the design of the value-added products, and the validation plan. The design of the adjustments and the upgrades of the different methods are based on the initial requirements gathered among potential users affected by TIDs [RD-1]. Some requirements were brought in from ESA Space Situational Awareness Space Weather (SSA SWE) [RD-2] users' requirements. This way, TID algorithms and product outputs will try to adapt to assess ESA SSA SWE Service Network prerequisites.

1. Introduction

1.1 Purpose and Scope of the Document

This document presents the design, adjustments and upgrades of the TIDs detection algorithms, the design of the value-added products, and validation methodology. The document is divided into four sections:

Section 1 (the current section) describes the purpose of this document and its organization.

Section 2 lists the applicable and reference documents and also contains the list of acronyms used in this document.

Section 3 describes the current status and capabilities of the TID detection methodologies.

Section 4 describes the design of adjustments and upgrades trying to adopt the initial requirements gathered among users affected by TIDs. This section is divided into four parts. The first part details the capability of each method to fulfill the users' requirements. The second part presents the upgrades that are required to meet the users' requirements, according to the current monitoring capabilities. The third part, summarizes the value-added products planned to be released in order to satisfy the requirements of the users.

Section 5 is the conclusion section providing the time plan of the WP2 activities also in relation to WP3 work plan where the results of all TID detection methodologies will be cross-validated and evaluated based on the assessment of current geospatial and lower atmosphere conditions.

2 Associated documents

2.1 Applicable Documents

The following table contains the list of applicable documents.

Table 1. List of applicable documents

AD	Document title
[AD-1]	Grant Agreement number: 776011 — TechTIDE — H2020-COMPET-2017

2.2 Reference Documents

The following table contains the list of references used in this document.

Table 2. List of reference documents

RD	Document title
[RD-1]	TechTIDE D1.1 Initial Users´ Requirements report. February 2018
[RD-2]	ESA SSA Team, "Space Situational Awareness – Space Weather Customer Requirements Document", Rev.5a, SSA-SWE-RS-CRD-1001, 2011-07-28
[RD-3]	Reinisch, B., Galkin, I., Belehaki, A., et al. (2018). Pilot ionosonde network for identification of traveling ionospheric disturbances. Radio Science, 53; doi; 10.1002/2017RS006263
[RD-4]	Huang, X., Reinisch, B. W., Sales, G. S., Paznukhov, V. V., & Galkin, I. A. (2016). Comparing TID simulations using 3-D ray tracing and mirror reflection. Radio Science, 51, 337–343; doi 10.1002/2015RS005872
[RD-5]	Paznukhov, V. V., Galushko, V. G., & Reinisch, B. W. (2012). Digisonde observations of AGWs/TIDs with Frequency and Angular Sounding Technique. Advances in Space Research, 49(4), 700–710; doi 10.1016/j.asr.2011.11.012
[RD-6]	Altadill, D., E. Blanch, V. Paznukhov, et al, Identification of travelling ionospheric disturbances applying interferometry analysis to classical ionogram data from an ionosonde network, IEEE-TGARS, 2017 (submitted)
[RD-7]	Hernandez-Pajares, M., Juan, J. M., & Sanz, J. (2006). Medium-scale traveling ionospheric disturbances affecting GPS measurements: Spatial and temporal analysis. Journal of Geophysical Research, 111, A07S11; doi 10.1029/2005JA011474
[RD-8]	Borries C., N. Jakowski, K. Kauristie, et al. (2017), On the dynamics of Large-Scale Travelling Ionospheric Disturbances over Europe on 20th November 2003, J. Geophys. Res., 122, doi:10.1002/2016JA023050.

RD	Document title
[RD-9]	Kutiev, I., P. Marinov, and A. Belehaki (2016), Real time 3-D electron density reconstruction over Europe by using TaD profiler, Radio Sci., 51, doi:10.1002/2015RS005932.
[RD-10]	Belehaki, A., I. Kutiev, P. Marinov, et al. (2016) Ionospheric electron density perturbations during the 7–10 March 2012 geomagnetic storm period, Advances in Space Research, ISSN 0273-1177, doi 10.1016/j.asr.2016.11.031
[RD-11]	Haldoupis, C., Meek, C., Christakis, N., Pancheva, D., Bourdillon, A. (2006). Ionogram height–time–intensity observations of descending sporadic E layers at mid- latitude. Journal of Atmospheric and Solar Terrestrial Physics 68, 539–557.
[RD-12]	Lastovicka, J., Chum, J., 2017, A review of results of the international ionospheric Doppler sounder network, Adv. Space Res. (in press).
[RD-13]	Sanz, J., J.M. Juan and G. González-Casado, et al. (2014) Novel Ionospheric Activity Indicator Specifically Tailored for GNSS Users. Proc. 27th International Technical Meeting of The ION GNSS+ 2014, Florida, September 8-12, 2014.
[RD-14]	Farmer J. D., Sidorowich J.J., Predicting chaotic time series, Physics Review Letters 59, 845-848, 1987.
[RD-15]	Farmer J. D., Sidorowich J.J, Exploiting chaos to predict the future and reduce noise, Evolution, Learning and Cognition, ed Y.C. Lee, World Scientific Press, New York, 1988.
[RD-16]	Juan J.M., Sanz J., Rovira-Garcia A., González-Casado G., D. Ibáñez-Segura, Orus R. (2018) “AATR an Ionospheric Activity Indicator Specifically based on GNSS Measurements”, Journal of Space Weather Space Climate 8:A14, pp 1-11, DOI 10.1051/swsc/2017044

2.3 Acronyms

The following table contains the list of all acronyms used in this document.

Table 3. List of acronyms

Acronym	Definition
2D	2-Dimension
3D	3-Dimension
AATR	Along-arc TEC rate
BGD	Borealis Global Designs Ltd.
CDSS	Continuous Doppler Sounding System
DLR	German Aerospace Center
DPS4D	Digisonde-Portable-Sounder-4D
EDD	electron density distribution
EGNOS	European Geostationary Navigation Overlay Service
FU	Frederick University
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
HF	High Frequency
HTI	Height-time-reflection intensity
IAP	Institute of Atmospheric Physics (Academy of Sciences of Czech Republic)
IdN	Identification Number
LSTID	Large Scale TID
MSTID	Medium Scale TID
MUF	Maximum Usable Frequency
NOA	National Observatory of Athens
OE	Fundació Observatori de l’Ebre
OI	Oblique Incidence
OTHR	Over The Horizon Radar
PFA	Probability of false alarm
POD	Probability of detection
ROT	Rate of TEC

Acronym	Definition
Rx	Receiver
SNR	Signal-to-Noise Ratio
SSA SWE	Space Situational Awareness Space Weather
SSN	Sunspot Number
TEC	Total Electron Content
TID	Travelling Ionospheric Disturbance
Tx	Transmitter
UPC	Universitat Politècnica de Catalunya
VI	Vertical Incidence
WP	Work-package

3. The TID methods and products in TechTIDE

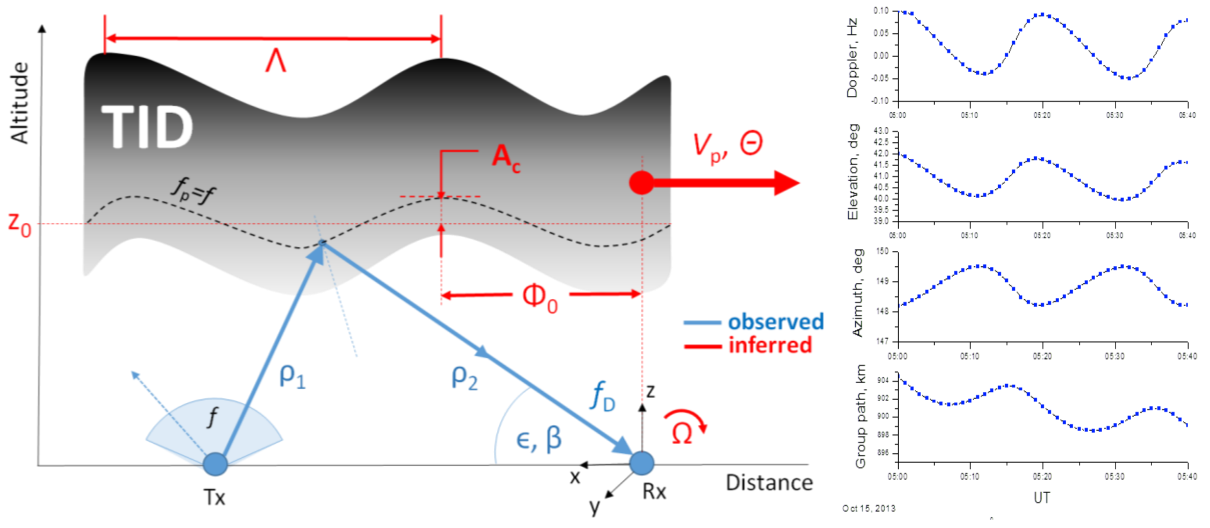
This section presents an introduction to the TIDs methodologies and products in TechTIDE. A summary table of such a TID identification methods can be found in section 5.

3.1 HF-TID

HF-TID is a direct sensing method for the monostatic/bistatic measurements of TIDs based on detection of quasi-periodic oscillations that the high-frequency (HF) sensor signal exhibits as it propagates the trans-ionospheric channel modulated by the traveling density perturbations. [RD-3].

3.1.1 Problem statement

In a simple case of one wave-like traveling disturbance of amplitude A and wavelength Λ (Figure 1a), propagating horizontally with a phase velocity V_p and travel azimuth Θ, the HF radio signal that traverses the ionospheric channel exhibits distinct oscillating patterns of the temporal variation of its properties (Figure 1b): Doppler frequency $\delta(t)$, angles of elevation $\varepsilon(t)$ and azimuth $\beta(t)$, and time-of-flight $\tau(t)$ (or the equivalent group path $\rho(t) = c \cdot \tau(t)$, where c is the free-space speed of light) [RD-4].



(a) (b)

Figure 1. HF-TID method
(a) TID model as a perfectly reflecting corrugated mirror (dashed line) moving across the area (red arrow) and causing variations of the OI signal (blue line) characteristics {ρ(t), δ(t), ε(t), β(t)}. (b) Simulation of 5 MHz signal variation on a 200 km radiolink for a 10% 20-minute southward TID.

HF-TID associates the *observed* signal variations of $\varepsilon(t)$, $\beta(t)$, $\delta(t)$, and $\rho(t)$ at the dominant TID wave angular frequency Ω with the *underlying* TID phenomenon defined by A, Λ, V_p, and Θ.

3.1.1 FAS method for TID evaluation

While all signal properties vary with the angular frequency Ω (Figure 1b), in practice it is the Doppler frequency variation $\delta(t)$ that proved to be the most reliable indicator for the detecting of such quasi-sinusoidal variations. To determine the dominant Ω value, HF-TID method therefore first calculates the spectrum S_δ by running a Discrete Fourier Transform (DFT) on the input $\delta(t)$ time series. The DFT operation uses analysis windows of various durations for improved frequency resolution and a better match to the naturally occurring TID period T_Ω. The frequency Ω at which $S_\delta(\Omega)$ has its maximum value over all computations is selected as the dominant TID wave frequency. At this selected Ω, the FFT operation is then applied over the elevation angle $\varepsilon(t)$ and the azimuth angle $\beta(t)$ to obtain $S_\varepsilon(\Omega)$ and $S_\beta(\Omega)$, respectively. Finally, the TID model parameters A, Λ, V_p, and Θ are obtained as:

$$A_N = iS_\delta(\Omega)\frac{\lambda}{2\Omega z_0 \sin\varepsilon_0} \tag{1}$$

$$K = \frac{2\pi}{\Lambda} = -\frac{2\Omega \operatorname{Im} S_\beta \cos\varepsilon_0}{\lambda \operatorname{Im} S_\delta \sin\Theta} \tag{2}$$

$$\tan\Theta = -\frac{2z_0\Omega \operatorname{Re} S_\beta}{2z_0\Omega \operatorname{Re} S_\varepsilon \tan\varepsilon_0 + \lambda \operatorname{Im} S_\delta \sin\varepsilon_0} \tag{3}$$

$$V_p = \frac{\Omega}{K} \tag{4}$$

where $\lambda = c/f$ is the free-space wavelength of the signal carrier at transmission frequency *f*, and the altitude z_0 of the reflecting mirror can be estimated using the average ε_0 of the measured elevation angles $\varepsilon(t)$ of the arriving signal and the ground distance G_{TR} between transmitter and receiver, $z_0 \cong 1/2\, G_{TR} \tan(\varepsilon_0)$.

TID parameters are computed using a simplified representation of the ionosphere as a sinusoidal-wave corrugated mirror moving at a constant horizontal phase velocity (Figure 1a). Computation of TID parameters using Eq.(1-4) is commonly referred to as Frequency-Angular Sounding technique (FAS) [RD-5].

3.2 HF Interferometry

HF Interferometry is a method to identify LSTIDs for the monostatic measurements of a given network of HF sensors (Ionosondes). The method detects quasi-periodic oscillations of ionospheric characteristics, identifies coherent oscillation activity at different measuring sites of the network and sets bounds to time intervals for which such activity occurs into a given region. The TID candidate effects on ionospheric variations are isolated by applying a disturbance model. The dominant period of oscillation and amplitude of the LSTID are obtained by spectral analysis. This allows for identification of TID activity from Digisonde Networks (Figure 2) [RD-6]. Note that shaded areas in figures 2(b) and 2(d) show incoherent disturbances and oscillation activity respectively.

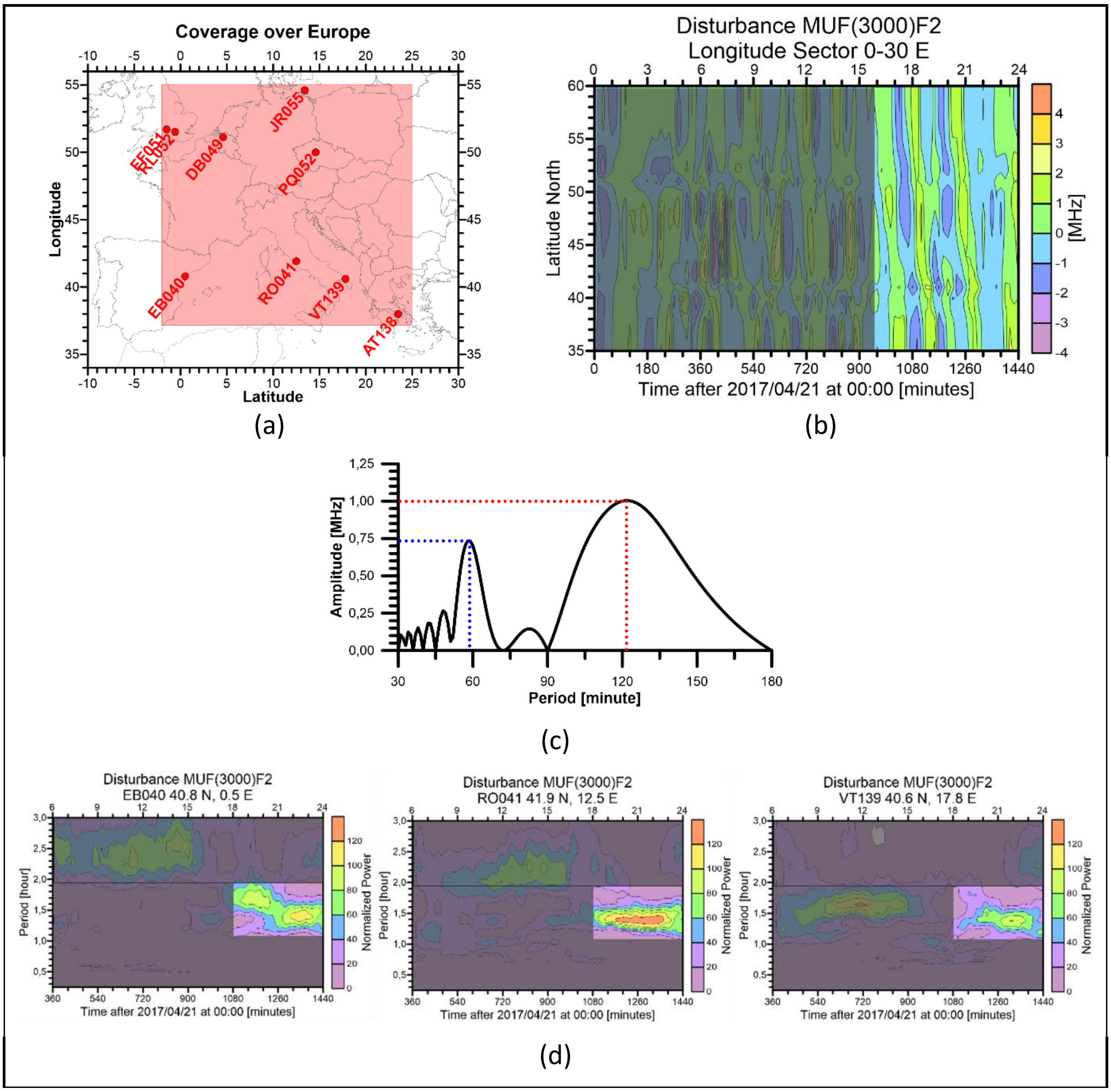


Figure 2. HF Interferometry Method

(a) Geographical distribution of the HF sensors in Europe. (b) Coherent disturbance of a given ionospheric characteristic in the European region. (c) Estimation of dominant period of oscillation and amplitude by spectral analysis. (d) Detection of coherent oscillation activity at different measuring sites.

The propagation parameters are reconstructed from the measured time delays of the disturbance of a given ionospheric characteristic at different sensor sites. The time delay Δt_i of the disturbance with respect to a reference sensor is expressed as $\Delta t_i = \vec{s} \cdot \Delta\vec{r}_i$, where $\vec{s} = \vec{v}/v^2$ is the slowness vector of the disturbance propagating with the velocity $\vec{v}$, and $\Delta\vec{r}_i$ is the relative position vector of the ith sensor with respect to the reference. Δt_i are obtained by correlation analysis to multi-site measurements and $\vec{s}$ is estimated solving Equation (5). Finally, the 2D vector velocity of the LSTID is obtained according to Equation (6).

$$\Delta t_i - \vec{s} \cdot \Delta\vec{r}_i = 0. \tag{5}$$

$$\vec{v} = \frac{\vec{s}}{s^2}. \tag{6}$$

Due to the geographical distribution of Digisonde sites within Europe network (distant by about 1000 km from to each other), only identification of LSTID is feasible in principle, which are associated with auroral and geomagnetic activity, directly related to Space Weather [RD-6].

3.3. *Spatial and Temporal GNSS Analysis*

The procedure to detect and to characterize TIDs, including velocity and period will be based on the Spatial and Temporal analysis of GNSS measurements [RD-7]. This procedure allows the study of any ionospheric perturbation (including MSTID or LSTID) and can be used for detecting the TID (with a single receiver) or estimating the propagation parameters (from a network of receivers). The basic GNSS measurement used is the geometry-free combination of carrier phases, with measurement noise at the level of few millimeters. The first step for the TID detection is to detrend the data in order to remove the well-known dependences, such as diurnal and elevation angle variations, having larger time scales than the TID. This detrending can be applied in real-time and for a single receiver. Therefore, information about the TID occurrence can be obtained for the monitored region (around the receiver). Figure 3 shows for three different receivers the original measurements on the left, and the de-trended data on the right. The baselines are less than 40 km, clearly under the MSTID wavelength.

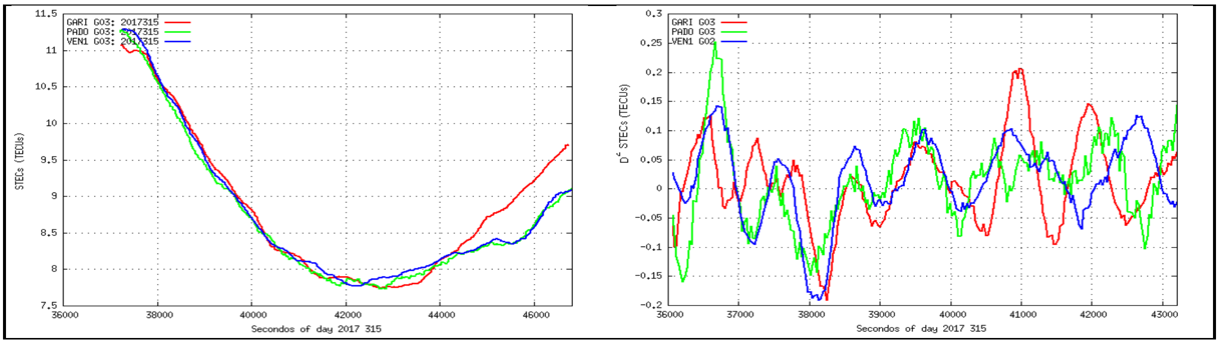


Figure 3. Spatial and Temporal GNSS Analysis
Example of de-trending and temporal variation procedure for three GNSS receivers.

After de-trending the measurements, it is possible to detect, in any of the receivers, the fluctuations associated with the TIDs. Similarly to the method above, it is possible to estimate the propagation parameters (propagation direction, velocity and amplitude) by correlating these fluctuations on the different receivers in the network. Here $\Delta t_i = \vec{s} \cdot (\Delta\vec{r}_i + \vec{v}_{IPP} \cdot \Delta t_i)$, where $\vec{s} = \vec{v}/v^2$ is the slowness vector of the disturbance propagating with the velocity $\vec{v}$, $\Delta\vec{r}_i$ is the relative position vector of the ith sensor with respect to the reference, and $\vec{v}_{IPP}$ is the velocity of the ionospheric pierce point. Δt_i are obtained by correlation analysis to multi-site measurements and $\vec{s}$ is estimated solving Equation (7). Finally, the 2D vector velocity of the LSTID is obtained according to Equation (6).

$$\Delta t_i - \vec{s} \cdot (\Delta\vec{r}_i + \vec{v}_{IPP} \cdot \Delta t_i) = 0. \tag{7}$$

The same procedure can be applied for LSTIDs and MSTIDs, but, for the detrending, one has to take into account the characteristic periods of these two TIDs.

3.4. GNSS TEC gradient algorithms

Large scale Travelling Ionospheric Disturbances (TIDs) occurring during geomagnetic storms produce strong temporal and spatial TEC gradients which are observed closest to the source region of LSTIDs. These gradients are attributed to heating and convection processes which are related to the excitation of LSTIDs [RD-8]. Temporal and spatial gradients are calculated based on maps of TEC. Figure 4 presents the results of this method applied on the 20 November 2003 storm.

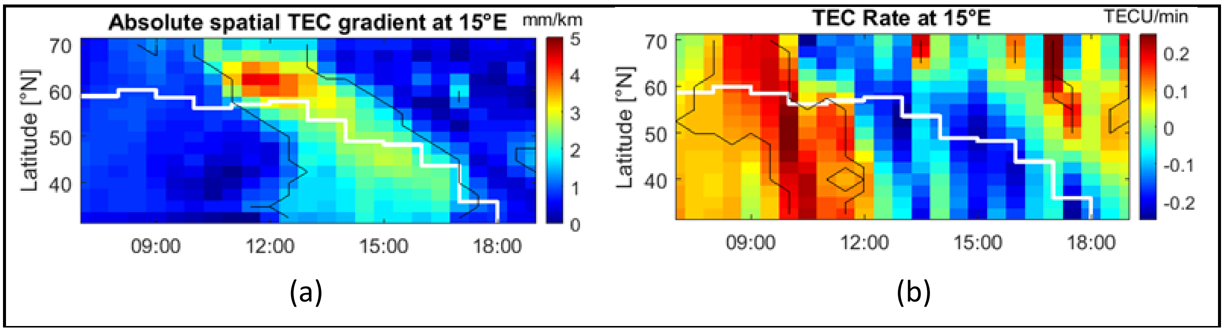


Figure 4. GNSS TEC gradient method
Results for 20 November 2003, (a) shows the spatial TEC gradients and (b) the TEC rate derived from DLR TEC maps at 15°E.

In Figure 4, both the spatial TEC gradients (a) and the TEC rate (b) are derived from DLR TEC maps at 15°E. The white line approximates the trough location. Large-scale TEC gradients are routinely produced by the DLR and the results will be used on TechTIDE for the real-time identification of LSTIDs and the identification of the source region.

3.5. 3D-EDD Maps

The method for the reconstruction of the 3D electron density distribution (EDD) over Europe in real time [RD-9] is developed on the basis of the TSM-assisted Digisonde (TaD) profiler [RD-10]. The TaD profiler, provides vertical electron density profiles (EDP) over Digisonde sounding stations operating in Europe, from the bottom of the ionosphere up to the GNSS orbit altitude. The 2D maps of the basic ionospheric plasma parameters for the height of maximum electron density concentration are developed by Polyweight interpolation method. TaD profiler calculates ED profiles at each node and adjusts them to the GNSS-TEC values extracted from the GNSS TEC maps, thus obtaining the 3D EDD.

Electron density at any arbitrary point within the 3D space is calculated by a linear interpolation from their respective values at the neighboring grid nodes The EDD between any two points in the space is then obtained by calculating successive ED values with a defined step along the ray-path (Figure 5). The model error based on the comparison of 3D EDD model values with vertical TEC (vTEC) and slant TEC (sTEC), calculated from individual GNSS receivers, is 10% for sTEC and 6% for vTEC. [RD-10] showed the sensitivity of the TaD EDD in TIDs and the model capability to detect the altitude of the maximum perturbation.

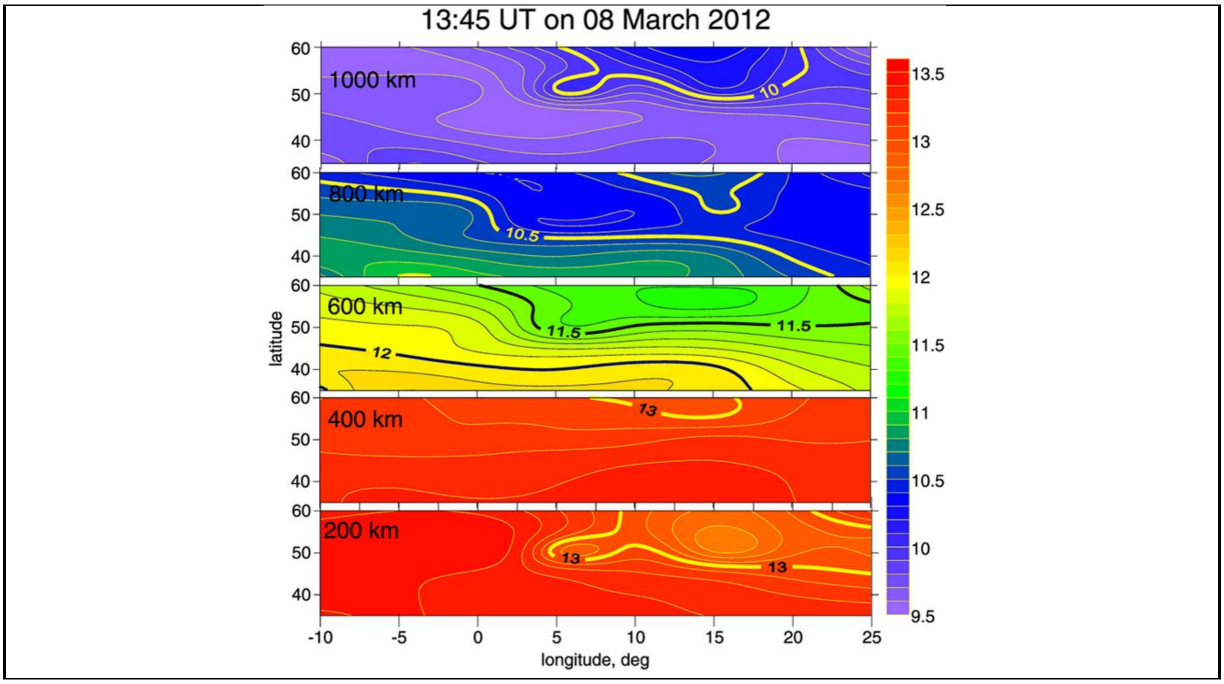


Figure 5. 3D EDD Maps

Performance of the TaD 3D EDD method for a fixed time stamp during the intense geomagnetic storm on 8 March 2012. Altitude slices of EDD are shown in steps of 200 km.

3.6. HTI Method

The height-time-reflection intensity (HTI) methodology [RD-11] is similar to the technique producing range-time intensity (RTI) radar displays within a given time interval. The application of this method in TechTIDE will enable the identification and tracking of the TID activity over each Digisonde station by using the actual ionograms produced over each station. This technique considers an ionogram as a ‘‘snapshot’’ of reflected intensity as a function of height and Digisonde signal frequency, and it uses a sequence of ionograms to compute an average HTI plot, (for a given frequency bin) that is essentially a 3-D plot of reflected signal-to-noise ratio in dB as a function of height within a given time interval. This display reveals dynamic changes in the ionosphere. Figure 6 depicts a typical output of the HTI method for three Digisonde stations over Europe (Nicosia, Athens and Pruhonice) showing TID-like variations, for 7 December 2016. It corresponds to a Digisonde frequency band, of 2-4 MHz. The periodicity of the dominant wave activity will be estimated by applying spectral analysis algorithms on the strongest reflected signals.

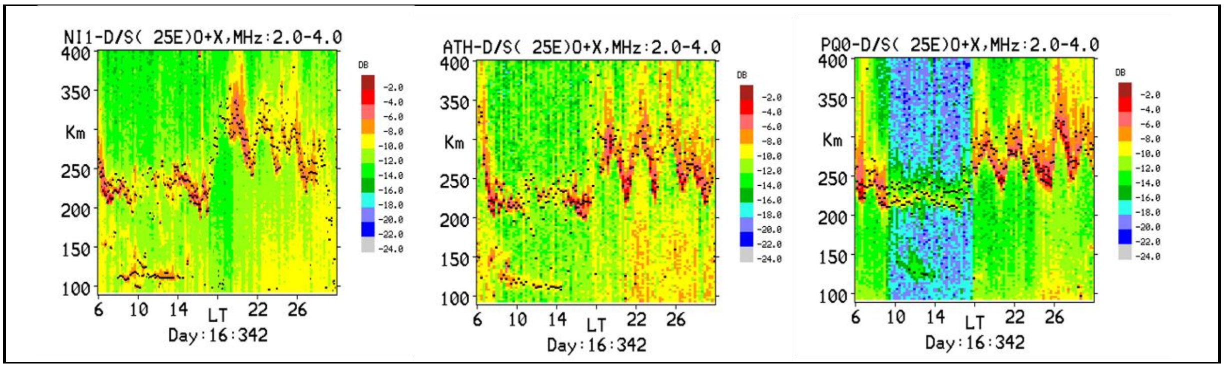


Figure 6. HTI Method
Digisonde HTI plots over Nicosia (left), Athens (middle) and Pruhonice (right) for December 7, 2016.

3.7. *CDSS-MSTID Method*

The multipoint Continuous Doppler Sounding System (CDSS) currently operating at three frequencies (f=3.59, 4.65 and 7.04 MHz) in the Czech Republic and in South Africa will be used to detect MSTID. The basic principles of the method have been tested [RD-12]. Thanks to several sounding paths (transmitter – receiver pairs) at each frequency, fluctuations of the Doppler shift of the transmitted frequencies caused by the TIDs passing over reflection point are detected and characteristics of MSTIDs can be estimated. CDSS method is suitable for the monitoring of infrasound and MSTIDs triggered by tropospheric events, increased seismic or geomagnetic activity but not for LSTIDs since the distances between Tx and Rx have a size of the order at about 50 to 100 km and because the slower temporal changes of LSTIDs have less effects in the Doppler making CDSS is less sensitive to it. Location of the Czech CDSS transmitters and receiver and an example of the 25 June, 2008 CDSS measurements during the intense convective storm is shown in the Figure 7. A squall line was formed at ~15:30 UT along the north-western boarders of the Czech Republic and moved to the south-east, abated after 19:00 UT easterly from CDSS.

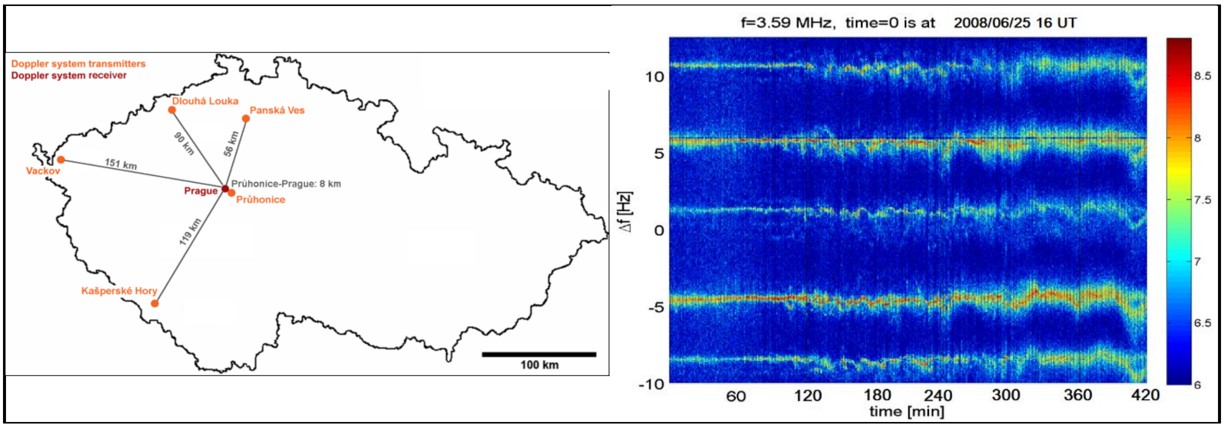


Figure 7. CDSS-MSTID Method
Left plot shows the Czech sites of the CDSS sensors. Right plot depicts a sample of a Doppler shift spectrograms recorded at the individual paths Kašperské Hory, Průhonice, Panská Ves, Dlouhá Louka, and Vackov.

In the Doppler shift measurements the extraordinary wave activity was observed at ~18:30 to 20:00 UT. The sounding wave reflected predominantly in the F region at heights ~200 km.

Wave periods were longer than 11 min. The waves propagated with horizontal phase speed ~166 m·s^{-1} and azimuth ~350°. At the time of observation convective storms were to the south and south-east from the ionospheric observation points and moved further to the east. According to the synoptic map at 18:00 UT, an instability line was situated southerly from the CDSS. The weather systems were the source of observed MSTIDs. The Wavelet transform of the CDSS records is shown in the Figure 8.

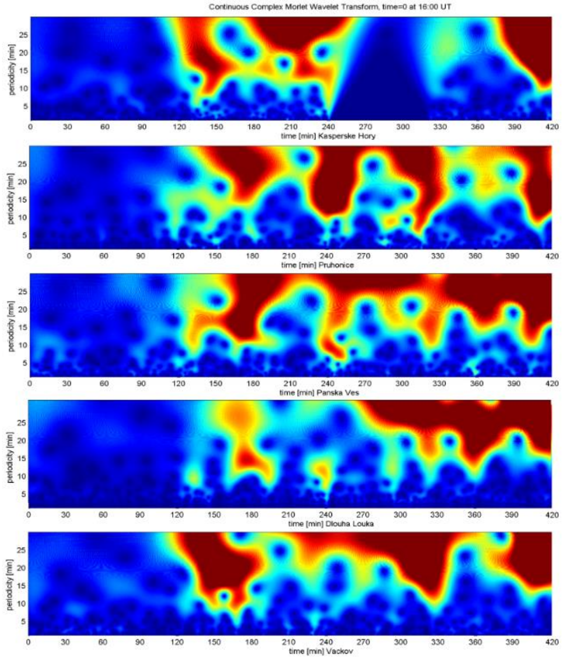


Figure 8. Wavelet transform of the CDSS records

From the top to bottom: measuring path Kašperské Hory, Průhonice, Panská Ves, Dlouhá Louka, Vackov for June 2088 convective storm event.

Figure 9 depicts fluctuations detected by CDSS-MSTID method showing the infrasound activity after Tohoku super-earthquake of March 2011.

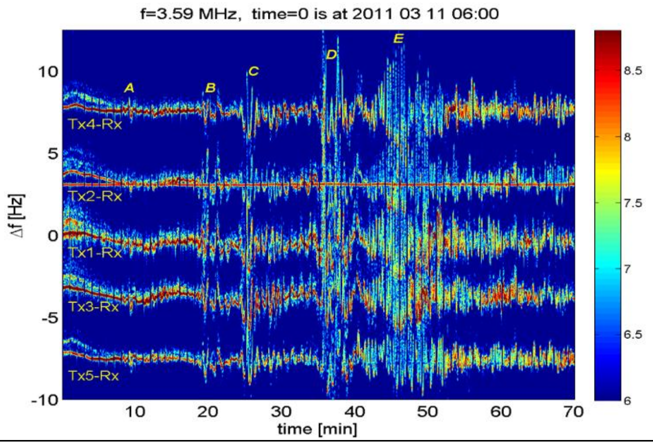


Figure 9. CDSS-MSTID Method

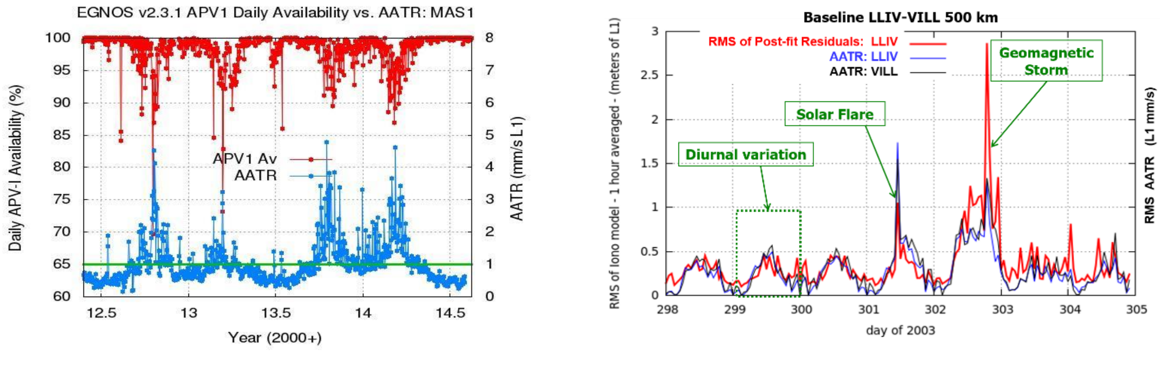
Doppler shift spectrogram recorded on 11 March 2011 from 06:00 UT to 07:10 UT. The individual transmitters are offset by 4 Hz. The scale is the common logarithm of power spectral intensity. Letters A to E mark enhanced ionospheric oscillation very similar to oscillations recorded in a local seismograph.

3.8. AATR Indicator

Along Track TEC Rate (AATR) index was defined in the context of ESA founded ICASES project [RD-13] and it has been used to identify the conditions where a degradation in the user performance of the SBAS systems in general, and in EGNOS in particular, is expected. Figure 10 (a), shows an example of the correlation between the AATR index and the EGNOS APV1 availability over a period of two years for a station in Canary Islands (MAS1), where high values of this AATR index lead to worse performances in the EGNOS APV1 availability due to the ionospheric conditions.

The AATR index has been chosen as the metric to characterize the ionosphere operational conditions in the frame of EGNOS activities. This indicator has been also proposed for joint analysis in the International SBAS-Ionosphere Working Group.

Moreover, AATR is sensitive to several ionospheric features and disturbances like diurnal variations (large values around noon), Solar Flares, geomagnetic storms, etc (Figure 10 (b)). Thus AATR will help to relate ionospheric events with the performance of SBAS systems.



(a) (b)

Figure 10. AATR Indicator
(a) Relationship between the daily EGNOS APV1 availability (red) and the daily maximum values of AATR (blue). The horizontal green line indicates an experimental threshold for AATR of 1 mm/s of L1 delay. (b) Response of the AATR to ionospheric features and disturbances.

4 Design of upgraded TID detection methodologies and of TechTIDE products

Thanks to the Task 1.1 of WP1, a catalog and a categorization of product requirements collected from several potential TechTIDE users' have been documented [RD-1]. Developers of methodologies in TechTIDE have analyzed the requirements potentially relevant to their respective TID identification methods and have evaluated if the product requirements can be fulfilled. In section 4.1 we present the comparison of the performance of the eight different TID detection methodologies with the users' requirements. In case of mismatch between methods' performance and users' requirements, the methods' developers have provided the degradation of such requirements. This comparison led to the design of adjustments need to be made to improve the current TID identification methodologies, which are presented in section 4.2. Finally, in section 4.3 we provide the description of the value-added products that will be resulted from the TID identification methodologies, in order to fulfill as much as possible the requirements of the users.

4.1 Comparison of TID detection methods' performance with users' requirements

Tables 4-6 list the results of the aforementioned analysis noting if a given requirement to specific product and other requirements possibly related to specific products pointed out by users can be fulfilled (**Y**), cannot be fulfilled (**N**), or if it is not applicable (**NA**) to the respective methods. Moreover, a degradation with what one actually plans to achieve in TechTIDE is provided for those requirements that cannot be fully achieved. Such a "no fulfillment" is mainly due to the limitation of available network sensors for probing the ionosphere and due to the limitation of available measurements and data of the existing sensors for probing the ionosphere. These tables are arranged according to the different categories of requirements listed in [RD-1]. Table 4, Table 5, and Table 6 apply for service, product and performance categories respectively. The user's requirements are identified by the ID codes as defined in [RD-1]. The TID methods in Tables 4-6 are identified by an IdN number as follow:

1. HF-TID method
2. HF Interferometry
3. Spatial and temporal GNSS analysis
4. GNSS TEC gradient
5. 3D-EDD maps
6. HTI
7. CDSS
8. AATR indicator

Table 4. Fulfillment of Service Requirements by the different methods.

Service requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation**
TeT-SRV-0020.1	Scope: TID detection (**Mandatory**) Users shall be informed in near real-time on TIDs occurrence: both LSTIDs and MSTIDs	ALL	1 - Y 2 - N 3 - Y 5 - N 6 - N 7 - N 8 - Y	1 - Nowcast detection has latency of 30-60 minutes (data accumulation needed for the analysis window); forecast capability needs evaluation 2 - only LSTIDs 5 - only LSTIDs 6 - only LSTIDs 7 - only MSTIDs
TeT-SRV-0060.1	Ionospheric conditions: background (**Mandatory**) The system shall assess the ionospheric background conditions	ALL	1 - Y 2 - Y 3 - Y 5 - Y 6 - Y 7 - Y 8 - Y	
TeT-SRV-0070.1	Ionospheric conditions: forecast (**Mandatory**) The system shall forecast ionospheric conditions for the next 24h	ALL	1 - Y 2 - N 3 - N 5 - N 6 - N 7 - N 8 - N	1 - 24-hr forecast is based on diurnal 24-hour trend without considering external space weather drivers.

Service requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation**
TeT-SRV-0080.1	Interhemispheric circulation (**Mandatory**) The system shall identify TIDs travelling equatorward and being observed in the other hemisphere	ALL	1 - Y 2 - N 5 - N 6 - N 7 - N	5 - can identify LSTID travelling equatorward 5 - can observe LSTIDs in North Hemisphere 5 - Can observe LSTIDs in the South Hemisphere, if 5 min cadence data from SANSA Digisondes is possible. 7 - only MSTIDs
TeT-SRV-0090.1	Geographical scope: Europe (**Mandatory**) Users shall be informed on TIDs in the area: 20 to 72 deg lat and -40 to 40 deg lon	EGNOS	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - Y	1 - Nowcast is limited to (35.55 N, 0.33 E); forecast capability needs evaluation. 2 - For ionospheric stations in the region (37 - 55 N, −2 - 25 E) 5 - Area currently covered is (32 - 55 N, −5 - 40 E) but we are working to satisfy this requirement. The exact capabilities will be known in the summer. 6 - For ionospheric stations in the region (32 - 55 N, −5 - 40 E) 7 - In the region (50°N - 50.6°N, 13.6°E - 14.6°E)
TeT-SRV-0100.1	Geographical scope: extended Europe (**Desirable**) Users shall be informed on TIDs in the area: 0 to 72 deg lat and -40 to 80 deg lon.	HF	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - N	1 - Forecast capability will unlikely work above 55 deg lat. 5 - We are working to satisfy this requirement. The exact capabilities will be known in the summer.

Service requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation**
TeT-SRV-0110.1	Geographical scope: South Africa (**Mandatory**) Users shall be informed on TIDs in the area: -20 to -35 deg lat and 15 to 35 deg lon	HF, NRTK	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - Y	1 - Nowcast is limited to (22.34 S, 19.31 E); forecast capability needs evaluation. 2 - For ionospheric stations in the region (−22 - −35 N, 19 - 31 E) 5 - We are working to satisfy this requirement. The exact capabilities will be known in the summer. 6 - For ionospheric stations in the region (−22 - −35 N, 19 - 31 E) 7 – In the region (33.8°S-34.6°S; 15.5°E- 20.2°E)
TeT-SRV-0120.1	Geographical scope: global real time (**Desirable**) The spatial coverage of near real-time data shall be: -90 to 90 deg lat and 0 to 360 deg long	ESA	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - Y	1 - Contributing observatories in Europe and South Africa only.
TeT-SRV-0130.1	Geographical scope: global archive (**Desirable**) The spatial coverage of near real-time data shall be: -90 to 90 deg lat and 0 to 360 deg long	ESA	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - Y	1 - Contributing observatories in Europe and South Africa only.

Service requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation**
TeT-SRV-0140.1	Geographical scope: global forecast (**Desirable**) The spatial coverage of forecast data shall be long: -90 to 90 deg lat and 0 to 360 deg long.	ESA	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N 8 - N	1 - Exact forecast capability is unknown, needs evaluation study.

Table 5. Fulfillment of Product Requirements by the different methods

Product requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRD-1010.1	HF-TID final (**Mandatory**) The system shall estimate for LSTIDs and MSTIDs the values of: TID period, phase velocity, direction of propagation, wavelength and amplitude.	ALL	1 - Y	
TeT-PRD-1020.1	HF-TID intermediate (**Desirable**) The system shall estimate for HF communication: the Doppler frequency, angle of arrival, and time-of-flight from transmitter to receiver, both OI and VI sounding	HF, NRTK	1 - Y	1 - Vertical incidence capability TBD.
TeT-PRD-1030.1	HF interferometry final (**Mandatory**) The system shall estimate for LSTID: dominant period, amplitude and 2D vector velocity	ALL	2 - Y	

Product requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRD-1040.1	HF interferometry intermediate (**Desirable**) The system shall estimate: de-trended ionospheric characteristics and spectral energy contribution for specific measuring stations.	ALL	2 - Y	
TeT-PRD-1050.1	Spatial and temporal GNSS analysis final (**Mandatory**) The system shall estimate TID velocity, direction of propagation and amplitude	ALL	3 - N	3 - This can be done in regions where baselines of some tens of km can be found.
TeT-PRD-1060.1	Spatial and temporal GNSS analysis intermediate (**Desirable**) The system shall estimate de-trended GNSS products that remove the nominal ionospheric variations	EGNOS, NRTK	3 - Y	
TeT-PRD-1070.1	GNSS TEC gradients final (**Mandatory**) The system shall deliver TEC gradients	EGNOS, HF, NRTK	4 - Y	
TeT-PRD-1080.1	GNSS TEC gradients intermediate (**Desirable**) The system shall deliver maps of TEC and TEC rate	EGNOS, HF, NRTK	4 - N	4 - The system will deliver TEC gradients, but no TEC maps and TEC-rate
TeT-PRD-1090.1	3D-EDD maps final (**Mandatory**) The system shall estimate for LSTIDs and MSTIDs: altitude of the maximum TID perturbation and TID propagation trajectory	ALL	5 - N	5 - The system will deliver the estimated altitude for the max disturbance due to LSTIDs and their propagation trajectory over Europe.

Product requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRD-1100.1	3D-EDD maps bottomside intermediate (**Desirable**) The system shall estimate 3D electron density distribution (EDD) for the bottomside ionosphere	EGNOS, HF, NRTK	5 - Y	
TeT-PRD-1110.1	3D-EDD maps topside intermediate (**Desirable**) The system shall estimate 3D electron density distribution (EDD) for the topside ionosphere	EGNOS, HF, NRTK	5 - Y	
TeT-PRD-1120.1	HTI intermediate (**Desirable**) The system shall estimate the dominant period of wave activity	HF	6 - Y	
TeT-PRD-1130.1	HTI final (**Mandatory**) The system shall estimate the signal-to-noise ratio variation of vertically reflected radio signals above a given measuring station	HF	6 - N	
TeT-PRD-1140.1	CDSS intermediate (**Mandatory**) The system shall estimate the period, amplitude and phase of Doppler shift measurements	HF	7 - Y	
TeT-PRD-1150.1	CDSS final (**Mandatory**) The system shall estimate continuous Doppler shifts of fixed sounding radio frequencies	HF	7 - Y	
TeT-PRD-1160.1	AATR intermediate (**Mandatory**) The system shall estimate TEC rate	EGNOS, HF, NRTK	8 - Y	
TeT-PRD-1170.1	AATR final (**Mandatory**) The system shall use AATR and TEC rate to identify regions where the ionosphere is disturbed with respect to nominal conditions	ALL	8 - Y	

Product requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRD-1180.1	foF2 maps (**Desirable**) The system shall deliver a real-time foF2 map showing the effects of the TID incorporated	NRTK	1 - Y 2 - NA 6 - NA 7 - NA	foF2 maps can be provided through DIAS.
TeT-PRD-1190.1	Maximum Usable Frequency (**Desirable**) The system shall deliver MUF	HF	1 - Y 7 - NA	MUF maps can be provided through DIAS.
TeT-PRD-1200.1	Sunspot Number (**Desirable**) The system shall deliver sunspot number	HF	2 - NA 6 - NA 7 - NA	SSN can be provided through the central TechTIDE warning system.
TeT-PRD-1220.1	Signal-to-Noise ratio on links (**Mandatory**) The system shall calculate the signal-to-noise ratio on link sections between the DPS4D sounders	HF	1 - Y 2 - NA 6 - NA 7 - NA	
TeT-PRD-1230.1	Path probability ratio on links (**Mandatory**) The system shall calculate path probability ratio on link sections between the DPS4D sounders	HF	1 - Y 2 - NA 6 - NA 7 - NA	
TeT-PRD-1240.1	Ionosphere perturbation index (**Mandatory**) The system shall calculate an ionosphere perturbation index indicating any current ionosphere small scale perturbations (scale below 80 km) in Europe	NRTK	1 - N 2 - N 3 - Y 5 - N 6 - N 7 - N	

Table 6. Fulfillment of Performance Requirements by the different methods

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2090.1	Timeliness: forecast (**Desirable**) Time between forecast and product provision shall be at least 15 minutes up to 3 days ahead	ESA	1 - N 2 - NA 3 - NA 4 - NA 5 - NA 6 - NA 7 - N 8 - NA	1 - TID forecast to 4 hours ahead maximum. 5 - Currently it is NA. However, we investigate the possibility to issue forecast based on Method # 5. This might be decided later.
TeT-PRF-2100.1	Timeliness: MSTID warnings (**Mandatory**) Warnings on the localized occurrence of MSTIDs shall be issued not later than 5 minutes after observation (completion of measurements)	NRTK	1 - N 2 - NA 3 - Y 5 - NA 6 - NA 7 - N 8 - NA	1 - Nowcast detection has latency of 30-60 minutes (data accumulation needed for the analysis window).
TeT-PRF-2110.1	Timeliness: TEC gradients (**Mandatory**) TEC gradients shall be provided not more than 5 minutes after observation (completion of measurements)	EGNOS, NRTK	1 - NA 2 - NA 5 - NA 6 - NA 7 - NA	
TeT-PRF-2120.1	Timeliness: TEC gradient warnings (**Mandatory**) Warnings on TEC gradients exceeding a certain threshold shall be issued not later than 5 minutes after observation (completion of measurements)	EGNOS, NRTK	1 - NA 2 - NA 4 - N 5 - NA 6 - NA 7 - NA	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2130.1	Timeliness: HF-TID (**Mandatory**) HF-TID (intermediate and final products) shall be issued not later than 5 minutes after observation (completion of measurements)	EGNOS, HF, NRTK	1 - Y	1 - Timely release of TID product is feasible, however nowcast detection has latency of 30-60 minutes (data accumulation needed for the analysis window).
TeT-PRF-2140.1	Timeliness: HF interferometry (**Mandatory**) HF interferometry (intermediate and final products) shall be issued not later than 5 minutes after observation (completion of measurements)	EGNOS, HF, NRTK	2 - Y	
TeT-PRF-2150.1	Timeliness: 3D-EDD maps (**Mandatory**) 3D-EDD maps (intermediate and final products) shall be issued not later than 5 minutes after observation (completion of measurements)	EGNOS, HF, NRTK	5 - N	5 - 3D-EDD maps will be issued not later than 20 minutes after observation
TeT-PRF-2160.1	Timeliness: CDSS (**Mandatory**) CDSS (intermediate and final products) shall be issued not later than 5 minutes after observation (completion of measurements)	HF	7 - Y	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2170.1	Timeliness: Ionosphere perturbation index (**Mandatory**) Ionosphere perturbation index shall be provided not more than 5 minutes after completion of measurements	NRTK	2 - NA 5 - NA 6 - NA 7 - N	
TeT-PRF-2180.1	Timeliness: Ionosphere perturbation index warnings (**Mandatory**) Warnings on ionosphere perturbation index exceeding a certain threshold shall be issued not later than 5 minutes after observation (completion of measurements)	NRTK	2 - NA 3 - Y 5 - NA 6 - NA 7 - NA 8 - Y	
TeT-PRF-2190.1	Timeliness: SNR on links warnings (**Desirable**) Warnings on SNR on links shall be issued less than 5 minutes after measurement	HF	2 - NA 6 - NA 7 - NA	
TeT-PRF-2200.1	Timeliness: Path probability ratio on links warnings (**Desirable**) Warnings on path probability ratio on links shall be issued and through the website in less than 5 minutes	HF	2 - NA 6 - NA 7 - NA	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2210.1	Timeliness: Spatial and temporal GNSS analysis (**Mandatory**) Spatial and temporal GNSS analysis (intermediate and final products) shall be issued not later than 5 minutes after observation (completion of measurements)	EGNOS, HF, NRTK	3 - Y 4 - Y 7 - NA	
TeT-PRF-2220.1	Spatial resolution: near real-time data (**Desirable**) The spatial resolution of near real-time data shall be 100 km	ESA	1 - N 2 - N 3 - N 4 - N 5 - N 6 - N 7 - N	1 - Only single-site detections are possible (at Digisonde sites and mid-points of oblique links); the sites are separated by more than 100 km. 2 - At ionospheric stations in the region (37 - 55 N, −2 - 25 E). 3 - This resolution can be achieved in a confident way only in some regions with enough receivers. 4 - spatial resolution is 1°x1° (approx. 111km) 5 - this depends on the density of Digisondes network and we are far away 7 - Limited geographical region (50°N-50.6°N, 13.6°E- 14.6°E) and (33.8°S-34.6°S, 15.5°E-20.2°E).

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2230.1	Spatial resolution: archive data (**Desirable**) The spatial resolution of archive data shall be 100 km	ESA	1 - N 2 - N 3 - N 4 - N 5 - N 6 - N 7 - N	1 - Only single-site detections are possible (at Digisonde sites and mid-points of oblique links); the sites are separated by more than 100 km. 3 - This resolution can be achieved in a confident way only in some regions with enough receivers. 4 - spatial resolution is 1°x1° (approx. 111km) 5 - this depends on the density of Digisondes network and we are far away 7 - Limited geographical region (50°N-50.6°N, 13.6°E- 14.6°E) and (33.8°S-34.6°S, 15.5°E-20.2°E).
TeT-PRF-2240.1	Spatial resolution: forecasts (**Desirable**) The spatial resolution of forecast data shall be 100 km	ESA	1 - N 2 - N 4 - NA 5 - N 6 - N 7 - N	1 - TID propagation forecast may not be accurate, TBD. 5 - this depends on the density of Digisondes network and we are far away
TeT-PRF-2250.1	Spatial resolution: MSTID (deg) (**Mandatory**) The localization of MSTIDs shall have a spatial resolution of 1 degree or better in latitude and longitude	NRTK	1 - N 2 - N 3 - N 5 - N 6 - N 7 - Y	1 - Only single-site detections are possible (at Digisonde sites and mid-points of oblique links); the sites are separated by more than 100 km. 3 - This resolution can be achieved in a confident way only in some regions with enough receivers.

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2260.1	Spatial resolution: MSTID (km) (**Desirable**) The TID amplitudes shall be provided with 30km x 30km spatial resolution	GBAS	1 - N 2 - N 3 - N 5 - N 6 - N 7 - N	1 - Only single-site detections are possible (at Digisonde sites and mid-points of oblique links); the sites are separated by more than 100 km. 3 - This resolution can be achieved in a confident way only in some regions with enough receivers.
TeT-PRF-2270.1	Spatial resolution: TEC gradients (deg) (**Mandatory**) TEC gradients shall have a spatial resolution of 1 degree or better in latitude and longitude	EGNOS, NRTK	4 - Y 5 - N 7 - NA	5 - This possibility will be confirmed within the next months.
TeT-PRF-2280.1	Spatial resolution: TEC gradients (km) (**Desirable**) The TEC gradients shall be provided with 30km x 30 km spatial resolution	GBAS	4 - N 5 - N 7 - NA	4 - 1°x1°
TeT-PRF-2290.1	Spatial resolution: Ionosphere perturbation index (**Mandatory**) Current ionosphere perturbation index shall have a spatial resolution of not more than 1 degree in latitude and longitude	NRTK	2 - NA 3 - N 5 - NA 6 - NA 7 - NA	3 - This resolution can be achieved in a confident way only in some regions with enough receivers.

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2310.1	Temporal resolution: near real-time data (**Desirable**) The time interval between two near real-time product/data points shall be less than 5 minutes	ESA	1 - Y 2 - N 3 - Y 4 - N 5 - N 6 - N 7 - N 8 - Y	2 - Lowest time resolution is expected to be 5 min. 4 - TEC gradients will be provided with 15 minutes temporal resolution.
TeT-PRF-2320.1	Temporal resolution: archived data (**Desirable**) The time interval between two near real-time product/data points shall be less than 5 minutes	ESA	1 - Y 2 - N 3 - Y 4 - N 5 - N 6 - N 7 - N 8 - Y	4 - 15 minutes.
TeT-PRF-2330.1	Temporal resolution: forecasts (**Desirable**) The time interval between two near real-time product/data points shall be less than 15 minutes	ESA	1 - Y 2 - NA 3 - NA 4 - NA 5 - N 6 - NA 7 - N 8 - NA	5 - This possibility will be confirmed within the next months.

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2340.1	Temporal resolution: MSTID warning (**Mandatory**) The localization of MSTIDs shall have a temporal resolution of 5 minutes	NRTK, GBAS	1 - Y 2 - N 3 - Y 5 - NA 6 - N 7 - Y	7 - This depends on the wave period.
TeT-PRF-2350.1	Temporal resolution: MSTID forecast (**Mandatory**) The forecast information on localized occurrence of MSTIDs shall be updated at least every 5 minutes	NRTK	1 - Y 2 - N 3 - NA 5 - NA 6 - N 7 - N	
TeT-PRF-2360.1	Temporal resolution: TEC gradients (**Mandatory**) Current TEC gradients shall have a temporal resolution of 5 minutes	EGNOS, NRTK	4 - N 5 - N 7 - NA	4 - 15 minutes 5 - This possibility will be confirmed within the next months.
TeT-PRF-2370.1	Temporal resolution: Ionosphere perturbation index (**Mandatory**) Current ionosphere perturbation index shall have a temporal resolution of 5 minutes	NRTK	2 - NA 3 - Y 5 - NA 6 - NA 7 - NA 8 - Y	
TeT-PRF-2380.1	Temporal resolution: ionosphere perturbation index forecast (**Mandatory**) The forecast ionosphere perturbation index shall be updated at least every 5 minutes	NRTK	2 - NA 3 - NA 5 - NA 6 - NA 7 - NA 8 - NA	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2400.1	Minimum advance: MSTID forecast (**Desirable**) Warnings on forecast of the localized occurrence of MSTIDs shall be issued at least 10 minutes ahead of forecast occurrence	NRTK	1 - N 2 - N 3 - NA 5 - NA 6 - N 7 - N	1 - Forecast of MSTID onset is subject to nowcast latency (that is driven by analysis window length) and TID propagation velocity. Actual advance time capability TBD.
TeT-PRF-2410.1	Minimum advance: TEC gradient forecast (**Mandatory**) Warnings on forecast of TEC gradients exceeding a certain threshold shall be issued at least 10 minutes ahead of forecasted occurrence	EGNOS, NRTK	2 - NA 4 - NA 5 - N 7 - NA	5 - This possibility will be confirmed within the next months.
TeT-PRF-2420.1	Minimum advance: Ionosphere perturbation index (**Mandatory**) Warnings on forecast of ionosphere perturbation index exceeding a certain threshold shall be issued at least 10 minutes ahead of forecasted occurrence	NRTK	2 - NA 5 - NA 7 - NA	
TeT-PRF-2430.1	HTI: postprocessing (**Mandatory**) HTI (intermediate and final product) shall be available in postprocessing	HF	6 - Y	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2440.1	POD: MSTID warnings (**Desirable**) Warnings for the occurrence of MSTIDs shall at least 50 % probability of detection	NRTK	1 - Y 2 - N 3 - Y 5 - NA 7 - Y	
TeT-PRF-2450.1	POD: TEC gradient warnings (**Desirable**) Warnings for TEC gradients exceeding a certain threshold shall at least 50 % probability of detection	EGNOS, NRTK	4 - NA 5 - NA 7 - NA	
TeT-PRF-2460.1	POD: Ionosphere perturbation index warnings (**Desirable**) Warnings for **Ionosphere perturbation index** exceeding a certain threshold shall at least 50 % probability of detection	NRTK	2 - NA 5 - NA 6 - NA 7 - NA 8 - Y	
TeT-PRF-2470.1	PFA: MSTID warnings (**Desirable**) Warnings for the occurrence of MSTIDs shall have a maximum of 5% probability of false alarm	NRTK	2 - N 3 - Y 5 - NA 6 - N 7 - N	
TeT-PRF-2480.1	PFA: TEC gradient warnings (**Desirable**) Warnings for TEC gradients exceeding a certain threshold shall have a maximum of 5 % probability of false alarm	EGNOS, NRTK	4 - NA 5 - NA 7 - NA	

Performance requirements				
ID	**Name**	**Users**	**Fulfilment**	**Degradation / Notes**
TeT-PRF-2490.1	PFA: Ionosphere perturbation index warnings (**Desirable**) Warnings for **Ionosphere perturbation index** exceeding a certain threshold shall have a maximum of 5 % probability of false alarm	NRTK	2 - NA 5 - NA 6 - NA 7 - NA 8 - Y	

4.2 Design of the required upgrades to meet the users' requirements

Based on the information presented in Tables 4-6, the different methodologies have to be adjusted. The designed upgrades are presented in the subsequent subsections of 4.2.

4.2.1 HF-TID

The main users' requirements connected with this methodology are:

- Detection of MSTIDs and LSTID in real time over Europe and South Africa regions.
- Estimation of the period, phase velocity, direction of propagation, wavelength and amplitude.
- Estimation of the Doppler frequency, angle of arrival, and time-of-flight from transmitter to receiver, both OI and VI sounding for HF communication.
- Estimation of the occurrence probability of TIDs in areas outside of the sensor coverage.

In order to try to fulfill the requirements, we will apply the following actions.

4.2.1.1 Improve quality of TID specification

Existing techniques developed for Net-TIDE will be reviewed to identify potential improvements of the data processing, analyze the outcome uncertainties, and provide means for discovering and mitigating the inconsistencies of the computation results. Special attention will be paid to techniques for signal tracking and spectral analysis to reliably characterize variation timelines of the HF signal properties.

4.2.1.2 Optimize detection of MSTIDs

Because even minor-strength MSTIDs are detrimental to the user applications, their detection and evaluation is especially important for TechTIDE. Given the identified interest of the users in the MSTIDs, the HF-TID capability to detect shorter-scale disturbances will be studied and optimized.

Data Collection. Reliable detection of MSTID will require higher cadence at which the sensor signal properties are acquired within the analysis window. The additional data collection events will have to be accommodated with other scheduled measurements that have to be made by the member observatories. We will develop the optimal observational schedules for DPS4D instruments and review the impact of additional data volume collected by observatories on prompt data delivery and analysis.

Extension of HF-TID to multi-TID environments. A common challenge of detecting medium and weak MS-TID is the need to resolve them in the mixture with other waves. When multiple non-similar waves interact, they form a complicated interference pattern that little resembles the original contributors. In order to detect medium and weak MSTIDs using HF-TID, it is not sufficient to discern one dominant wave period for its subsequent targeted analysis. The method must be enhanced to also ensure reliable resolution of two or more spectral contributors in their observed superposition. If MSTIDs are accompanied by other, stronger and slower pseudo-sinusoidal variations, the $\sin(x)/x$ sidelobes from the DFT operation applied to the dominant component will often mask out the weaker spectral signatures. Development of the multi-scale version of HF-TID method can be considered as a possibility to assess in the framework of TechTIDE the capability of the method to detect MSTIDs.

4.2.1.3 Activate all bistatic links in the sensor network

Currently available configuration of DPS4D instruments in Europe will be expanded by adding new observatories (including the European and South African collaborators) and activating all existing radio links (Figure 11)

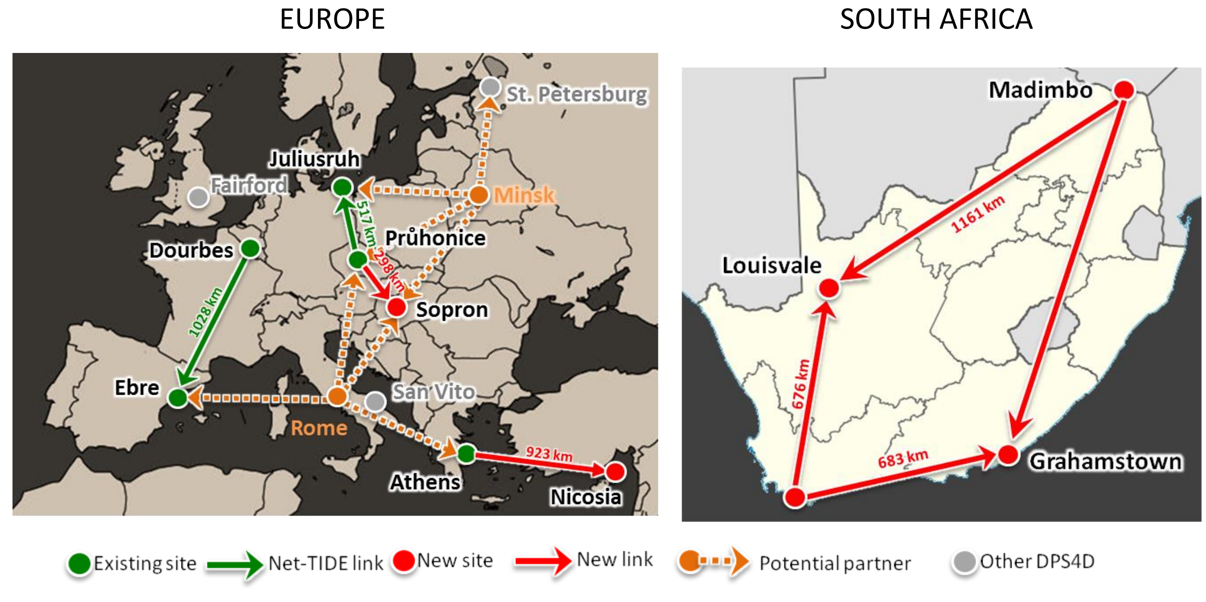


Figure 11. DPS4D instruments in Europe and South Africa

Configuration of the contributing Digisonde DPS4D instruments in Europe and South Africa; (green) existing locations and links tested in 2014-2017; (red) upcoming new locations and links; (orange) potential future partners that would significantly increase TechTIDE coverage area; (gray) other instruments of the same Digisonde model, compatible with the nominal bistatic configuration.

4.2.1.4 Investigate monostatic HF-TID capability

Preliminary analysis suggests that HF-TID observations can be performed using collocated transmitter and receiver (monostatic) configuration, which may present additional capability of sensing TIDs at the nodes of the ionosonde network. The investigation of this potential capability has to address several concerns. Quality of the angle of arrival measurements may be superior in the OI (bistatic) sounding configuration, because

a) knowledge of the transmitter bearing angle allows easy resolution of the 2π-ambiguity in directional analysis, which has been a challenging problem for the sparse antenna arrays like the one used by DPS4D, and

b) precision and resolution of the angle measurements is expected to be inferior in the near-vertical signal propagation geometry: the line-of-sight Doppler shift of the signal frequency is smaller at propagation angles perpendicular to the line of TID motion.

From the other hand, stock Digisonde DPS4D instruments that participate in TechTIDE are optimized for the vertical sounding regime. Their performance at off-vertical angles, especially for low-elevation transmissions required for radiolinks of 1000+ km ground distance, is poor because the transmitter antenna beam pattern approaches null at such low elevations. Quantification of various factors affecting HF-TID in monostatic versus bistatic operation is one of the important technical objectives of the project.

4.2.1.5 TID Situation Forecast using HF-TID method

Because phase velocity and propagation azimuth of detected TID wave are evaluated in the course of HF-TID analysis, a simple algorithm for *TID occurrence probability* becomes feasible that estimates times of TID arrival to areas outside the TID detection site under a reasonable assumption of its continuing travel in the same direction, with a suitable attenuation.

4.2.1.6 User requirements incompatible with HF-TID

There are user’s requirements that cannot be fulfilled by the HF-TID method in the framework for TechTIDE.

Traveling ionospheric disturbances are omnipresent and manifold. Strong individual trans-ionospheric density oscillations are rather uncommon and usually are associated with rare, major events of the auroral origin or other outstanding natural and anthropogenic phenomena. The “everyday”-magnitude MS-TIDs are however most detrimental to the multitude of user applications, which makes their detection and evaluation most important for TechTIDE.

- A group of spatial coverage and resolution requirements cannot be met by HF-TID due to the coverage constrains of existing HF-TID sensor network. However, a follow-on project can be considered to expand the sensor network to meet the spatial coverage needs.

- Timeliness of issuing a TID warning is affected by the need to accumulate one TID period for its detection (i.e., 30-60 minutes). While it is universally difficult to characterize a wave from its fragment, HF-TID may be able to issue prompt and timely TID occurrence probability reports for the areas away from the detection site that are likely to be affected by the traveling wave.

4.2.2 HF Interferometry

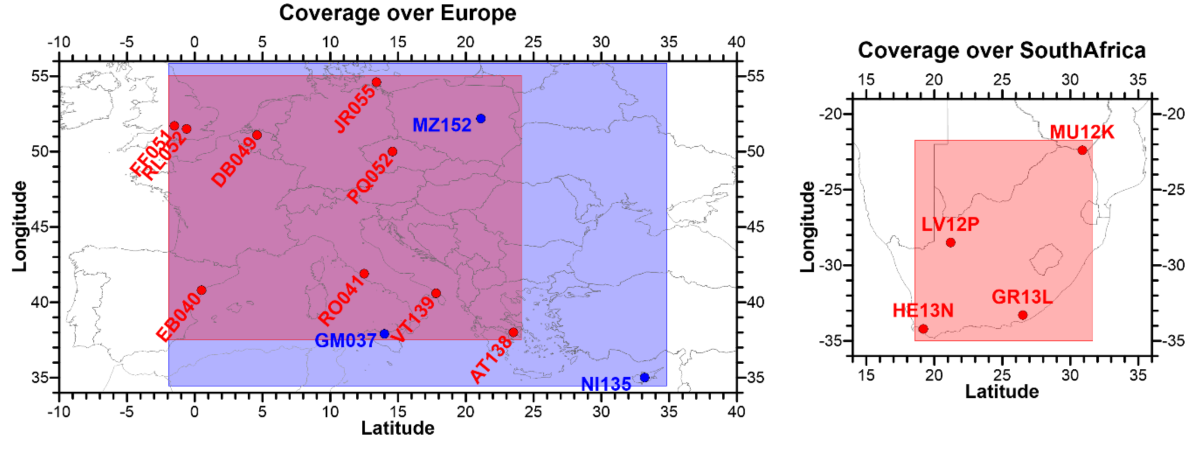
The main users' requirements connected with this methodology are:

- Detection of LSTID in real time over Europe and South Africa regions.
- Estimation the dominant period, amplitude and 2D vector velocity of the LSTID.
- Estimation of de-trended ionospheric characteristics and spectral energy contribution for specific measuring stations.

In order to try to fulfill the requirements, we will apply the following actions.

4.2.2.1 Densification and enlargement of European network

To detect the horizontal structure of the ionospheric irregularities, we have to consider ionospheric characteristics foF2 and MUF(3000)F2 estimated from vertical incidence measurements of the available European Ionosondes. We are currently using data of Athens, Chilton, Dourbes, Ebro, Fairford, Juliusruh, Pruhonice, Rome, and San Vito. However, we can enlarge the region by adding data of Gibilmanna, Nicosia, and Warsaw that can provide data in near-real-time (Figure 12(a)). Test with available OI data of 1F2(MUF) will be used also to make the network denser for particular events. The current codes are running off-line and new code should run in 5 min cadence which can track LSTIDs only.



(a) (b)

Figure 12. Ionosonde sensors used for HF interferometry
(a) Position of the European ionosonde sensors used for HF interferometry method; red labels indicate the current stations, and blue labels indicates future stations adopted for the method. (b) Position of the South African Digisonde DPS4D instruments to be used for HF interferometry method.

4.2.2.2 Adapting to South African network

To detect the horizontal structure of the ionospheric irregularities, we have to consider ionospheric characteristics foF2 and MUF(3000)F2 estimated from vertical incidence measurements of the available South African Ionosondes. We will use data of Grahamstown, Hermanus, Louisvale, and Madimbo (Figure 12(b)). Current measurements are not available in near-real-time and codes will run off-line in 5 min cadence which can track LSTIDs only.

4.2.2.3 Upgrading for near-real-time operation

Current HF interferometry method apply off-line for test cases characterized by TID activity. The test cases and the required data are be obtained from the TechTIDE open access repository and on time intervals when persistent TID activity of significant amplitude is observed by the Net-TIDE experiment (http://tid.space.noa.gr). The final code should provide near-real-time information of detected LSTID activity above given measuring sites within European and South African regions. See shaded areas in Figure 12.

4.2.2.4 Upgrading for obtaining Spectral Energy Contribution of LTIDs

Current HF interferometry lacks of information about the LSTID contribution to the variability of the ionospheric characteristics under analysis. Applying the Parseval's relation we will estimate the *Spectral Energy Contribution* (SEC) of the periodic range of the LTIDs to the total energy which is equivalent to the contribution of the LTIDs to the total variability of the given time series (Equations 8-9),

$$\sum_{n=-\infty}^{\infty} |x[n]|^2 = \frac{1}{2\pi}\int_{-\pi}^{\pi} |X(\omega)|^2 d\omega \sim \sum_{T=T_S}^{T=T_E} A(\omega)^2 \tag{8}$$

$$SEC(\%) = \frac{\sum_{T=T_{TID_S}}^{T=T_{TID_E}} A(T)^2}{\sum_{T=T_S}^{T=T_E} A(T)^2} \tag{9}$$

where ω is the angular frequency of the period T, T_{TIDS} and T_{TIDE} are the starting and ending periods of the periodic range of the LSTID respectively, and T_S and T_E are the starting and ending periods of the total periodic range under analysis.

4.2.2.5 Background specification

For the development of the HF interferometry method we propose to use as background specification of the daily variation the contribution of the main diurnal harmonics based on a Fourier model for a 24-h time interval. The disturbance potentially associated to TID in the last 6-h interval will be related to the de-trended ionospheric characteristics after removing the main daily harmonics (Figure 13).

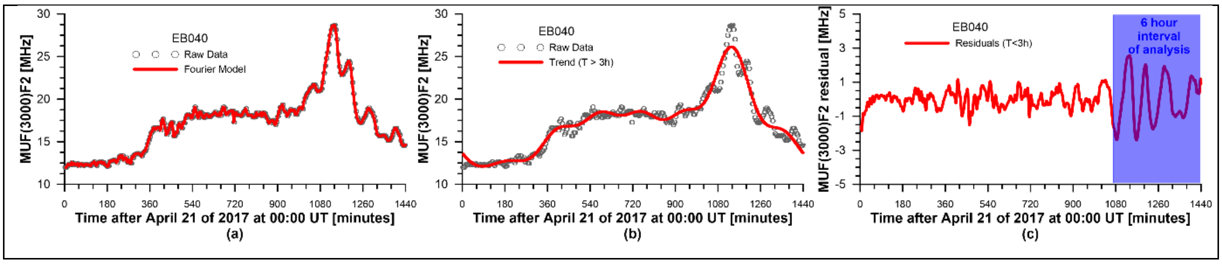


Figure 13. HF Interferometry Background model and residuals

(a) Fourier model of an ionospheric characteristic for a given 24-h. (b) Background specification of the daily variation considering the main diurnal harmonics (periods larger than 3 hour). (c) De-trended ionospheric characteristic after removing the background specification.

However, there are two additional user's requirements that cannot be fulfilled by the HF Interferometry method in the framework for TechTIDE:

- The detection of MSTIDs. To detect MSTIDs we need to have a very dense network of ionosonde sensors which provide ionospheric characteristics with a very high cadence data (less than 5 min). However, current ionosonde sensors in the European African regions are sparsely distributed. Moreover, the current operational schedules combine different measurements for probing the ionosphere and they have technical restrictions for achieving data sampling less than 5 min.

- The forecast of LSTIDs and MSTIDs for the next 24 hrs ahead. The HF interferometry method is based on current measurements; i. e. nowcast. That is why, to forecast LSTIDs we should forecast the data input to the method. This will need a different methodology that includes the development of a data assimilation models which is a task that goes beyond the scope of TechTIDE project.

In addition to the above, the method cannot support on site an archive time coverage of the products for the past six months.

4.2.3 Spatial and Temporal GNSS analysis

The main users' requirements connected with this methodology are:

- Detection of MSTIDs and LSTID in real time over Europe and South Africa regions.

- Estimation the TID velocity, direction of propagation, and amplitude.

- Estimation de-trended GNSS products that mitigate the nominal ionospheric variations.

In order to try to fulfill the requirements, we will apply the following actions.

This is currently a preliminary methodology for MSTID detection and characterization through spatial and temporal analysis of GNSS signals which is working off-line. NRTK baselines are usually larger than 50 km. In this context, MSTIDs with wavelengths close to 100km can break the linearity assumptions for the ionospheric corrections as it is assumed in NRTK. The goal of this tool is to detect such kind of perturbations following the approach defined in [RD-7].

- The algorithm for detecting MSTIDs can run in an automatic way. It can be implemented for a near real time purpose. The only limiting factor for its implementation in real time is the GNSS data availability. Nowadays, there are available streams of GNSS data that would allow the computation of the index for these receivers.

- The MSTID detector can be adapted to a refreshing time of few minutes in order to fit with the requirements.
- Unlike the detector defined in [RD-7], the new detector will be linked to the degradation of the navigation solution in NRTK.

However, there are user's requirements that cannot be fulfilled by the Spatial and temporal GNSS analysis in the framework for TechTIDE. In particular, those related with the forecast. Moreover, a 1x1 resolution (or propagation parameters) could be only achieved on areas where enough receivers would be available.

4.2.4 GNSS TEC Gradient

The main users' requirements connected with this methodology are:

- To deliver TEC gradients.
- To deliver maps of TEC and TEC rate.

In order to try to fulfill the requirements, we will apply the following actions.

TEC gradients will be calculated from TEC maps. Latitudinal and longitudinal differences between the grid cells will be the basis for the computation. Therefore, the Quality of the generated TEC gradients depends on the Quality of the underlying TEC maps. Higher spatial and temporal Resolution of the TEC maps increases the Quality of the TEC gradients (given that the density of the measurements in each grid cell of the TEC maps is sufficient). Because users (especially aviation) require TEC Gradient represented in mm/km, the computed TEC Gradient (TECU/degree) are converted into mm/km.

The TEC gradients will be delivered with a latency of about 5 minutes and a temporal resolution of 15 minutes. The spatial coverage is 30°W to 50°E and 30°N to 72°N and the spatial resolution of 1°x1°.

As stated above, there are user's requirements that cannot be fulfilled by the GNSS TEC Gradient method in the framework for TechTIDE. In particular this method cannot provide time resolution lower than 15 minutes and spatial resolution lower than 111 km (1°x1°). Related to service requirements, the method cannot provide warnings for conditions on the geospace or aurora oval are likely to generate TIDs or significant TEC gradients ([RD-1], TeT-SRV-0040.1). Related to interface requirements, the method cannot provide an archive of forecast images on TEC gradients for the past 6 months ([RD-1], TeT-INT-3510.1).

4.2.5 3D-EDD Maps

The main users' requirements connected with this methodology are:

- Provision of 3D EDD maps over Europe and Africa regions, for the bottomside and the topside ionosphere.

- Detection of LSTIDs in real-time.
- Indication of the altitude of the maximum disturbance

In order to fulfill the requirements, we will provide the following two basic codes:

4.2.5.1 The electron density reconstruction above each Digisonde

The electron density reconstruction above each Digisonde for European and South African stations are based on the TaD code [RD-9]. The following input characteristics and parameters are required to run the code:

- The ionospheric characteristics at the height of the maximum electron density (foF2 and hmF2)
- The bottomside electron density profile provided by the Digisonde
- The vertical TEC parameter corresponding at the geographic coordinates of the Digisonde
- Solar and geomagnetic indices f10.7 and Kp.

All the above data need to be provided in real-time, in 5 min cadence. Especially regarding the ionospheric characteristics, these need to be corrected from autoscaling errors. To fulfill this requirement, the following upgrades are necessary:

1. To develop an algorithm that simulates the ingestion of data from Digisondes with measurements of 15 min cadence. The simulation will be based on the derivation of a relation between the 5 min TEC and the foF2. This is under development and the code will be available for implementation in the first TechTIDE prototype. This code is necessary in order to exploit as much as possible all available Digisondes even if they operate with 15 min resolution schedule and collect 5 min resolution data that facilitate the detection of TIDs.

2. To develop an algorithm that fills in the gaps and removes the spikes from the autoscaled ionospheric characteristics. This can be achieved with the application of the linear approximation method [RD-14] [RD-15]. The first tests applied in real-time autoscaled ionospheric characteristics from the Athens Digisonde, give a performance compared to the median estimate for foF2 which has a MSE=0.02 MHz for a system memory of 6 measurements, with a max error of 1.03 MHz for the period 16 April to 26 April 2017 which includes both quiet and disturbed conditions. For the hmF2 parameter the corresponding performance gives MSE=13.96 km with max error 122.85 km. The results are quite encouraging however more tests are necessary in order to organize better functionality issues and especially the selection of the system memory for each Digisonde.

4.2.5.2 The 3D EDD code

The 3D EDD code provides the reconstructed electron density over a region. The code has been developed recently and the results are validated with slant TEC parameters from GNSS receivers [RD-10]. Using an interface, the user will be able to select the region and the type of the map between a vertical, a horizontal and a slant surface in space to map the electron density. To guarantee the smooth operation of this software suit, we will use the two algorithms described above for simulated ingestion of low cadence measurements and for filling in the gaps.

There are two additional user's requirements that it is very uncertain that can be fulfilled in the framework for TechTIDE:

1. The detection of MSTIDs with the TaD code, as the result of the analysis of 3D EDD maps: to detect MSTID we need to have very high cadence data (less than 5 min) and a very dense network of Digisondes in the European-African region. We are still very far away from meeting these requirements because of the sparsity of the Digisondes and the technical restriction that make the operational schedule with data sampling less than 5 min very uncertain.

2. The forecast of LSTIDs and MSTIDs for the next 24 hrs ahead: this is a very ambitious task given that the 3D EDD are the result of the TaD data-driven model. Therefore, to forecast the 3D EDDs we should either forecast the data input to the TaD model, or apply a forecasting method to the 3D EDD results directly. In both cases there are many model errors that are transferred to the end result, and finally the forecasted parameters will carry very large uncertainties. After some tests and considerations, we have resulted to the conclusion that a reliable forecast based on the TaD model could have a short time window of not more than 1 hour. This is an experiment that we will perform with WP2 and we will report the results in D2.2. For longer forecasting window, a different methodology is needed that includes the development of a data assimilation model, a task that goes beyond the scope of TechTIDE project.

4.2.6 HTI

The main users' requirements connected with this methodology are:

- Detection of LSTID in real time over Europe and South Africa regions.
- Estimation of the dominant period of the LSTID.
- To estimate the SNR variation of vertically reflected radio signals above a given measuring station.

4.2.6.1 Densification and enlargement of European network

To detect the presence of TIDs we will consider virtual height variations extracted from raw ionograms from available Digisondes and attempt to test algorithms to detect periodicities in these variations. To follow the F region over each station and select the optimal frequency window to monitor F region TID activity, automatically scaled foF2 characteristics will be used as they are provided in near-real time by ARTIST over each station through GIRO.

We are currently able to use ionograms from Nicosia, Athens, Chilton, Dourbes, Ebro, Fairford, Juliusruh, Pruhonice, Rome, and San Vito. The current codes are running off-line and new code should run in 5 min cadence which can track LSTIDs only.

4.2.6.2 Adapting to South African network

To detect LSTID activity over South Africa, we have to consider ionograms from vertical incidence measurements of the available South African Digisondes. We will use data of Grahamstown, Hermanus, Louisvale, and Madimbo. Current measurements are not available in near-real-time and codes will run off-line in 5 min cadence which can track LSTIDs only.

4.2.6.3 Upgrading for near-real-time operation

Currently the HTI method is applied off-line for test cases characterized by TID activity. The test cases and the required ionograms are obtained from GIRO. The final code should provide near-real-time information of detected LSTID activity above given measuring sites within European and South African regions.

However, there are two additional user's requirements that cannot be fulfilled by the HTI method in the framework for TechTIDE:

- The detection of MSTIDs. To detect MSTIDs we need to have ionosondes which provide ionograms with a very high cadence (less than 5 min). Current operational schedules combine different measurements for probing the ionosphere and they have technical restrictions for achieving ionograms at less than 5 min.

- The forecast of LSTIDs and MSTIDs for the next 24 hrs ahead. The HTI method is based on current measurements; i. e. nowcast. That is why, to forecast LSTIDs we should forecast the data input to the method which is impossible to do with ionograms that represent raw instrument measurements.

4.2.7 CDSS-MSTID

The main users' requirements connected with this methodology are:

- To estimate the period, amplitude and phase of Doppler shift measurements.

- To estimate continuous Doppler shifts of fixed sounding radio frequencies.

In order to try to fulfill the requirements, we will apply the following actions.

AGW activity will be continuously monitored using CDSS networks in the Czech Republic and South Africa (Hermanus and Louisvale sites), Pruhonice, Hermanus and Louisvale Digisonde data, meteorological radar data, satellite images and data from geomagnetic observatories closest to the locations of the Digisondes. The spectral content of the waves observed by continuous sounding are obtained in following way:

- The received signal is converted (shifted) to low frequencies, and a spectral analysis is performed resulting in Doppler shift spectrograms.

- To achieve high frequency-time resolution of the observed Doppler shift, the successive spectra are obtained by shifting Gaussian window of the width ~10 s by a time step less than the width of the window in the time domain. That means the successive time intervals, in which spectra were calculated, overlap each other. Therefore, the resulting spectrogram has a smoother character comparing to the analysis with no overlap in time.

- In further analysis, we will select time intervals, in which we will receive signal containing one frequency we observed one clear trace in the Doppler shift spectrograms. That means we excluded time intervals, during which we received two different frequencies for extraordinary and ordinary waves with comparable amplitudes or any kind of multi-ray reflection, relatively broad-band spectrum of Doppler shift owing to reflection from a spread layer etc.

- In the selected time intervals we will find one value of the Doppler shift which fits best the observation in each time step, thus obtaining an unambiguous function of Doppler shift on time. Analyzing the spectral content of this function, we will get information on typical periods of the observed waves at each time. To obtain simultaneously a maximum frequency and time resolution for different periods, we will apply Continuous Wavelet Transform (CWT) based on complex Morlet wavelets.

- The virtual height of reflection of the CDSS sounding frequencies are obtained directly from ionograms.

- Wave periods, amplitudes and phase velocities will be calculated. We will focus on detection of waves of periods 1-30 min.

However, there are user’s requirements that cannot be fulfilled by the CDSS-MSTID method in the framework for TechTIDE:

The CDSS-MSTID method could not fully meet the user’s requirement of warnings for the occurrence of MSTIDs shall have a maximum of 5% probability of false alarm. Due to the complicated dynamics and evolution of the severe tropospheric convection.

CDSS-MSTID measurements cover only limited area of Central Europe and South Africa, where the instrumentation is located.

4.2.8 AATR Indicator

The main users’ requirements connected with this methodology are:

- To estimate TEC rate.

- To identify regions where the ionosphere is disturbed.

In order to try to fulfill the requirements, we will apply the following actions.

The algorithm for computing AATR runs daily in an automatic way. It can be implemented for a near real time purpose. The only limiting factor for its implementation in real time is the GNSS data availability, but nowadays, thanks to the IGS-RT, there are streams of GNSS data collected by hundreds of receivers worldwide distributed.

The current refreshing time for the AATR computation is of 1 hour, but it can be reduced to few minutes in order to fit with the requirements.

Because one of the goal of the TechTIDE project is to relate ionospheric events with the performance of SBAS systems, the automatic computation of the AATR for 34 WAAS RIMS and 37 EGNOS RIMS will help to this goal.

However, there are user's requirements that cannot be fulfilled by the AATR method in the framework for TechTIDE. In particular, a resolution of 1x1 degrees cannot be applied to this index. This is because the AATR has a correlation radius of several hundreds of kilometers. Moreover, AATR, on its original definition, is linked to the receivers and the observations from any receiver usually cover tens of degrees around the receiver position.

4.3 Value-added products

4.3.1 HF-TID

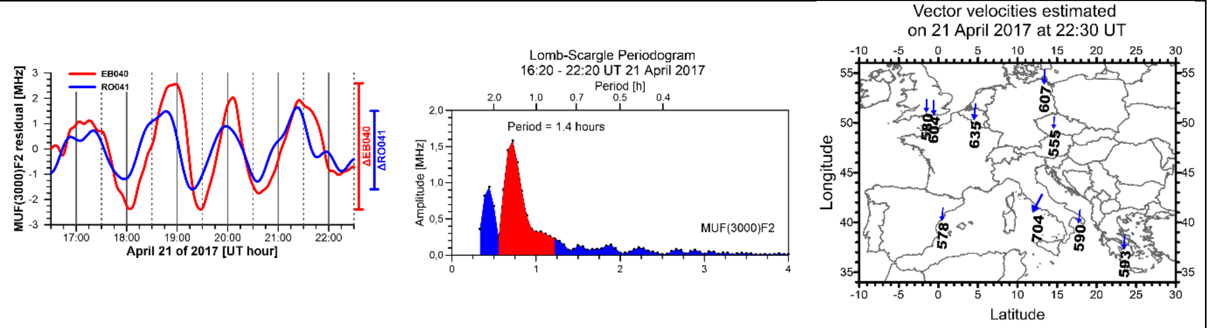
Based on the method's capabilities and the users' requirements, the value-added products to be resulted from this methodology are TID Maps with the probability of occurrence to areas outside the detection network: individual TID detections by sensor nodes will be assembled into a consistent representation of the Pan-European TID activity and then used to synthesize forecast of upcoming TID impact.

4.3.2 HF Interferometry

Based on the method's capabilities and the users' requirements, we present below the design concept for the value-added products.

- The de-trending method will be applied to the ionospheric characteristics to estimate the specific site and region of the network with larger disturbance (Figure 14(a)).
- The spectral energy contribution will give us an indication of the relative contribution of detected LSTID to the total variance of the given ionospheric characteristics measured at specific sites (Figure 14(b)).
- The 2D Vector velocity will give us an indication of the dominant horizontal direction of energy propagation of the LSTID above specific measuring sites (Figure 14(c)).
- The dominant period will give us an indication of the oscillating period of the LSTID, and considering the modulus of the velocity we can also estimate the scale size of the disturbance.

- The obtained main LSTID characteristics based on the HF interferometry method will provide an estimate of the LSTID propagation in 2D over Europe and South Africa, mainly under LSTID activity.



(a) (b) (c)

Figure 14. HF Interferometry added value products
(a) Estimated maximum disturbance of a given LSTID event above given stations. (b) Estimated relative Spectral Energy Contribution of a given LSTID event. (c) Estimated 2D velocity vector of a given LSTID event.

4.3.3 Spatial & Temporal GNSS Analysis

Based on the method's capabilities and the users' requirements, we present below the design concept for the value-added products.

- Time series about the characterization of MSTIDs parameters such as amplitude, velocity and azimuth. This can be done in areas where the baselines between receivers are of few tens of km.

- Climatology of MSTIDs over the European region. Using the data collected during a long time series, it will possible to establish the main dependencies of the MSTIDs occurrences in terms of location, local time, season, … .

- From the two previous points one can try to extract the physical origin for the MSTDs (solar terminator, atmospheric gravity waves, auroral activity, ...).

4.3.4 GNSS TEC Gradient

The product will include latitudinal, longitudinal and absolute TEC Gradient amplitudes. Based on the method's capabilities and the users' requirements, following design concept for the value-added products is assumed.

The data is delivered in JSON format. This data product is delivered along with meta data in XML format and with graphical presentation in an image.

4.3.5 3D-EDD Maps

Considering the requirements of the users and based on the primary output of the 3D EDD code, the specification of the height of the maximum disturbance due to TIDs is the value-added product that can be provided. Below we provide the product design concept:

The 3D EDD code has the capability to provide the integral of the electron density over any part of the path between the lower altitude of the ionosphere (i.e. ~ 90 km) up to the GNSS heights (i.e. 22,000 km). The TIDs mainly perturb the ionization at the F2 layer however there are cases where the TID travel upwards or downward depending on their source. Using the EDD results from the 3D EDD code, we can calculate the time and spatial gradients of the partial electron density integrals over the E layer, the F layer, the whole bottomside and parts of the topside ionosphere for a specific geographic region. The comparison of the gradients of the maps can give us an indication regarding the ionospheric layer where the maximum perturbation is detected. Some basic TID characteristics such as the velocity and the direction of propagation can also be extracted, especially for large scale TIDs.

4.3.6 HTI

Based on the method's capabilities and the users' requirements, we present below the design concept for the value-added products.

- The HTI method will be applied to raw ionograms to estimate the region of the network with larger disturbance.
- The spectral energy contribution will give us an indication of the relative contribution of detected LSTID to the total variance of the given virtual height variations measured at specific sites.
- The dominant period will give us an indication of the oscillating period of the LSTID.

4.3.7 CDSS-MSTID

Based on the method's capabilities and the users' requirements, we present below the design concept for the value-added products.

- Horizontal characteristics (velocity, azimuth, and wavelength) of the MSTIDs can be determined from the Czech and South African CDSSs measurements by continuous multi-point sounding at all working frequencies.
- Three measuring points forming a triangle are used for velocity and azimuth calculations. Horizontal velocities and their azimuths can be computed from the time differences between observation of corresponding signatures on different sounding paths and known topology (distances) between reflection points of sounding radio waves.
- Prevailing GW propagation directions can be obtained above Central Europe and South African regions covered by CDSS measurements.
- Ionospheric response to various kinds of seismic waves (P, S, SS, and Rayleigh waves) can be monitored and studied.
- CDSS data could be used to evaluate the HWM07 model and improve background neutral wind calculations.

4.3.8 AATR Indicator

Based on the method’s capabilities and the users’ requirements, we present below the design concept for the value-added products.

- AATR can be computed for any GNSS receiver, therefore, because there are thousands of available receivers worldwide distributed, it is possible to have information about the ionospheric activity in wide regions around the world.
- As it shown in [RD-16], there is a clear correlation between AATR and the EGNOS availability degradation. Therefore, the automatic computation of the AATR values for EGNOS and WAAS receivers can help to elaborate warnings about the availability in SBAS systems.
- AATR is sensitive to most of the effects occurring in the ionosphere. In this sense, AATR is a helpful tool for monitoring space weather events.

4.4 Validation methodologies

Systematic efforts will be needed to verify and validate the different methods and algorithms. Comparative studies of the results obtained by the different methodologies in TechTIDE for LSTID and MSTID detection will be performed which will serve as independent cross-verification of each individual method and will also support its detection capabilities. This is mainly one of the aims of WP3, however in WP2, specific validation methodologies will be applied for given methods and algorithms.

A validation campaign for HF-TID method is planned to test the accuracy of restoring parameters of a single TID wave using synthesized time series of signal properties based on the HR2006 raytracing algorithm and IRI or IRTAM background models. Additional tests for HF-TID method will use the signal synthesizer based on IRTAM ionosphere modulated by more than one overlapping TIDs of different periods. Finally, comparisons to the observations from companion instruments of the project will be made to validate the nowcast and forecast outcomes of HF-TID.

The MSTIDs detector of the Spatial & Temporal GNSS Analysis will be assessed routinely against the navigation solutions in the CATNET.

TechTIDE TEC gradients can be validated also with TEC gradients computed from "quasi-independent" TEC maps (like those from IGS or RTIM). However, this validation is limited because the spatial resolution and spatial coverage is different from one method to the other and because none of the methods represent the "true" vertical TEC which is actually unknown.

Applying the 3D EDD reconstruction model, it is expected to reveal the different behavior in bottomside-topside ionospheric plasma redistribution processes during atmospheric-triggered and solar-triggered TIDs. For example, it is important to verify possible agreement between the 3D EDD and the Net-TIDE results in the case of bottomside propagating TIDs, and an agreement between the GNSS gradient method results and topside propagating TIDs calculated with the 3D EDD method.

Also EGNOS degradation availability will be compared automatically against the AATR values for receivers in the region where this degradation occur, and large AATR values will be analyzed in order to relate them with space weather events.

5. Summary and conclusions

This report presents the current status and capabilities of the TID detection methodologies and analyses required adjustments and upgrades. Different methods tried to adopt the initial requirements gathered among users affected by TIDs according to the current monitoring capabilities. A degradation of the users' requirements in order to bridge the TID detection codes capabilities, is also provided for each methodology. Such a "no fulfillment" is mainly due to the limitation of available network sensors for probing the ionosphere and due to operational limitations of the existing sensors (low cadence of observations, high timeliness due to delays in data transfer, etc.). Initial specification of the planned upgrades in all methodologies and design of the products have been presented. Also, a set of value-added products planned to be released in order to satisfy the requirements of the user has been presented. This is summarized in the Table 7. Overall three groups of products are defined: (a) the Intermediate Product, which is the direct outcome of each methodology (b) the Final Product, which is based on the processing of the direct outcome (c) the Value-added Product, which is a new product design based on the outcome of each methodology taking into account specific users requirements.

The WP2 activities will be evolved in relation to the WP3 work plan where the results of all TID detection methodologies will be cross-validated and evaluated based on the assessment of current geospatial and lower atmosphere conditions. The algorithms for the intermediate products will be released in September 2018 and their capabilities will be demonstrated in the first release of the TechTIDE warning system. The final and value-added products will be released towards the end of 2019 and will be implemented in the final version of the TechTIDE warning system.

Table 7. Summary of TechTIDE TID identification methodologies.

IdN. Method	Main Characteristics	Potential Application	Potential Users	Intermediate Product	Final Product	Value added Product	Effective Area	Real-time
1. HF-TID Detects perturbations in space from all possible sources (solar and lower atmosphere origin) and it is suitable for the identification of both MS and LS TIDs	Input: signal characteristics from Digisonde synchronized operation. Output: TID velocity, amplitude, propagation direction at the signal reflection point between the stations	Application in synchronized Digisondes in Europe and South Africa to provide a consistent view of the TID propagation.	HF communication and geolocation users (OTHR, Civil protection and radio-ham, Defense systems, Humanitarian aid organizations, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services); GNSS NTRK Precision Point Positioning (PPP)	Doppler frequency, angle of arrival, and time-of-flight from Tx to Rx, both OI and VI sounding	Separately for MS and LS TID: 1+ detections of {TID Period, Phase Velocity, Direction of propagation, Wavelength, and Amplitude}	Maps of the current TID activity Maps of TID occurrence probability	Europe and South Africa	Yes
2. HF Interferometry Finds oscillation activity in ionospheric characteristics and it can detect LSTIDs only.	Input: ionospheric characteristics from VI and OI soundings. Output: 2D TID vector velocity, amplitude and period.	Potential application in Europe and South Africa to provide in near real time propagation characteristics and warning of LSTIDs.	HF communication and geolocation users (OTHR, Civil protection and radio-ham, Defense systems, Humanitarian aid organizations, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services.	De-trended ionospheric characteristics and contribution of LSTID to the data variability.	Dominant period, Amplitude and 2D Vector velocity of detected LSTID.	Estimation of LSTID propagation	Europe and South African sites	Not now but will be.

IdN. Method	Main Characteristics	Potential Application	Potential Users	Intermediate Product	Final Product	Value added Product	Effective Area	Real-time
3. Spatial & Temporal GNSS Analysis Can detect perturbations in space from all possible sources (solar and lower atmosphere origin) and it is suitable for the identification of both MS and LS TIDs	Input: GNSS TEC from single receivers over a region. Output: Fluctuations associated to the TIDs and estimation of the propagation parameters (direction, velocity and amplitude).	Suitable for identification of both MS and LS TIDs and to provide in near-real time the propagation pattern over Europe and South Africa.	Trans-ionospheric propagation users (Communication between ground based stations and satellites, Communication of aerospace and maritime systems with satellites; Satellite navigation as EGNOS and SBAS systems, NRTK-users, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	De-trended GNSS data measurements.	TID Velocity, Direction of propagation and Amplitude	Climatology and physical origin of MSTID	Europe and South Africa	Not now but will be.
4. GNSS TEC Gradient Analyze TEC maps and it is mostly sensitive to perturbations from LSTIDs.	Input: Grids of TEC maps over a region. Output: Latitude-time maps of TEC gradients and indication of significant gradients.	Application to provide near-real time maps of TEC gradients over Europe and globally as indicator for LSTIDs.	Trans-ionospheric propagation users (Communication between ground based stations and satellites, Communication of aerospace and maritime systems with satellites; Satellite navigation as EGNOS and SBAS systems, NRTK-users, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	Maps of TEC and TEC rate	TEC Gradients	Graphical presentation in an image	Europe and South Africa	Not now but will be.

IdN. Method	Main Characteristics	Potential Application	Potential Users	Intermediate Product	Final Product	Value added Product	Effective Area	Real-time
5. 3D EDD Maps Analyze maps of TEC and ionospheric characteristics and it is sensitive to perturbation from LSTIDs only.	Input: ionospheric characteristics at the hmF2 altitude and TEC maps. Output: Analytical function of the electron density distribution with altitude from 90 km to 22000 km	Application to operate in real-time to provide an estimate of the altitude of the highest electron density perturbation and the region affected.	Trans-ionospheric propagation users (Communication between ground based stations and satellites, Communication of aerospace and maritime systems with satellites; Satellite navigation as EGNOS and SBAS systems, NRTK-users, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	1D electron density distribution (EDD) over the Digisonde locations	3D EDD results over a user-specified area. Maps of ED for vertical, horizontal and slant surfaces, specified by the user.	Maps of gradients of the integrated electron density for altitudinal ranges defined by the user.	Europe and South Africa	Yes
6. HTI Reconstructs a daily plot of the vertical movement of the ionospheric layers and it can capture oscillations detected in space from all possible sources.	Input: raw vertical ionogram binary data from single station Output: Reconstructed daily variability of virtual height within a certain frequency range.	Application to operate in a post processing for validating previous HF methods. Potential routine implementation will be considered.	HF communication and geolocation users (OTHR, Civil protection and radio-ham, Defense systems, Humanitarian aid organizations, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	Signal to Noise ratio variation of vertically reflected radio frequency above a given measuring station	Period of dominant wave activity.	Relative contribution of detected LSTID to the total variance	Europe and South African sites.	No
7. CDSS-MSTID Analyze Doppler shift of radio signals and it can identify perturbations in space mainly caused by MSTIDs.	Input: CDSS reflected signals, ionospheric characteristics and irregularities. Output: Doppler shift, SNR and confidence level.	Application to operate in real-time to provide warnings for MSTID activity	HF communication and geolocation users (OTHR, Civil protection and radio-ham, Defense systems, Humanitarian aid organizations, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	Continuous Doppler shifts of fixed sounding radio frequency.	Period, Amplitude and Phase of Doppler measurements.	MSTIDs Characteristics Seismic response	Europe and South Africa	Yes

IdN. Method	Main Characteristics	Potential Application	Potential Users	Intermediate Product	Final Product	Value added Product	Effective Area	Real-time
8. AATR Indicator Analyze TEC data oven specific region and it is mostly sensitive to perturbations from LSTIDs	Input: slant TEC parameters. Output: the Along Arc STEC Rate, metric to characterize the ionosphere operational conditions of EGNOS.	Application to operate in real-time to provide warnings of LS disturbances.	Trans-ionospheric propagation users (Communication between ground based stations and satellites, Communication of aerospace and maritime systems with satellites; Satellite navigation as EGNOS and SBAS systems, NRTK-users, radio astronomy observations at low frequencies as LOFAR, Space agencies, Emergency management services).	TEC rate	Warning of ionospheric activity.	Warning about the availability in SBAS systems	Europe	Yes