Pilot network for identification of travelling ionospheric disturbances

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ABSTRACT

Travelling Ionospheric Disturbances (TIDs) are the ionospheric signatures of atmospheric gravity waves. TIDs carry along information about their sources of excitations which may be either natural (energy input from the auroral region, earthquakes/tsunamis, hurricanes, solar terminator, and others) or artificial (ionospheric modification experiments, nuclear explosions, and other powerful blasts like industrial accidents). TIDs contribute to the energy and momentum exchange between different regions of the ionosphere, especially during geomagnetic storms. Their tracking is important because the TIDs affect all services that rely on predictable ionospheric radio wave propagation. Although a number of methods have been proposed to measure TID characteristics, none is able to operate in real time for monitoring purposes. In the framework of a new NATO Science for Peace and Security multi-year project (2014 - 2017) we are exploiting for the first time the European network of high precision ionospheric DPS4D sounders (and the related software) to directly identify TIDs over Europe and specify in real-time the TID wave parameters based on measuring the variations of the angles-of-arrival and Doppler frequencies of ionospherically reflected high-frequency (HF) radio signals. The project will run until 2017 and is expected to result in the development of a pilot network of DPS4D ionospheric sounders in Europe, enhanced by a real-time processing system of the TID observations for diagnostics and warnings purposes of TIDs and associated potential disturbances over the area. Based on these warnings, the end-users would be able to put in action specific mitigation techniques to protect their systems.

1. INTRODUCTION

Travelling Ionospheric Disturbances (TIDs) play an important role in the momentum and energy exchange between various regions of the upper atmosphere and in the coupling between the neutral atmosphere and ionospheric plasma. TIDs result in deviations of the Total Electron Content (TEC) that may affect the normal operation of HF geolocation, HF communication, GNSS, satellite communications and explosion monitoring. TIDs cause TEC changes of up to 10 TECU depending on their wavelengths. Large-scale TIDs (LSTIDs) propagate with wavelengths of 1000 to 3000 km and a velocity of 300 – 1000 m/s. Their amplitudes are greater than 5-10 TECU and are associated with auroral and geomagnetic activity (Tsugawa et al., 2004). Medium-scale TIDs (MSTIDs) propagate with wavelengths of 100-300 km and a velocity of ~100 m/s. MSTIDs are mostly associated with ionospheric coupling from below and, having no clear correlation with the geomagnetic activity, makes their identification even more difficult. The majority of MSTIDs cause TEC changes of less than 1 TECU; however, super MSTIDs, with amplitudes reaching 10 TECU, have been occasionally observed (Hernandez-Pajares et al., 2006). Given that differential ionospheric errors greater than 34 cm (2 TECU) cause problems in high precision differential GPS applications, it is important to identify TIDs, track their propagation over a wide area, and warn operators of the affected systems.

It is well known that the accuracy of the Single-Site-Location (SSL) HF radio wave direction finding technique is severely compromised by the passage of TIDs through the ionospheric reflection area. It is also known that MSTIDs occur virtually all the time with varying amplitudes similar to cloud occurrences in the troposphere. They can tilt the reflecting surface by up to 3° to 5°. These time-varying tilts cause variances in the measured bearings of about 1° for emitter distances of 1000 km to about 10° for 100 km, the “short-range catastrophe” (Ross, 1947).

Current TID identification techniques use maps of vertical TEC values derived from slant TEC measurements from the ground-based GPS receiver network (e.g. Ding et al., 2013; and references therein). There are a number of issues with this approach. First, the TEC values represent the integral of the electron density over the entire path from the bottomside ionosphere to the altitude of the GNSS satellite. The inversion from slant to vertical TEC uses algorithms that have a number of assumptions introducing considerable uncertainty in the resulting maps. Second, the mapping techniques include a good amount of “data smoothing” which can inadvertently mask the TIDs, given that the accuracy of the TEC values (3 TECU) is of the order to the TID disturbances (1-10 TECU). Third, the largest density variations caused by TIDs occur at and below the altitude of the F2 layer peak in the ionosphere, while approximately two-third of TEC is controlled by the topside ionosphere and plasmasphere. The electron density disturbances in the bottomside ionosphere may cause a redistribution of the ionization at higher altitudes, but the initial slant TEC measurements will be ambiguous in terms of TID specification. Fourth, the TEC TID identification is currently done only retrospectively because high resolution vertical TEC maps are only available with a considerable time delay. Overall, the TEC TID identification approach is indirect and approximate, and a more direct and accurate system to identify and track TIDs must be developed.

In this project we propose the development of a direct method of TIDs detection based on the establishment of bistatic HF propagation links between DPS4D Digisondes and the analysis of the oblique ionogram and skymap measurements with the Frequency & Angular Sounding (FAS) technique. This project requires high skills on HF experiments, analysis of ionogram and skymap records, and development and validation of ionospheric models.

2. OBSERVING NETWORK AND DATA ANALYSIS

To achieve the objectives of this project, we exploit the new capabilities of several DPS4D ionospheric stations operating in Europe. The advanced capabilities of DPS4Ds are presented in details by Reinisch et al. (2009). In summary, DPS4Ds have digital transmitters and receivers in which no analog circuitry is used for conversion between the baseband and the RF. In comparison with the older Digisonde systems, the new hardware design has enabled the implementation of new software solutions that offer significantly enhanced measurement flexibility, enhanced signal selectivity, and new types of data, e.g., the complete set of time domain samples of all four receive antenna signals suitable for independent scientific analysis. With a new method of mitigating in-band RF interference, the ionogram running time can be made as short as a couple of seconds even though the transmitted RF power is only <15 W_{ave}. These capabilities make successful observations possible in an electromagnetically polluted area such as Europe. The h'(f) precision ranging technique (Reinisch et al., 2009), with an accuracy of better than 1 km, can be used on a routine basis. The 4D model runs the new ARTIST-5 ionogram autoscaling software (Galkin et al., 2008) which provides in real time the required data for assimilation in ionospheric models (Galkin et al. 2012).

In contrast to the earlier Digisondes, which output only Fourier-transformed data, the DPS4D has an additional time domain data output. The two 16-bit quadrature samples for each sampled range and all four receiver channels are stored. For a typical ionogram with 500 frequency steps and 512 h'-samples per frequency, this results in 262 MB per ionogram of raw time domain data, considering complementary intrapulse phase coding, ordinary and extraordinary polarization, dual frequencies for precision range measurements, 8 repetitions for Doppler analysis, and 4 receive antennas. While this data volume is generally too large for routine operation, it can be afforded for special campaigns. This feature will make it possible for the DPS4D users to process the data anyway they like with their own algorithms suitable for specific scientific research.

Using the DPS4D systems it is possible to apply the Frequency-and-Angular Sounding (FAS) technique to measure angles of arrival and Doppler frequency shifts of the probe signals. The method was initially developed for obliquely incidence HF skywave signals (Beley et al., 1995), assuming a perfectly reflecting mirror model representing TIDs propagating at ionospheric heights. Paznukhov et al. (2012) extended the technique to vertical incidence sounding.

In Europe five DPS4Ds participate in this program, and their Principal Investigators participate in this project. These are the DPS4Ds in Athens (Greece), Ebro (Spain), Dourbes (Belgium), Juliusruh (Germany), and Pruhonice (Czech Republic). These stations are able to operate in synchronized mode, and -in collaboration with the USAF NEXION stations installed in Italy and UK- can establish a pilot network able to fulfill the operational specifications for the identification of TIDs. The map showing the locations of the DPS4D stations is presented in Figure 1.

Potential TID sensing capabilities have already been reviewed and a preliminary TID measurement schedule has been designed and tested. Four relevant measurement modes are considered:

#1: Digisonde-to-Digisonde (D2D) Skymapping
This is a periodic 40-sec fixed-frequency (selectable) transmission with 4-channel spectral data collected at the receiving DPS4D; a 5-min cadence is currently implemented, and 2 or 2.5 minute cadences are options under consideration. The D2D skymapping where one Digisonde transmits and

the other operates in radio-silent reception mode is the main data resource for the FAS calculations of the TID parameters.

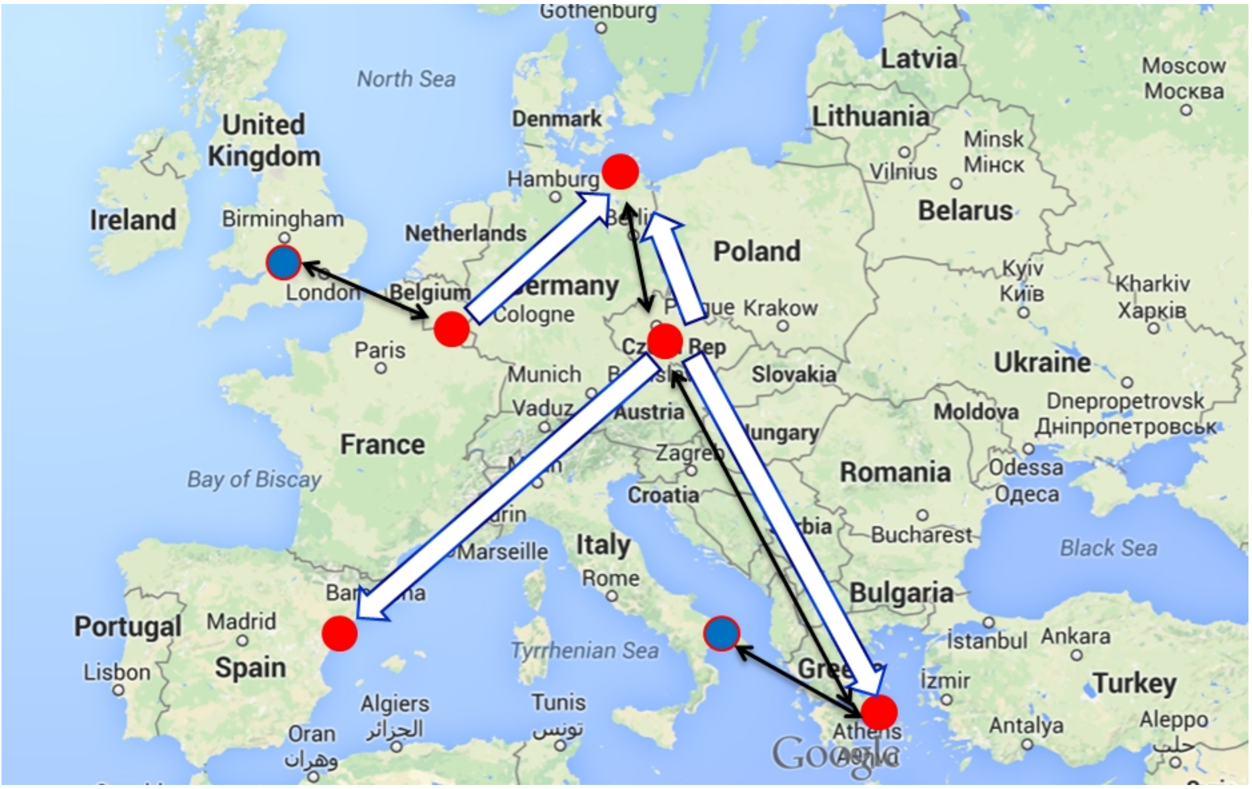

Figure 1. DPS4D locations and possible short and long path links under consideration for the pilot network. The DPS4D stations already participating in the project are indicated by the red dots. The NEXION stations are indicated with blue dots. Black arrows denote synchronized vertical and oblique "ionogramming", white arrows denote Digisonde-to- Digisonde "skymapping".

#2: Synchronous ionogramming with reception of both vertical incidence (VI) and oblique incidence (OI) echoes

When DPS4Ds operate with identical schedule and ionogram programs, they collect not only their own VI signal, but also the OI signals from neighbouring stations. While OI ionograms are not directly used for FAS TID calculations, the science team can study their signatures for anomalous propagation caused by TIDs.

#3: Dedicated OI ionogram mode

Ionogramming with one station transmitting and the other operating in radio silent reception mode has been already done between Dourbes, Roquetes, and Juliusruh. The mode is similar to #2, but such ionograms must be scheduled in addition to the regular VI mode, and longer radio paths can be involved. OI ionograms will not be used by FAS, but rather used for studies of special signatures.

#4: Reception of HF signals from Transmitters-of-Opportunity

This is a periodic 40 sec fixed-frequency reception with 4-channel time-domain data that will be Fourier analysed at the Lowell Global Ionosphere Radio Observatory (GIRO) Data Center to serve as input to the FAS analysis (Galushko et al., 2003). Several broadcasting HF stations in Europe are being considered.

3. FIRST RESULTS

Figure 2 shows a VI+OI ionogram at Athens with OI signals from San Vito (magenta color = West).

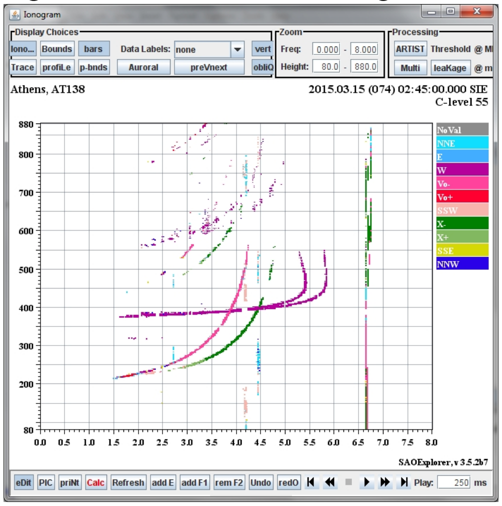

Figure 2. An example of VI+OI synchronization between Athens and San Vito DPS4D.

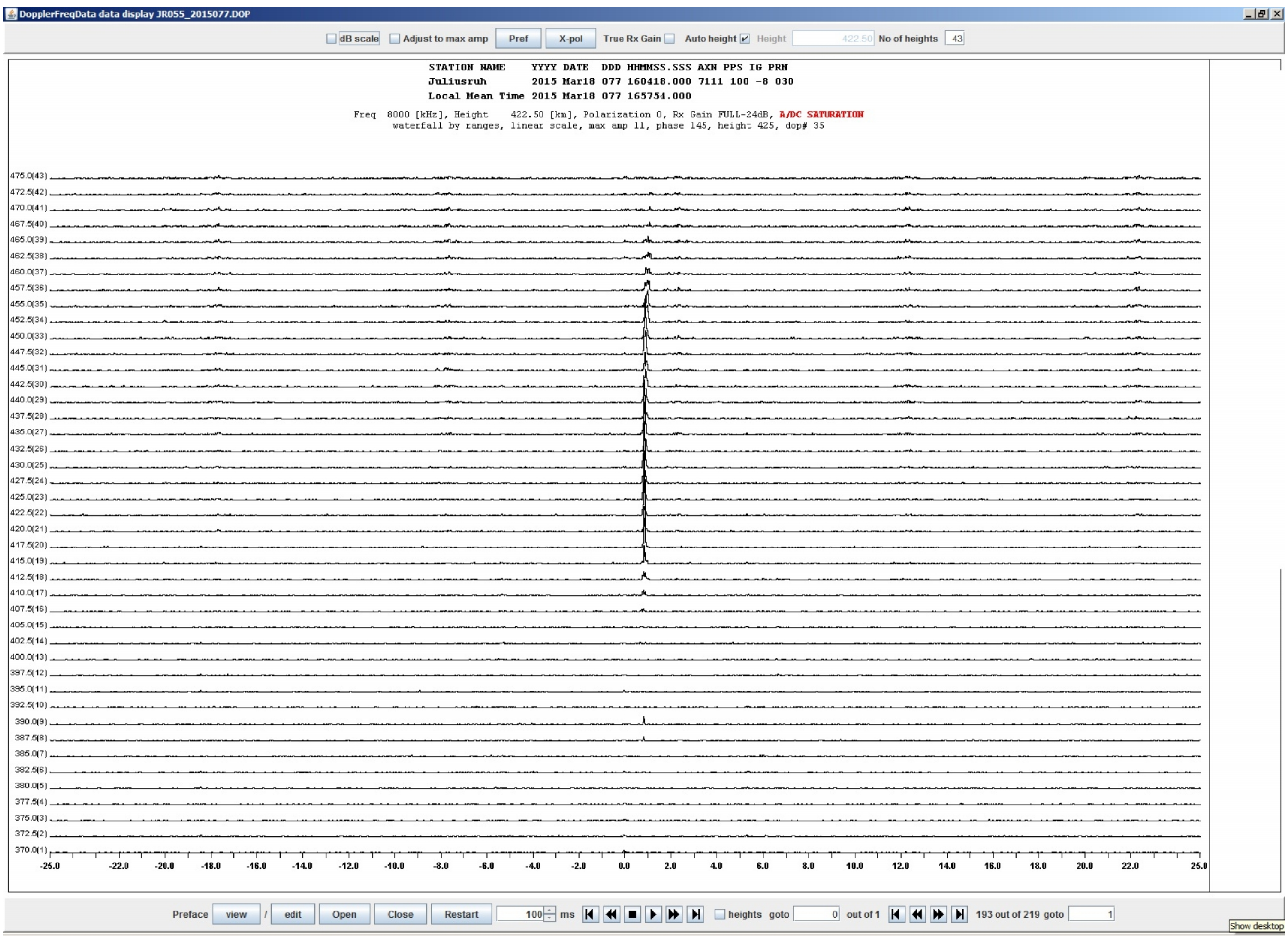

Figure 3. D2D waterfall display at Juliusruh listening to the 8.0 MHz transmissions from Pruhonice, recorded on 18 March 2015.

First D2D skymap results are shown for the relatively short path Pruhonice (transmitting) -> Juliusruh (receiving). The D2D "waterfall" display of the (Doppler) spectral amplitudes in Figure 3 displays the amplitudes as a function of range for the 8.0 MHz transmissions. The HF pulse arrived at an apparent range of 2x600 km.

A special testing campaign has been started on 17 March 2015 with all participating stations operating in synchronized mode. It so happened that on that very day, one of the most intense geomagnetic storms of the current solar cycle started (with Dst falling bellow -200 nT).

While the D2D skymapping measurements are still being analyzed we are providing here some indicative plasma frequency contour plots from the Ebre DPS4D. There is evidence of TID occurrences during this storm that can be seen in Figure 5 (a and b) from the contour plots of the true height for selected plasma frequencies as a function of time. Large scale TIDs can also be confirmed from visual ionogram inspection.

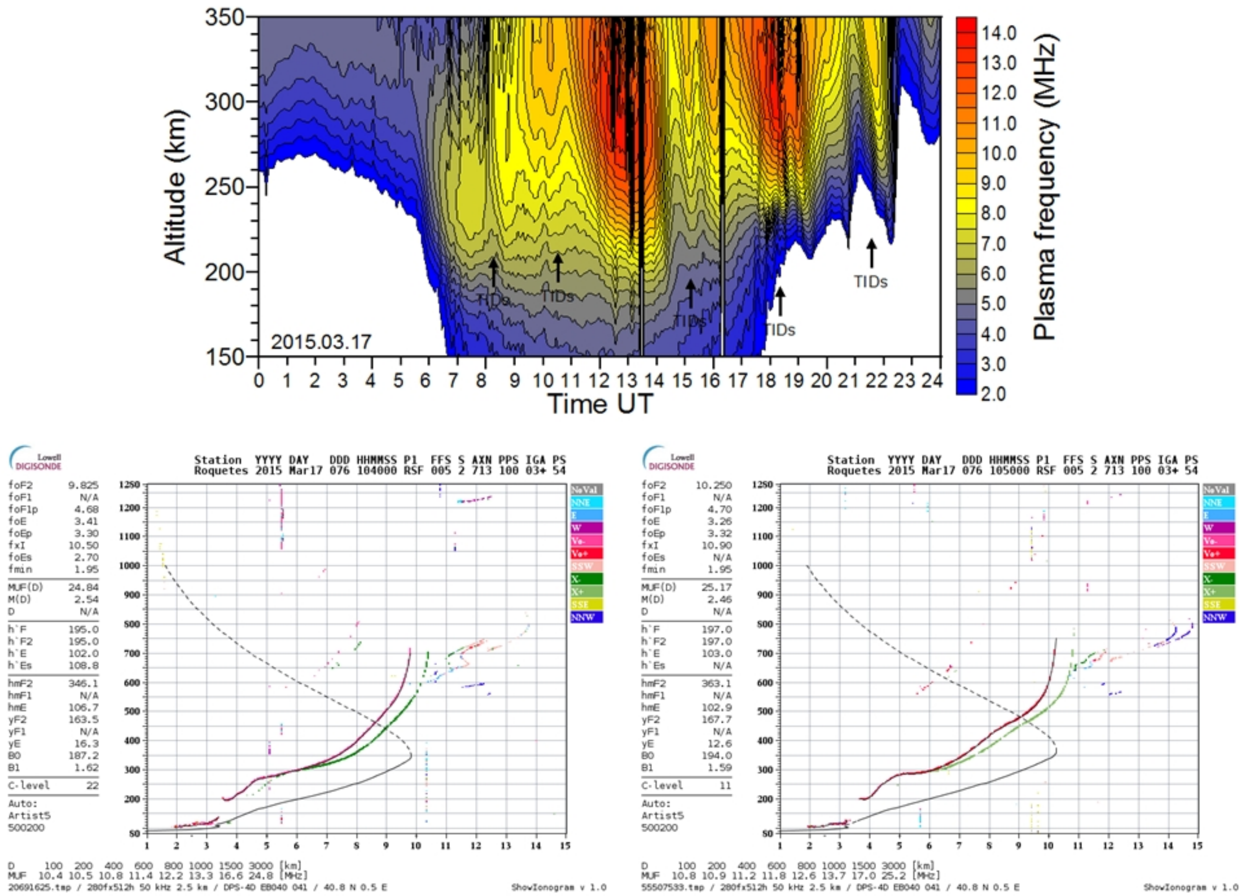

Figure 5 (a) The contour plots of the true height for selected plasma frequencies as a function of time derived from the 5-min sequence of electron density profiles measured by Ebre DPS4D (Roquetes) on 17 March 2015. That date at 0500 UT an intense geomagnetic storm has initiated, with the Dst index exceeding the 200 nT in absolute values. The ionogram recordings shown also TID traces.

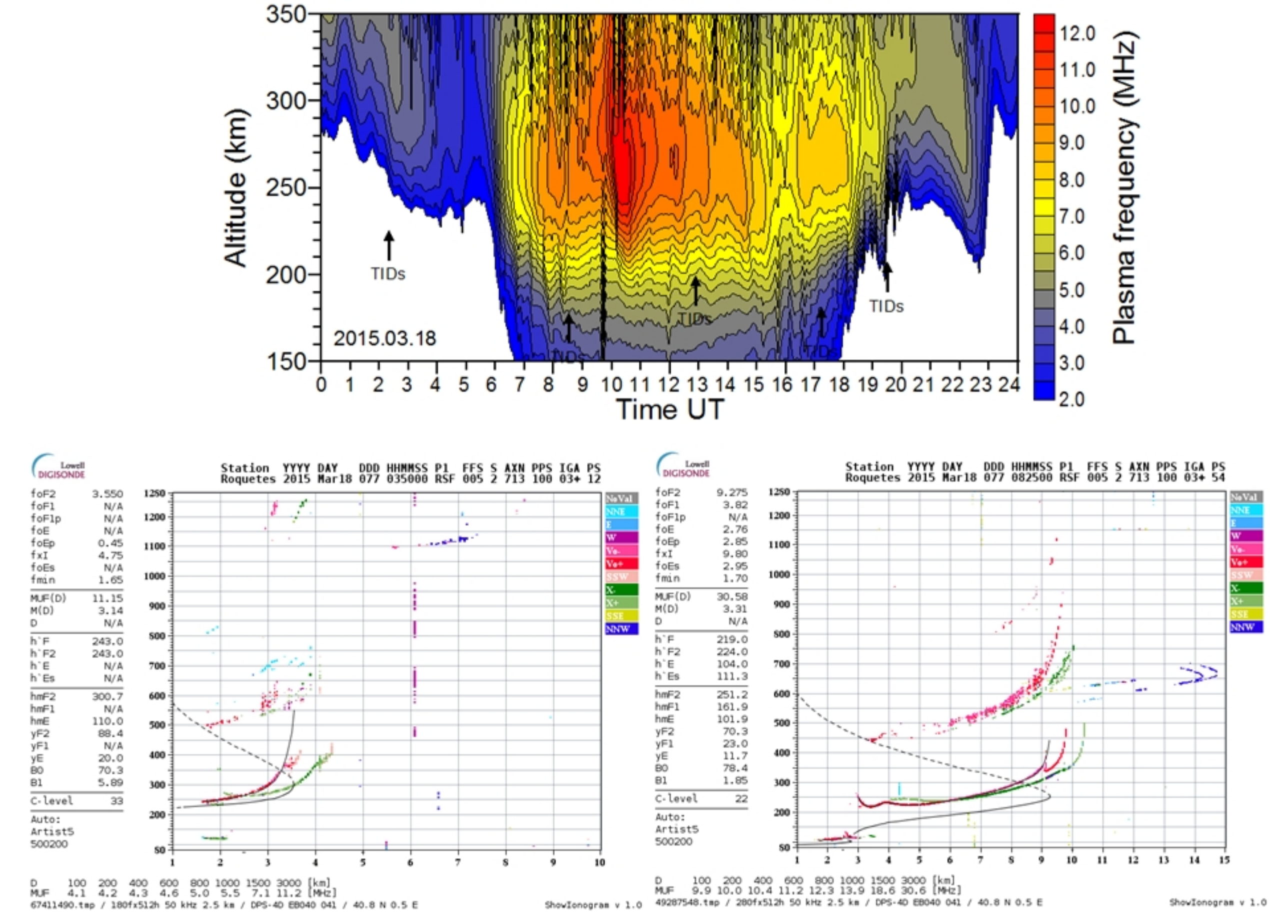

Figure 5(b). Same as Figure 5(a) for the 18th March 2015. The geomagnetic storm has a positive effect over Ebre. Typical TID signatures ("hooks") are seen in the VI ionograms.

4. CONCLUSIONS AND OUTLOOK

The first conclusions from the short special campaign organised in March 2015 is that automatic synchronized sounding between existing DPS4Ds can be achieved, and measured data can be deposited in real time in the Lowell GIRO Data Center for analysis of ionospheric disturbances, especially TIDs using the FAS technique. Databases for the OI ionogram and TID data will be developed together with the TID Explorer software for visualization of TID data. For this to become possible, a number of critical metadata and data must be stored in the TID database providing information for the reference time, the location of TID, the location of instruments, the azimuth, zenith angle, and Doppler frequency shift, the TID wave period, the amplitude of TID perturbation, the k-vector of TID wave propagation, and the phase of TID wave. The project effort for the next months will focus on the developments of all required databases and software tools that will support the on-line analysis of collected data.

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