Warning and Mitigation Technologies for Travelling Ionospheric Disturbances Effects

TechTIDE

User Manual

Continuous Doppler sounding method

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1. Measurements

The principle of continuous Doppler sounding (CDS) can be in a simplified way described as follows: A vertically-propagating radio wave reflects at the height where its frequency matches the local plasma frequency, which is determined by the electron density. TIDs or acoustic gravity waves (AGWs) which are frequently the source of TIDs cause via collisions between neutral and charged particles fluctuations (movement) of the reflecting level, and hence the Doppler shift of the reflected radio wave.

To analyze horizontal propagation of TIDs or AGWs at least three spatially separated reflection points are needed. In other words, at least three different transmitter-receiver pairs are required. The horizontal propagation of TIDs can be determined from the phase (time) delays observed between the individual reflection points. It is assumed that the reflection points are (in horizontal plane) in the midpoints between the individual transmitters and receiver. Three currently used multi-point CDS installed in the central and north-western part of the Czech Republic operate at sounding frequency f=3.59, 4.65 and 7.04 MHz. The sounding system at each frequency consists of 3 transmitters and one receiver; their locations in the coordinate systems are displayed in Figure 1.

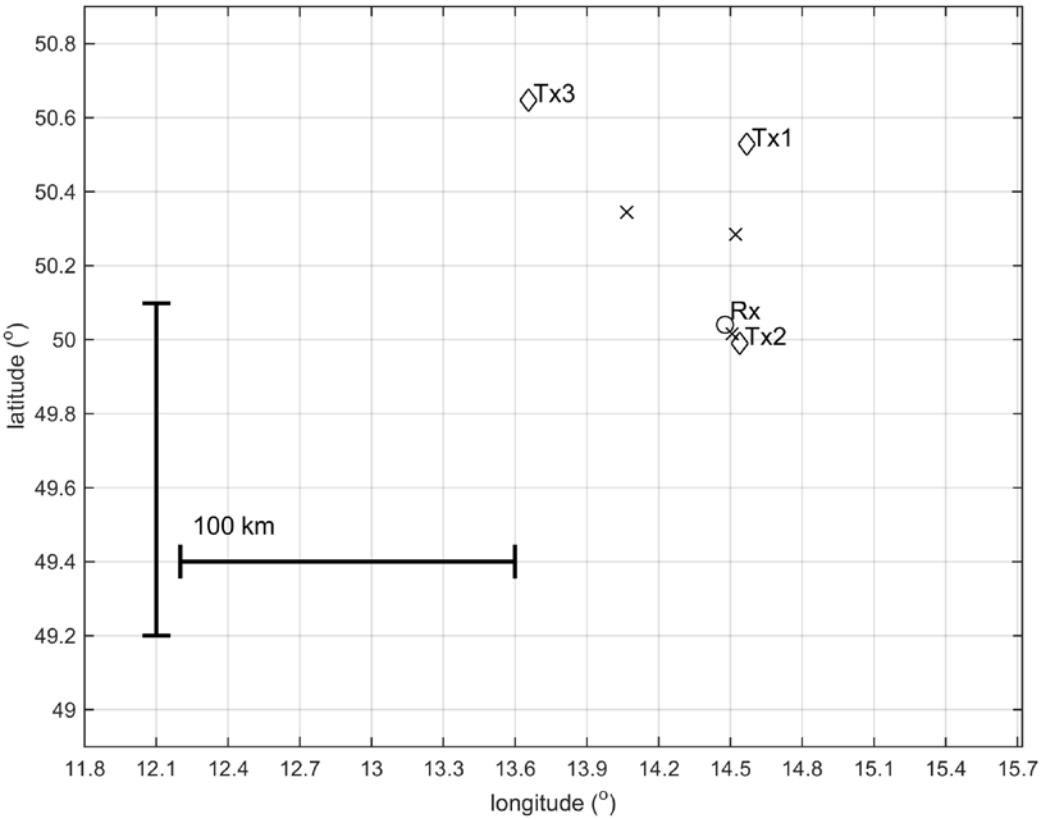

Fig. 1. Locations of transmitters Tx1 – Tx3 and receiver Rx.

The transmitter Tx2 is close to receiver Rx and nearby digital portable sounder DPS4. This makes it possible to perform common volume studies with DPS4, on the other hand it partly complicates data processing as the ground wave from Tx2 is also received by the receiver Rx. The frequencies of individual transmitters are shifted by about 4 Hz. This makes it possible to process the signals from all the transmitters simultaneously and to display them in one Doppler shift spectrogram. The data are stored in 15 min binary data files.

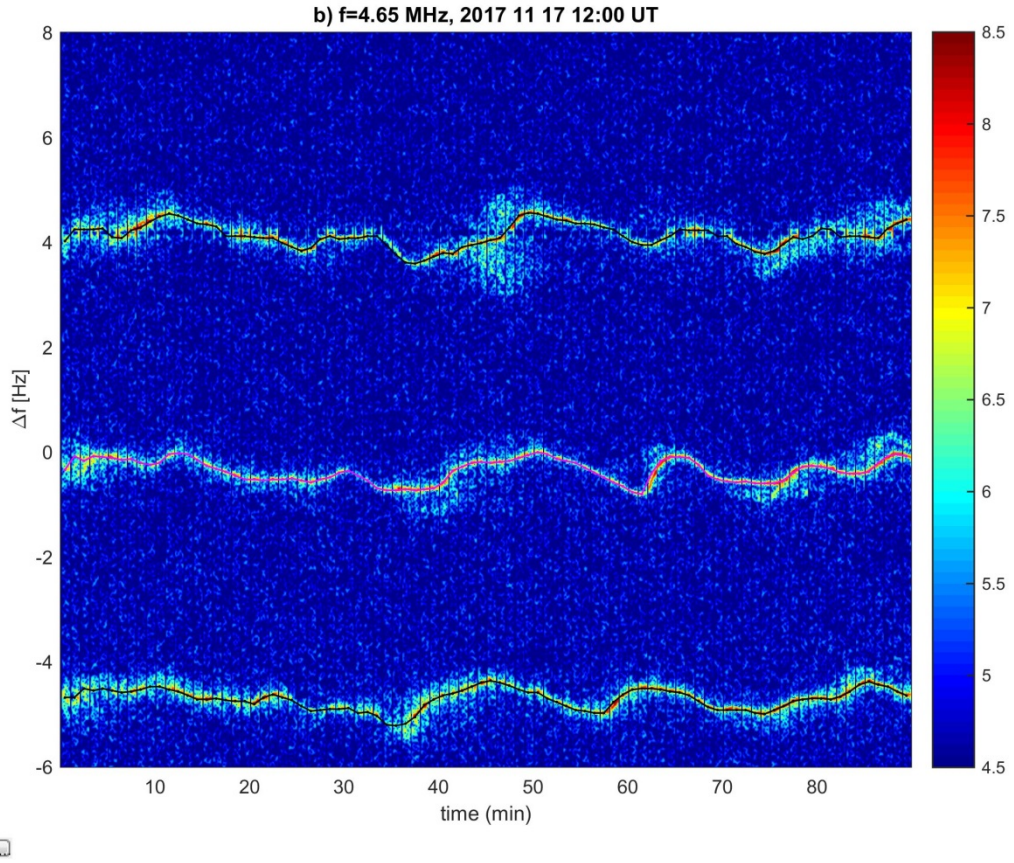

Figure 2. Example of 90-min Doppler shift spectrogram recorded from 12:00 UT on 17.11.2017. The maxima of spectral intensities corresponding to the Tx-Rx pairs are marked by magenta or black lines.

2. Data Analysis and available preprocessed data

The TIDs analysis is based either on automatically approximated or manually approximated data. The purpose of the approximation is to obtain time-series (single-valued functions of time) for individual sounding paths (transmitter-receiver pairs). The Doppler shift spectrograms are computed first in both cases. Specifically, Doppler shift spectrograms are computed over 90-min record for this purpose (example in Figure 2). In addition, the frequency corresponding to the ground wave is removed from the spectrogram. Then maxima of spectral intensities are searched in three preselected frequency bands that correspond to the frequency bands of the individual transmitter-receiver pairs. The Doppler shift frequencies f_{Di} corresponding to the maxima of spectral intensities then represent the

time series that are further analyzed. We used two different approaches to find the time series: a) with manual correction and b) fully automatic approach for TID detection

2.1. Time series with manual corrections

The automatically found maxima are visually checked against the Doppler shift spectrograms and if necessary (for example in the case of trace splitting, interference, etc) corrected by clicking on the spectrogram. The data are stored in the next format and contain 90-min time interval.

2.1.1. Format of data files for time series with manual corrections

File name =YYMMDD_hhmm_XMHz_f.dat (e.g., 181025_1000_4MHz_f.dat),
where YY is the year-2000, MM is month, DD is day, hh and mm are the hour and minute of the begging of the time interval. X is the sounding frequency in MHz

Each file is actually a text file of four columns that contain the following information
time f_{D1} f_{D2} f_{D3}
time is in seconds related to the beginning of interval (time defined by the file name)
f_{D1} f_{D2} f_{D3} are Doppler shift frequencies corresponding to the maximum of spectral intensity for Tx1-Rx, Tx2-Rx and Tx3-Rx sounding path, respectively.
time step of 30 s is usually used
Note that f_{D1} f_{D2} f_{D3} contain artificial offsets given by their position in the spectrogram, and it is convenient to use f_{Di} -mean(f_{Di}) values in the next processing (TID analysis); the mean(f_{Di}) values represent the estimates of zero Doppler shift.

The corresponding Doppler shift spectrograms with displayed approximations have the same name but extension jpg. (In addition, 8-hour or 2-hour spectrograms can be browsed at http://datacenter.ufa.cas.cz/archive/)

2.1.2 Format of Time series from automatic TID detection

The automatic procedure has only been run on the CDS operating at 4.65 MHz.
The same format as in section 2.1.1 is used. There are, however, 6 additional columns (compared to manual data), which can be used for automatic TID detection described in Section 2.4. The meaning of these columns correspond to quantities p_{pi} and r_i described in the Section 2.4. These quantities are, however, not used for the calculation of propagation characteristics. They are only used for automatic decision about the character of data and possibility to processes them as described in the section 2.4. This is done on dedicated webpage. It is more reliable to check the quality of data and their approximation using the corresponding Doppler shift spectrograms.

Note that the data files from automatic approximation can also contain pure noise, for example if the sounding signals did not reflect because of low foF2 or spread F conditions. This, can be partly recognized from p_{pi} and r_i columns (Section 2.4) or more reliably from Doppler shift spectrograms.

2.2 Access to data

Data Files and corresponding Doppler shift spectrograms with found f_{Di} can be obtained at the ftp of the IAP CAS. The access will obtained after sending the username, password and range of the user's IP addresses to the email: jba@ufa.cas.cz
The manual data are in the subdirectory manual_data.
The automatically obtained data are in the subdirectory data/Praha.3.

2.2.1 Notes to data

Not all the time intervals were manually approximated. Only systematically processed months are on the ftp.
Not all the time intervals from automatic approximation are suitable for analysis. Moreover, automatic processing started approximately in the middle of 2018 and was tested (sometimes debugged) in 2018. The time interval written over the Spectrogram is mostly wrong (the time obtained from the filename is correct). This issue will be fixed.

2.3 Analysing TID and running the code

First the f_{DCi} series are bandpassed filtered to keep only periods from 4 to 50 min (can be set to other values). This aims to remove a possible high frequency noise and to remove long-period fluctuations (large-scale TIDs) that cannot be reliably analyzed with respect to 90-min intervals and with respect to the relatively small spatial scale (tens of km) of the measuring array defined by the reflection points.

Propagation characteristics of TIDs and their uncertainties can be analyzed e.g. by the 2D version of the method described by Chum, J., & Podolská, K. (2018). 3D analysis of GW propagation in the ionosphere. *Geophysical Research Letters, 45, 11,562–11,571.* https://doi.org/10.1029/2018GL079695
Specifically, three independent methods are applied to determine the observed horizontal velocity v_H and azimuth *AZ* of propagation i) slowness search, ii) least squares fitting to the time delays obtained from cross-correlation of the f_{DCi} series, iii) weighted least squares fitting to the time delays obtained from cross-correlation of the f_{DCi} series; the weights are the maxima of the cross-correlation functions. The values of propagation velocity v_H and azimuth *AZ* that are finally reported are the mean values of v_H and *AZ* quantities obtained by the three different methods; their uncertainties are estimated as corresponding standard deviations.

MATLAB code (tids_bt.m) is provided in the same ftp as data. It computes propagation characteristics of TIDs and period. The code can be run under the MATLAB. Important instructions are written in the beginning of the code. These specify how to set parameters. Namely:

```
% TIDs_bt.m computes propagation velocities of GWs in 2D from
Doppler signals a detect TIDs
% Set path for data to read (variable cestadata) and to store
results (variable cestaprint)
```

```
% Set tiskni to 2 if you want to store slowness maps, 1 otherwise
% the files to analyse are specified in the listTID.txt file that
has to be located in the same directory as this code
% It is possible to specify if all files will be analysed (justo=0)
or just
% specific number of files
% Bandwidth can be changed by changing the HPF and LPF variables
(4*60 and 50*60 are the recommended values)

clear all
Re=6378000;
c=2.99792458e8;

cestadata='D:\Data_obr\selected_3D_3f\20141108_foF2_OK_test\'; %
path to read data
cestaprint='D:\Data_obr\selected_3D_3f\20141108_foF2_OK_test\'; %
path to store results

outtext='slowness_results_' ; % file to store-append the results
filelist='listTID.txt'
justo=0; % 0.. analyze all, M(1..x)..analyze M files

HPF=50*60; % periods longer than HPF (in seconds) are filtred
(supressed)
LPF=4*60; % periods shorter than HPF (in seconds) are filtred
(supressed)

tiskni=1; % 0 no print, 1..print output parameters i text file,
2..print output parameters in text file and slowness maps
auto=0;  % 0.. standard processing, reading only Doppler shifts
         % 1.. process data from automatic approximation including
power parameters
```

The text output contains information about date and time of the interval center, velocity of propagation (v_H) and estimate of its uncertainty, Azimuth (AZ) and estimate of its uncertainty, psedocoherency from slowness search (rEm), average RMS value of Doppler fluctuations (dfRMS), estimate of dominant period (Tpm) and its uncertainty, and sounding frequency in MHz.
Optional output (if tiskni=2) are slowness maps

Example of text output:

Date	time	v_H (m/s)	dv_H (m/s)	AZ(°)	dAZ(°)	rEm	dfRMS	Tpm	dTpm	f
2014 11 08	14 45	0177.2	0001.58	134.2	005.53	0.758	0.138	24.9	5.33	3
2014 11 08	14 45	0177.2	0001.59	134.2	005.52	0.774	0.181	21.8	8.89	4
2014 11 08	14 45	0193.8	0004.90	129.2	001.81	0.803	0.260	21.6	8.89	7

2.4 Automatic TID detection

The recorded data are processed in several steps. The whole calculation is repeated each 15-min, which corresponds to the length of recorded data files.

First, Doppler shift spectrograms are computed for the last 90-min record. The frequency corresponding to the ground wave is removed from the spectrogram. Then maxima of spectral intensities are searched in three preselected frequency bands that correspond to the frequency bands of the individual transmitter-receiver pairs. The frequencies f_{Di} corresponding to the maxima of spectral intensities for each transmitter-receiver are stored together with powers p_{pi} calculated in the narrow frequency band around these maxima (bandwidth on the order of ~0.1 Hz). In addition, powers p_{Ti} in the whole frequency bands in which the maxima are searched are evaluated (frequency band of about 4 Hz). In addition to the values of f_{Di} and p_{pi} the power ratios $r_i = p_{pi}/p_{Ti}$ are also stored to a file with 1-min step (the stored values are 1 min averages). High values of r_i approaching to 1 indicate clear signals suitable for further analysis, whereas low values of r_i indicate signals with insignificant and featureless spectral maxima that occur e.g. during spread F conditions. Such signals are inconvenient for further analysis.

In the next step, the stored values of f_{Di}, p_{pi} and r_i are analyzed. First the offsets are removed and it is worked with values $f_{DCi} = f_{Di} - \langle f_{Di} \rangle$ further, where $\langle f_{Di} \rangle$ is the mean value over the 90-min intervals.

Next it is decided if TID or spread F likely occurred in the last 45 min and if propagation analysis of the TIDs makes sense in the last 90 min. These decisions are performed by checking if the following criteria are fulfilled.

a) TIDs are likely detected in the last 45 minutes if conditions (1) and (2) are fulfilled

$$(p_{pi} > Th1) \text{ and } (r_i >= Th2) \quad (1)$$

Condition (1) is required for at least 2/3 data points in the last 45 minutes, where *Th1*, *Th2* are experimentally found thresholds. The requirement ($p_{pi} > Th1$) ensures that sufficient signal power was received. Insufficient power is received, e.g., if the critical frequency is lower than f=4.65 MHz and the signals do not reflect from the ionosphere. As discussed before, the second requirement ($r_i > Th2$) ensures that the spectral maxima are significant.

$$\sigma_{fD} > Th3 \quad (2)$$

Where σ_{fD} is the average root mean square power (in other words variance) of f_{DCi} fluctuations calculated over all three sounding paths (transmitter-receiver pairs) for data points that fulfill condition (1) and *Th3* is an experimentally found threshold. Condition (2) ensures that there are distinct fluctuations of the Doppler shifts f_{DCi}. If *Th3* is large, only large TIDs are detected.

b) Spread F is likely detected in the last 45 minutes if condition (3) is fulfilled at least for 2/3 data points in the last 45 minutes.

$$(p_{pi} > Th1) \text{ and } (r_i < Th2) \quad (3)$$

Conditions (3) means that there is relatively large power distributed in relatively large spectral bandwidths.

c) TIDs are only analyzed if condition (1) is fulfilled over the last 90 min; it is required that 7/9 of data points in the last 90 min fulfill the condition (1).

2.4.1 Notes.

The proper values of thresholds *Th1*, *Th2*, *Th3* were found experimentally by visual checking of spectrograms. Their optimum values might change if the background noise changes or if the character of signal changes, e.g., frequent splitting to ordinary and extraordinary mode or a partial spread F conditions might cause problems. Current values of *Th1*, *Th2*, *Th3* are based on initial testing on limited number of examples, and may be changed in future after getting larger experience with automatic detection.

Also, current software package uses an external value of ground wave from transmitter Tx2 that has to be removed to reliably find spectral maximum of the Tx2-Rx sky wave. This external value has to be updated if necessary (e.g. owing to long-term drift).

The information is updated each 15 minutes. So, there is an overlap as the analyzed intervals are longer.