Retrospective Analysis Toolbox for Ionospheric Total Electron Content Maps

User Manual

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February 2024

1 Overview of the Toolbox

The Retrospective Analysis Toolbox for Ionospheric Total Electron Content (TEC) Maps is Python3-based software for analyzing gridded ionospheric TEC maps retrospectively. The toolbox consists of two parts, Feature Extraction Program and Transfer Entropy Calculator. Feature Extraction Program utilizes image processing techniques to extract characteristics of TEC intensifications, i.e., local regions of elevated TEC, from global ionospheric TEC maps [1-3]. Transfer Entropy Calculator quantifies solar and interplanetary driving of the extracted TEC intensifications via information theoretical approaches [4]. In addition, the toolbox includes a twenty-year TEC intensification dataset generated with Feature Extraction Program [5].

The structure of the toolbox is:

```
FeatureExtractionProgram/
        src/find_intensification.py
        src/fetch_jpld.py
        sample_datain/
        sample_dataout/
        sample_plots/

TransferEntropyCalculator/
        src/calc_information.py
        src/plot_information.py
        src/fetch_omni.py
        src/write_sw_15min.py
        src/write_intensfn_daily.py
        sample_datain/
        sample_dataout/
        sample_plots/

TECIntensificationDataset/
```

2 Feature Extraction Program

2.1 Prerequisites

Feature Extraction Program requires Python3 and the following packages:
numpy, cv2, netCDF4, matplotlib, and basemap.

2.2 Quick Start

find_intensification.py is the core script of Feature Extraction Program. Users can start with two quick tests using input files provided in sample_datain/.

To extract TEC intensifications from JPLD TEC maps on 1 January 2016:

```
python3 find_intensification.py --mapfiledir
../sample_datain/netcdf/ --mapfiletype netcdf --label jpld --
plotdir ../sample_plots/plots --stationloc
../sample_datain/netcdf/STLOCS.16jan01
```

Sample test output file and plots are sample_dataout/intensifications_jpld.dat and figures in sample_plots/plots_jpld/.

To extract TEC intensifications from IGSG TEC maps on 1 - 3 January 2016:

```
python3 find_intensification.py --mapfiledir
../sample_datain/ionex/ --mapfiletype ionex --label igsg --plotdir
../sample_plots/plots --thressiz 5
```

Sample test output file and plots are sample_dataout/intensifications_igsg.dat and figures in sample_plots/plots_igsg/.

2.3 Inputs

find_intensification.py takes the following input arguments (required arguments are marked as *):

--mapfiledir [*]
path to map files.

--mapfiletype [*]
map file type, can be netcdf or ionex.
JPLD TEC maps are in netcdf format and available at
https://sideshow.jpl.nasa.gov/pub/iono_daily/gim_for_research/jpld/
JPLD TEC maps for specific years can be obtained using src/fetch_jpld.py.
IONEX format TEC maps are offered by IGS
https://cddis.nasa.gov/archive/gnss/products/ionex/

--label [*]
label to append to the output file name and plot directory name.

--plotdir

directory to save plots, label will be appended to the provided plotdir as [plotdir]_[label]. If plotdir is not provides, the default directory is ./plots_[label].

--plotdt

save plots every [plotdt] maps, set to 0 to not save plots, default is 12. Saved plots are tecmap_[yyyymmdd]_[hhmm].pdf and imgprocessing_ [yyyymmdd]_[hhmm].pdf.

--threstec

TEC threshold in percentile, between 0 and 100, default is 97. Grid points with TEC values below the TEC threshold are excluded from being identified as TEC intensification regions.

--threslap

threshold for Laplacian operator, typically between-1 and 0, default is 0.

--thressiz

threshold for intensification minimum area in number of grid cells. Default is 65, which is good for capturing large-scale intensifications from 1°X1° maps. The value should be reduced for lower-resolution maps.

--stationloc

path and name of the file containing locations of GNSS ground stations used to generate the TEC map. If provided, count the number of GNSS stations within/nearby each intensification region and write to the output file.

--boundarywidth

width in number of grid cells to add as the boundary of an intensification region, for counting the GNSS ground stations within the intensification including the boundary. Default is 3, which is good for 1°X1° maps. The value should be reduced for lower-resolution maps.

2.4 Outputs

find_intensification.py generates an ASCII file intensifications_[label].dat, which contains the number of TEC intensifications identified on given TEC maps and characteristics of each TEC intensification: the maximum, median, and minimum TEC within the intensification region, the geographic longitude and latitude of the TEC maximum, the Regional Electron Content (REC) of the intensification, the size of the intensification, and optionally the number of GNSS receivers located within and nearby the intensification region. Users are encouraged to look into sample_dataout/intensifications_igsg.dat and sample_dataout/intensifications_jpld.dat as examples of the output file.

3 Transfer Entropy Calculator

3.1 Prerequisites

Transfer Entropy Calculator requires Python3 as well as numpy and matplotlib packages.

3.2 Quick Start

calc_information.py is the core script of Transfer Entropy Calculator. It computes the mutual information, transfer entropy, and entropy rate for given driver (F10.7 or solar wind) data and TEC intensification data. Users can start with two quick tests using input files provided in sample_datain/.

Test for daily F10.7 and daily TEC intensification data during years 2005-2006:

```
python3 calc_information.py --beginyear 2005 --endyear 2006
--maxdelay 3
```

Test for 15-minute resolution solar wind and TEC intensification data during 2005-2006:

```
python3 calc_information.py --beginyear 2005 --endyear 2006
--maxdelay 3 --npermu 20 -o ../datatmp --datafreq '15min' --driver
'solarwind'
```

Sample output files are in sample_dataout/. Note that while ER, MI, and TE data files from the tests should be identical to the corresponding sample output files, TEshuffle data files could be different due to different random permutation each time calc_information.py is run.

3.3 Inputs

calc_information.py takes the following input arguments (required arguments are marked as *):

--beginyear [*]
: begin year of data, in yyyy.

--endyear [*]
: end year of data, in yyyy.

-i,--indir
: path to input F10.7, solar wind, and TEC intensification data.

-o,--outdir
: directory to store output MI, TE, ER data files.

--datafreq
: frequency of input data, can be ‘daily’ (default) or ‘15min’.

--driver

'f107' (default) or 'solarwind'.

--maxdelay

maximum delay time tau in number of data points, recommend 365 (365 days) for daily data and 480 (5 days) for 15-min data.

--npermu

number of times to randomly shuffle driver data for computing TEshuffle, default is 100.

The toolbox provides scripts to obtain and generate input files of the desired format:
fetch_omni.py obtains 5-minute resolution OMNI solar wind data for a specified year range.
write_sw_15min.py converts the downloaded 5-minute OMNI data to 15-minute average data in the format required by calc_information.py.
write_intensfn_daily.py generates intensification data file at daily resolution for input to calc_information.py, when the driver is specified as daily F10.7 data.

3.4 Outputs

calc_information.py produces four data files: MI, TE, TEshuffle, and ER. MI data file contains the mutual information between the driver and TEC intensification data. TE data file contains the transfer entropy from the driver to the TEC intensification data. TEshuffle file contains the mean and 3-sigma of transfer entropy values from a number of randomly permutated driver data to the TEC intensification data. ER file is the entropy rate of the TEC intensification data.

3.5 Visualization

plot_information.py is offered as a tool to visualize the outputs of calc_information.py. In addition, it computes and visualizes the normalized transfer entropy. Example plots can be found in sample_plots/.

4 TEC Intensification Dataset

The TEC intensification dataset is generated from JPLD TEC maps of 2003 - 2022 using Feature Extraction Program. The dataset contains the number and characteristics of large-scale TEC intensifications extracted from the TEC maps every 15 minutes. The dataset offers valuable long-term data of large-scale ionospheric structures and can be used for ionospheric research.

5 Other Information

The toolbox was developed by:
Xing Meng (JPL)
Olga P. Verkhoglyadova (JPL)
Natalie Maus (University of Pennsylvania, developed the first version of Feature Extraction Program during internship at JPL)

Acknowledgement:
The toolbox was developed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. Sponsorship of NASA ROSES Living With a Star Tools and Methods Program is gratefully acknowledged. The OpenCV team is gratefully acknowledged as well (https://opencv.org/).

Attribution:
For publishing any work using the toolbox, please provide appropriate credit to the developers via citation or acknowledgement.

Contact:
Please contact Xing Meng (xingm@umich.edu) for questions, issues, and bug reporting.

References

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