Open-source Toolbox for Tomographic Reconstruction of Atmospheric Wet Refractivity Model Using GNSS Observations

User manual

Authors:

Bence Turák
Abir Khaldi
Szabolcs Rózsa

Description

This toolbox provides a tomographic algorithm that capable of estimate a 3D wet refractivity model in Eastern Europe. The sizes of the tomographic grid are specified in the input files listed below. This algorithm uses an approximate cartesian reference system in which the length of the rays can be easily calculated. This Cartesian reference system is defined in the *getlocal.py* file and must be modified in case it is used in another area.

The toolbox has been tested on the Ubuntu 20 operation system using Python 3.8. The other required packages are listed below.

Requirements

- Python 3.8
- Python modules
    - NumPy
    - SciPy
    - Wget
    - Matplotlib

Usage

Tomography processing is a python3 compatible script on Linux OS. (On Ubuntu OS is stable.)

```
gnssct.py  [OPTION]
    -s,  --satellites      location of satellite orbits file in .SP3 format
    -S,  --stations        location of the station coordinates file in Bernese .CRD format
         --gridp           location of grid file in the direction of North-South in .csv
format (degrees)
         --gridl           location of grid file in the direction of East-West in .csv
format (degrees)
         --gridh           location of elevation grid file .csv format (metres)
    -v,  --vmf1loc         location of VMF1 parameters grid files directory
    -i,  --initial_w       location of the initial wet refractivity values in .csv format
    -e,  --epoch           epoch in format YYYY-MM-DD-hh-mm-ss
    -d,  --database        name of the python modul for the database configuration

Example:
python3 gnssct.py --satellites=./sample_data/orbit/CDU23005_00.EPH --
stations=./sample_data/METEONET.CRD --tropofile=./sample_data/TRP/CO24040C.TRP --
gridp=./sample_data/gridp.csv --gridl=./sample_data/gridl.csv --
gridh=./sample_data/gridh.csv --vmf1loc=./sample_data/vmf1/ --epoch=2024-2-9-2-0-0 --
initial_w=./sample_data/raobs/files/12843_2024-2-8_11.csv
```

Fig. 1. Usage of GNSS tomography toolbox

The VMF1 parameters grid files must be placed in this directory, and the name format must be: YYYY/VMFG_YYYYMMDD.Hhh

Input files

For the tomographic processing, the following input files are required:

- The tomographic grid file (csv format)
  - Latitude
  - Longitude
  - Height
- GNSS stations coordinates file (Bernese CRD format)
- Tropospheric delays file (Bernese TRP format)
- VMF1 grid parameters file (VMF1 grid file)
- Satellite orbit file (SP3 format)
- Initial wet refractivity values (csv format)

Tomographic grid files

Tomographic grid files define the size of the cells in each direction (latitude, longitude, height borders) over the entire area. Each file is a list of coordinates. In the case of latitude and longitude, the script expects the coordinates in degrees (WGS84), and the heights to be in meters.

```
45.5
46.2
46.9
47.6
48.3
49.0
49.7
```

Fig. 2. Tomographic grid (longitude) in csv format

GNSS station coordinates file

The GNSS station coordinates file contains all the GNSS stations and their coordinates forthe given epoch in CRD format

```
Weekly solution for Week 2310                                       04-FEB-24 05:50
--------------------------------------------------------------------------------
LOCAL GEODETIC DATUM: IGS14             EPOCH: 2024-01-31 12:00:00
.
NUM  STATION NAME           X (M)          Y (M)          Z (M)     FLAG

  1  BAIA              3945839.43919  1720428.58296  4691082.90436    A
143  BAJ1              4183093.74170  1439191.16597  4579512.35582    A
  2  BAJA              4183094.39352  1439190.59467  4579511.94882
140  BARA              3805783.52640  1629895.39810  4835969.94890
  4  BBYS              3980358.47759  1382292.41144  4772772.14404    A
. . .
```

Fig. 3. Bernese CRD file

Tropospheric delays file

For calculating Slant Wet Delay (SWD) values, the Zenith Wet Delays ZWD and Tropospheric Gradient Values are required for each station. These files must be in Bernese TRP format, where ZWDs are in column CORR_U and Tropospheric gradients are in CORR_E and CORR_N.

```
                                                                   13-FEB-24 02:43
-------------------------------------------------------------------------------------------------------------------------------------
 A PRIORI MODEL:  -17   MAPPING FUNCTION:    8   GRADIENT MODEL:    4   MIN. ELEVATION:    5   TABULAR INTERVAL:  3600 / 86400

 STATION NAME     FLG   YYYY MM DD HH MM SS   YYYY MM DD HH MM SS   MOD_U   CORR_U  SIGMA_U TOTAL_U  CORR_N  SIGMA_N  CORR_E  SIGMA_E

 BAIA              A    2024 02 12 13 00 00                         2.2196  0.09388 0.00077 2.31352  0.00030 0.00007 -0.00045 0.00008
 BAIA              A    2024 02 12 14 00 00                         2.2204  0.09501 0.00065 2.31546  0.00027 0.00006 -0.00043 0.00007
 BAIA              A    2024 02 12 15 00 00                         2.2213  0.09834 0.00061 2.31959  0.00024 0.00005 -0.00042 0.00006
 BAIA              A    2024 02 12 16 00 00                         2.2221  0.10192 0.00059 2.32398  0.00020 0.00004 -0.00041 0.00005
 BAIA              A    2024 02 12 17 00 00                         2.2229  0.10583 0.00065 2.32870  0.00017 0.00004 -0.00040 0.00004
 BAIA              A    2024 02 12 18 00 00                         2.2237  0.10097 0.00062 2.32464  0.00014 0.00003 -0.00039 0.00004
 BAIA              A    2024 02 12 19 00 00                         2.2243  0.11003 0.00057 2.33429  0.00011 0.00004 -0.00038 0.00004
 BAIA              A    2024 02 12 20 00 00                         2.2249  0.10984 0.00057 2.33470  0.00008 0.00004 -0.00037 0.00005
 BAIA              A    2024 02 12 21 00 00                         2.2255  0.10986 0.00062 2.33532  0.00005 0.00004 -0.00036 0.00005
 BAIA              A    2024 02 12 22 00 00                         2.2260  0.10691 0.00054 2.33296  0.00002 0.00005 -0.00035 0.00006
 BAIA              A    2024 02 12 23 00 00                         2.2266  0.10955 0.00097 2.33619 -0.00001 0.00006 -0.00034 0.00007
 BAIA              A    2024 02 13 00 00 00                         2.2272  0.11208 0.00085 2.33931 -0.00004 0.00007 -0.00033 0.00008
 BAIA              A    2024 02 13 01 00 00                         2.2281  0.11455 0.00147 2.34270 -0.00114 0.00018  0.00096 0.00022
 BAJ1              A    2024 02 12 13 00 00                         2.2523  0.10312 0.00069 2.35542 -0.00008 0.00005  0.00009 0.00005
 BAJ1              A    2024 02 12 14 00 00                         2.2535  0.09919 0.00058 2.35268 -0.00011 0.00005  0.00007 0.00005
 BAJ1              A    2024 02 12 15 00 00                         2.2547  0.10126 0.00054 2.35593 -0.00014 0.00004  0.00005 0.00004
 BAJ1              A    2024 02 12 16 00 00                         2.2558  0.09740 0.00051 2.35325 -0.00017 0.00004  0.00002 0.00004
 BAJ1              A    2024 02 12 17 00 00                         2.2570  0.10381 0.00057 2.36084 -0.00021 0.00003  0.00000 0.00003
```

Fig. 4. Bernese TRP file

VMF1 grid parameter files

The calculation of the SWDs requires a mapping function. For this purpose, the script uses the VMF1, which needs the a_w coefficients. These coefficients are available on the website of the Vienna University of Technology. These parameters are provided in grid files for every 6 hours. For the hourly interpolation in time, the script expects two files.

```
! Version:             1.0
! Source:              J. Boehm, TU Vienna (created: 2024-02-14)
! Data_types:          VMF1 (lat lon ah aw zhd zwd)
! Epoch:               2024 02 15 00 00  0.0
! Scale_factor:        1.e+00
! Range/resolution:    -90 90 0 360 2 2.5
! Comment:             http://vmf.geo.tuwien.ac.at/trop_products/GRID/2.5x2/VMF1/VMF1_OP/
 90.0   0.0 0.00117044  0.00060490  2.2998  0.0204
 90.0   2.5 0.00117044  0.00060490  2.2998  0.0204
 90.0   5.0 0.00117044  0.00060490  2.2998  0.0204
 90.0   7.5 0.00117044  0.00060490  2.2998  0.0204
 90.0  10.0 0.00117044  0.00060490  2.2998  0.0204
 90.0  12.5 0.00117044  0.00060490  2.2998  0.0204
 90.0  15.0 0.00117044  0.00060490  2.2998  0.0204
 90.0  17.5 0.00117044  0.00060490  2.2998  0.0204
 90.0  20.0 0.00117044  0.00060490  2.2998  0.0204
 90.0  22.5 0.00117044  0.00060490  2.2998  0.0204
 90.0  25.0 0.00117044  0.00060490  2.2998  0.0204
 90.0  27.5 0.00117044  0.00060490  2.2998  0.0204
. . .
```

Fig. 5. VMF1 grid file

Satellite orbit file

To calculate the azimuth and elevation angle from the station to the satellite, besides the station coordinates, the satellite orbits are also required in SP3 format. The ultra-rapid satellite orbits for GPS, GLONASS, and Galileo constellations are available from the Center for Orbit Determination in Europe at the University of Bern.

```
#cP2024  2 12 18  0  0.00000000     577 d+D   IGS20 EXT AIUB
## 2301 151200.00000000   300.00000000 60352 0.7500000000000
+   78   G01G02G03G04G05G06G07G08G09G10G11G12G13G14G15G16G17
+        G18G19G20G21G22G23G24G25G26G27G28G29G30G31G32R01R02
+        R03R04R05R07R08R09R11R12R13R14R15R16R17R18R19R20R21
+        R22R24E02E03E04E05E07E08E09E10E11E12E13E14E15E18E19
+        E21E24E25E26E27E30E31E33E34E36  0  0  0  0  0  0  0
++         5  7  6  6  7  6  7  6  6  6  7  7  6  6  7  7  7
++         7  7  7  7  7  6  6  7  6  6  6  7  5  7  6  9  7
++         8  8  8  8  8  7  6  7  7  6  6  6  8  7  9  9  8
++         7  8  6  6  6  6  7  6  7  7  7  6  6  7  7  7  6
++         6  6  6  7  6 10  6  7  6  7  0  0  0  0  0  0  0
%c M  cc GPS ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%c cc cc ccc ccc cccc cccc cccc cccc ccccc ccccc ccccc ccccc
%f  1.2500000  1.025000000  0.00000000000  0.000000000000000
%f  0.0000000  0.000000000  0.00000000000  0.000000000000000
%i    0    0    0    0      0      0      0      0         0
%i    0    0    0    0      0      0      0      0         0
/* Center for Orbit Determination in Europe (CODE)
/* Ultra-rapid GRE orbits starting year-day 24043 18 hour
/* Observed/predicted: 24/24 hours (data used up to 044R)
/* PCV:IGS20      OL/AL:FES2014b NONE     YN ORB:CoN CLK:BRD
*  2024  2 12 18  0  0.00000000
PG01  10017.227962 -21757.155189 -11451.757387    169.286245
PG02  14675.739771 -21822.976616  -2052.019267   -486.484832
```

```
PG03   8469.065183 -12995.901194 -21686.432325    188.867787
PG04   3600.602597 -22237.722088 -13945.053317    290.029824
PG05 -20341.276134   7377.183933  15289.811367   -161.559994
PG06 -16369.020521  -2296.830107 -20745.620735    409.693247
PG07  -1894.045106 -18515.401534  19259.776594    -60.352554
PG08   8973.397509 -15470.338889  19399.830924   -166.689337
PG09  -7116.144195 -25433.994890  -2585.513683     89.933932
PG10  22629.595338  10998.556186   9210.119432      0.062606
PG11 -21242.149685   8170.890518 -13627.298892   -573.517674
PG12  -9883.448912  12694.506995 -21410.063052   -477.323298
PG13 -13937.859196   5903.727931  21603.132559    624.913034
PG14 -19730.979185 -13446.930472  11852.906315    323.976361
PG15  -7222.733526  16617.677119  18862.775701    127.009782
PG16  24409.248046   -401.590168  10670.590254   -364.118237
. . .
```

Fig. 6. Satellite orbit file (SP3)

Initial Wet refractivity file

The initial values of the 3D Wet Refractivity model are necessary to solve the equation system with the MART algorithm. Radio Sonde (RS) profiles are used to calculate these values, and these profiles are expanded to cover the entire area. After the calculation of the Wet refractivity values, they are stored in csv format (Fig7).

```
WMOID,HEIGHT,DATE,TIME,HEIGHT,N_DRY,N_WET,TEMPERATURE,PRESSURE,DEWPOINT,RHOWV
12843,139,2024-02-01,11:00:00,139,279.0515,31.90512,278.56,10080,273.56,0.004893853
12843,209,2024-02-01,11:00:00,209,278.1079,30.57998,277.36,10000,272.86,0.00467139
12843,250,2024-02-01,11:00:00,250,276.9208,30.4007,277.16,9950,272.76,0.00464082
12843,440,2024-02-01,11:00:00,440,267.8434,32.1,279.76,9720,273.76,0.004943895
12843,601,2024-02-01,11:00:00,601,262.9998,31.27059,279.36,9530,273.36,0.004809611
12843,846,2024-02-01,11:00:00,846,257.0624,31.71184,277.36,9250,273.36,0.004844292
12843,1496,2024-02-01,11:00:00,1496,241.7266,25.98888,272.26,8530,270.16,0.003900615
. . .
```

Fig. 7. Radio Sonde profiles with the Wet refractivity values

Results

The results of the Tomographic Reconstruction are stored in .npy (NumPy) format as a 3D matrix in the results directory. The matrix values represent the wet refractivity values. The matrix indexes are in the following order: latitude, longitude, height. The indices represent the number of the voxel in the specified direction corresponding to the given tomographic grid files.