ATom GNSS software package v1.0 Manual

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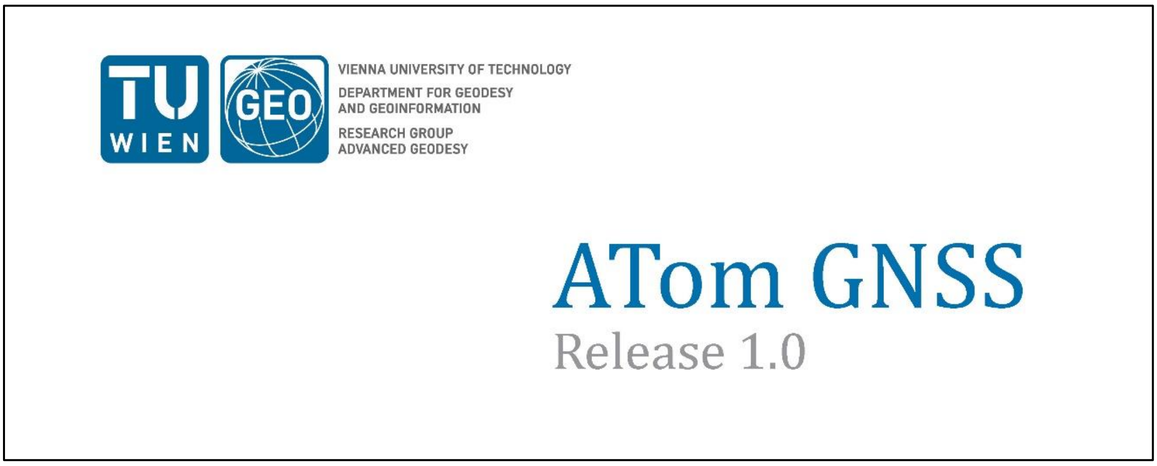


ATom GNSS is a MATLAB GUI based software package, which has been developed within the GNSS-ATom project (840098) - financed by the Austrian Research Promotion Agency (FFG) in the years 2013 to 2015.

'ATom' stands for **A**tmospheric **Tom**ography, the core part of the ATom software package.

In addition, ATom allows for conversion of

- broadcast ephemerides into ECEF satellite positions, elevation or azimuth angles
- zenith total delays into zenith wet delays or slant delays
- numerical weather model data into refractivity fields
- refractivity fields into zenith delays
- slant delays into total or wet refractivity fields

Therefore, common formats like Napeos, Bernese, IGS SINEX Tropo or the 'new' SINEX Tropo format, navigation messages for GPS and GLONASS as well as several formats for post-fit residuals and in-situ measurements are supported.

In the following, the individual ATom software panels and functions but also the supported formats are described in more detail.

Content

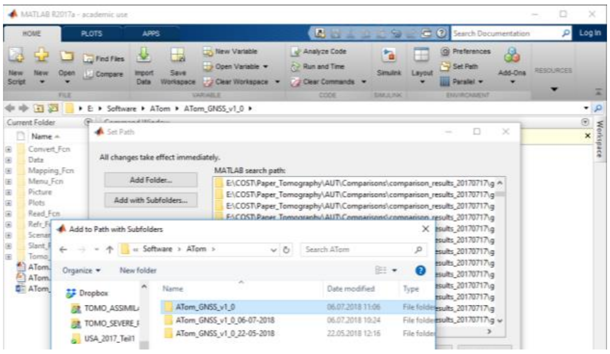
Installation

ATom GNSS is not a self-executing program but requires a MATLAB installation. Therefore, MATLAB version R2017a or higher is recommended.

The ATom software package is provided via git (https://github.com/GregorMoeller/ATom.git).

For installation,

1. get current version of 'ATom_GNSS_v1_0' from github.com
2. open MATLAB and add folder 'ATom_GNSS_v1_0' with all subfolders to MATLAB search paths
   Alternative: Uncomment Line 27 and 28 in ATom.m. It will add all necessary software folders to MATLAB search paths when ATom is started the first time. **Comment these lines again after you have finished installation, otherwise ATom start will last significantly longer.**



3. type in MATLAB Command Window '**ATom**' to start the program **The first time make sure that you are in 'ATom_GNSS_v1_0' directory, e.g. E:\Software\ATom\ATom_GNSS_v1_0, otherwise the program will not start**

ATom folder overview

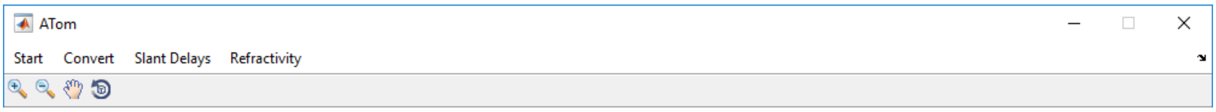
The ATom main program and GUI settings are provided by 'ATom.m' and 'ATom.fig' in the main directory together with this manual, all other functions and data are stored in subfolders as follows:

<u>ATom subfolder structure:</u>

Convert_Fcn	MATLAB functions for conversion of Kepler elements to satellite positions and time conversion functions
Data	User defined folder which should include all input and output data. It is recommended to create subfolders, e.g. for each campaign or data type **Be aware, folder Data is not updated in git.**
Mapping_Fcn	MATLAB functions for gmf, gpt2w and vmf1 – **including** vmf1 grib files in 'vmf1' folder **The vmf1 folder is not updated in git.**
Menu_Fcn	MATLAB functions to load/save ATom software settings from/to file **Not fully implemented yet.**
Picture	Logo and graphics implemented in ATom software
Plots	User defined folder to store figures and plots. It is recommended to create subfolders, e.g. for each campaign. **The Plots folder is not updated in git.**
Read_Fcn	MATLAB functions to read in input files (SINEX, grib, ZTD, …)
Refr_Fcn	MATLAB functions for handling of refractivity fields, e.g. for ray-tracing
Slant_Fcn	MATLAB functions for computation of slant delays, including SINEX header information for writing data in the new SINEX format
Tomo_Fcn	MATLAB functions for GNSS tomography incl. mixed ray-tracing approach (see Möller and Landskron, 2018)

ATom software panels

The ATom software package is organized in panels and sub-panels.



In the following the panels ‘Start’, ‘Convert’, ‘Slant Delays’, and ‘Refractivity’ and the workflow for specific tasks are described in more detail.

Panel ‘Start’ (ATom.m line 134 – 194)

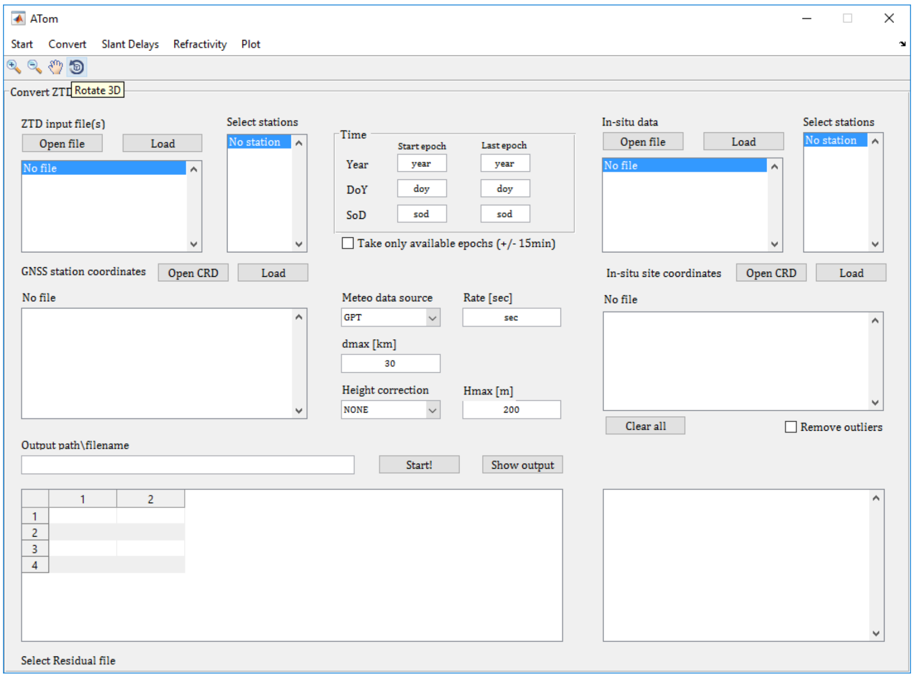
Panel ‘Start’ is the first panel, which shows up automatically when ATom is started. Here you have to set ‘Input folder’ and ‘Output folder’. These are the standard search folders for all panels. If you would like to continue with any previously defined settings ‘Load settings’ from file. At the end of your session, you can save your settings with ‘Save settings’ for future sessions. **Not fully implemented yet.**

Panel 'Convert' (ATom.m line 197 – 1621)

Panel 'Convert' contains the two sub-panels 'ZTD to ZWD' and 'Brdc to AER'.

Sub-panel 'ZTD to ZWD' (ATom.m line 197 – 1134)

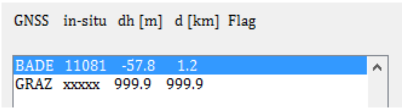
Within this sub-panel, the zenith hydrostatic delay (ZHD) is computed and removed from the ZTD time series. Therefore, the Saastamoinen (1972) model, refined by Davis et al. (1985) is used with air pressure data obtained by **GPT**, **GPT2w** or **in-situ** measurements. Beforehand (if desired), height correction is applied for air pressure (see Möller, 2017 for possible interpolation errors).



<u>How to convert?</u>

1. 'Open file' to select ZTD input file(s). The following formats are supported:
    - IGS SINEX Tropo files (*.zpd) as provided e.g. by IGS Troposphere working group (http://twg.igs.org/)
    - Bernese Tropo files (*.TRP) as generated by Bernese software. **Be aware: Bernese provides also SINEX Tropo files (*.TRO)**
    - New SINEX Tropo files (*.SNX): This is the new SINEX Tropo format, defined within COST action GNSS4SWEC, see COST (2018). **Not fully implemented yet.**
    - NAPEOS SINEX Tropo files (*.TRO): These files are similar to the *.zpd files but contain an additional column for ZWD called 'TROWET'.
2. 'Load' ZTD file(s). Thereby, time variables (Year, Day of Year and Second of Day) are computed from the first and last epochs available. Time variable 'Rate [sec]' is computed from the first two consecutive epochs. In addition, a suggestion for the output filename is provided (output folder and the first input filename, whereby the filename extension is replaced by 'ZWD'). Currently, ATom supports 1-day and 3-day arc files. In case of 3-day arc files, only the middle day is extracted.
3. 'Select stations' from listbox
4. Open 'GNSS station coordinates' in *.NEU format, i.e. ellipsoidal coordinates in lat, lon and h (ellipsoidal heights are mandatory for GPT and GPT2w). Make sure that all selected stations in listbox are available in the coordinate file, otherwise an error message will show up (see next step)

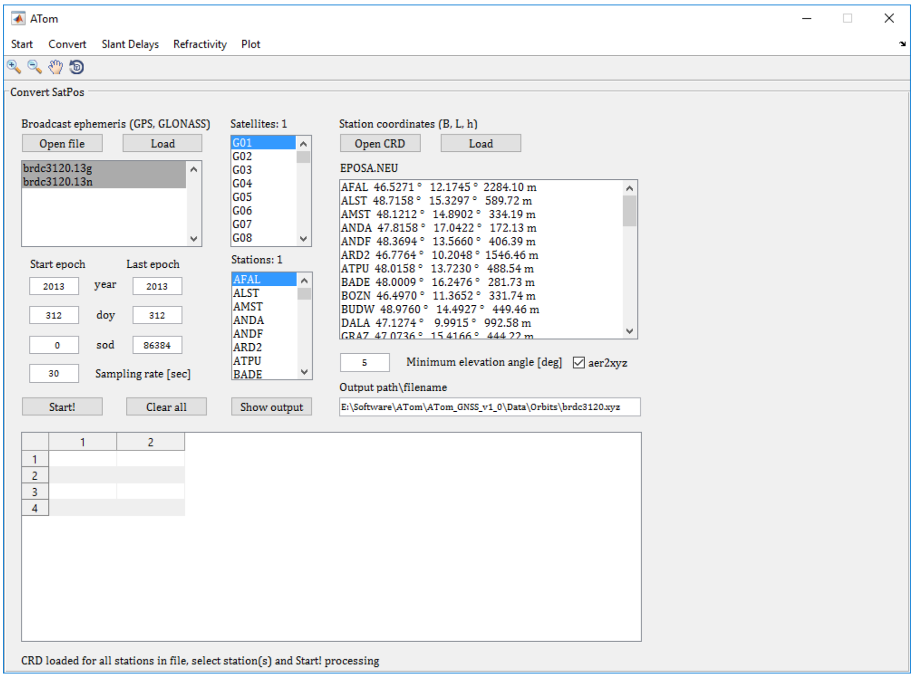
5. ‘Load’ coordinates from file: All stations with coordinates will be listed (check status line, in case not all stations are available in coordinate-file an error message will indicate the missing site)
6. Select ‘Meteo data source’
   - In case of ‘**GPT’** the ZHD is computed for each selected GNSS site using pressure values obtained by GPT model (Böhm et al., 2007)
   - In case of ‘**GPT2w**’ the ZHD is computed for each selected GNSS site using pressure values obtained by GPT2w model (Böhm et al., 2015)
   - In case of ‘**In-situ’:** measurements of pressure, temperature and relative humidity are read in and interpolated to GNSS site (see step 11)
7. Select ‘Rate [sec]’. This option is inactive if option ‘Take only available epochs’ is ticked.
8. In case option ‘Take only available epochs’ is selected, ZWDs are computed for available epochs only. Otherwise, GNSS tropospheric estimates are linearly interpolated between the nodal points. **Be aware of interpolation errors in case of larger gaps in the input data.**
9. In case you would like to make an outlier check, tick ‘Remove outliers in ZTD/In-situ data’, than all entries with
   - ZTD formal error > 10 mm,
   - T < -80°C,
   - p < 0 hPa or p <> 3sigma,
   - rh < 0 or rh > 1 or
   - NaN entries in the in-situ data are removed.
10. Press ‘Start!’ to create output file. Beforehand, in the background multiple entries in the ZTD time series are removed (so far, it keeps one entry per epoch, otherwise the interpolation approach would fail). Check output file by pushing the ‘Show output’ button.
11. In case of **in-situ** data
   - Select ‘In-situ’ as ‘Meteo data source’ (see step 6)
   - ‘Open file’ with in-situ data in TAWES- (*.dat) or COST-format (*.syn). If necessary, open multiple files. **The in-situ data have to be provided for the same period as for the GNSS data, or at least for parts of it, otherwise the processing fails.**
   - ‘Load’ in-situ file(s)
   - ‘Open CRD’ file with coordinates for all in-situ stations.
   - ‘Load’ coordinates **Be aware, that the stations heights should be defined in the same height system as the GNSS station heights, otherwise an error in height correction is introduced.**
   - Define search radius ‘dmax [km]’ for co-located sites (default: 30 km).
   - Define maximum height difference ‘Hmax [m]’ between GNSS and in-situ sites (default: 200 m)
   - Select method for ‘Height correction’ (‘None’, ‘Karabatic et al. (2011)’ or ‘Exponential’)
   - ‘Start!’ processing (see step 10)
   - When processing starts, the listbox in the lower right corner will show the co-located GNSS/In-situ sites which have been found and processed as follows:

     In case of multiple co-located sites, the closest in-situ site is selected. In case in-situ is ‘xxxxx’, no in-situ site was found within the search radius. In case of flag ‘T’ no meteo data was available for the GNSS epochs.
12. ‘Clear all’ settings to start a new session

Sub-panel ‘Brdc to AER’ (ATom.m line 1137 – 1621)

Conversion of satellite broadcast ephemerides into satellite positions (xyz) or azimuth, elevation angle and range (aer).



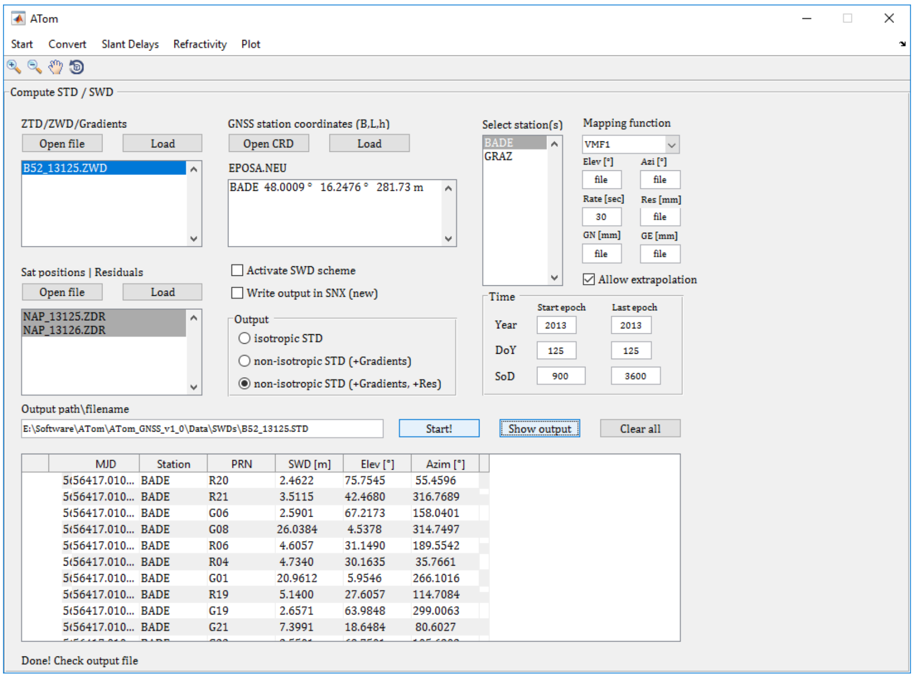
<u>How to convert?</u>

1. ‘Open file’ to select broadcast ephemerides. Currently, ATom supports GPS and GLONASS navigation files only (brdc*, *n, *g). **Be aware that the filetype is checked by filename extension, only *g and *n files are currently supported.**
2. ‘Load’ navigation file(s): In case of mixed GPS and GLONASS files, all files are identified by their file extension (*.n for GPS or *.g for GLONASS) and are processed together.
3. Select epoch(s) of interest and ‘Sampling rate’. A suggestion is provided based on the input data. **Avoid epochs several days before or after the date of the input data to minimize orbit errors.**
4. Select satellite(s) of interest in listbox. Multiple selection is possible
5. ‘Open CRD’ file with station coordinates (lat, lon, h)
6. ‘Load’ coordinate file
7. Select station(s) of interest in listbox. Multiple selection is possible
8. Define ‘Minimum elevation angle [deg]’ as cut-off angle for processing. Satellites below these angle are not considered in aer output file (cut-off is not applied for xyz files)
9. Define output format:
    - aer: Azimuth, elevation angle and slant range for each station and satellite in view
    - xyz: Satellite positions in Cartesian ECEF-coordinates

13. ‘Start!’ processing and check output by pushing the ‘Show output’ button.
14. ‘Clear all’ settings to start a new session from scratch

Panel 'Slant Delays' (ATom.m line 1624 – 2816)

Panel 'Slant Delays' allows for computing slant total and slant wet delays for any satellite in view by mapping of ZTD/ZWD and gradient parameters into direction of the satellite in view. Therefore, mapping function GMF, GPT2w, VMF1 and the Chen and Herring (1997) gradient mapping function is implemented.

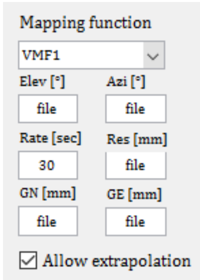


<u>How to compute slant delays?</u>

1. 'Open file' to select 'ZTD/ZWD/Gradients' input file(s). The following formats are supported:
    - Zenith Wet Delays as computed in panel 'ZTD to ZWD' in*.ZWD format
    - IGS SINEX Tropo files (*.zpd) as provided e.g. by IGS Troposphere working group (http://twg.igs.org/)
    - NAPEOS SINEX Tropo files (*.TRO): These files are similar to the *.zpd files but contain in additional a column for ZWD called 'TROWET'. **Be aware that Bernese *.TRO* files do not contain ZWDs. Thus, these files **cannot** be used for SWD computation, only for STD computation.**
2. 'Load' input file(s). Thereby, time variables (Year, Day of Year and Second of Day) are computed from the first and last epochs available. Time variable 'Rate [sec]' is computed from the first two consecutive epochs. In addition, a suggestion for the output filename is provided (output folder and the first input filename, whereby the input filename extension is replaced by 'SWD', 'STD' or 'SNX' - dependent on the output settings).
3. 'Select station(s)' from listbox
4. Open 'GNSS station coordinates (B,L,h)' in *.NEU format, i.e. ellipsoidal coordinates in lat, lon and h. Make sure that all selected stations in listbox are available in the coordinate file, otherwise an error message will show up (see next step)
5. 'Load' coordinates from file: All stations with coordinates will be listed (check status line, in case not all stations are available in coordinate-file an error message will indicate the missing site)
6. 'Activate SWD scheme' in order to get slant wet delay files (*.SWD), otherwise slant total delay files (*.STD) are generated. **In case of SWD make sure that ZWDs are provided in input file.**
   <u>Alternatively:</u> select option 'Write output in SNX (new)' to generate output files in the new SNX format, see final COST report (available by end 2018) for format description. The new SNX format contains both, total and wet zenith and slant delays. The SNX header information has to be

provided in directory **'\Slant_Fcn** as **SNX_Header.txt'**. *Not fully implemented yet and be aware that only <u>one</u> station is selected in listbox 'Select stations(s)', the results of multiple stations are currently not stored correctly.**

7. Select 'Mapping function'
    - In case of '**GMF'** the STD/SWD is computed using Global Mapping Function (Böhm et al., 2006a)
    - In case of '**GPT2w**' the STD/SWD is computed using the gridded GPT2w mapping function (Böhm et al., 2015)
    - In case of '**VMF1'** the STD/SWD is computed using gridded Vienna Mapping Function (Böhm et al., 2006b). The necessary VMF1 grid files have to be stored in **\Mapping_Fcn\vmf1**, otherwise ATom will generate an error message.
8. Define elevation angle (Elev), azimuth angle (Azi), rate (Rate), the residual to be added to the slant delays (Res), N-Gradient (GN) and E-Gradient (GE). These values are treated as constants over the entire period and for all satellites in view. <u>Alternatively:</u> read in a file with individual values (see step 11).



9. Option 'Allow extrapolation' enables extrapolation of ZTD/ZWD/Gradient time series, e.g. if they are not provided for the entire period between 'Start epoch' and 'Last epoch'. However, in case epochs are read in by file via step 11, the ZTD/ZWD/Gradients are extrapolated but only for the available epochs provided in the '*.aer', '*.ZDR' or '*.FRS' files.
10. Define 'Output' option. The following options can be selected
    - **Isotropic STD/SWD**: Considers ZTDs/ZWDs from input file and selected mapping function to compute slant delays for defined elevation and azimuth angles (see step 8). Both, the gradient parameters and residuals are set to zero. *This option does not allow reading individual satellite parameters from file.**
    - **Non-isotropic STD/SWD** (+Gradients): Considers ZTDs/ZWDs and gradients (GN, GE) from input file and selected mapping function to compute slant delays for defined elevation and azimuth angles (see step 8). The residuals are set to zero. *This option does not allow reading individual satellite parameters from file.**
    - **Non-isotropic STD/SWD** (+Gradients, +Res): All necessary data (ZTDs or ZWDs, gradients, epochs, residuals, elevation angles, azimuth angles, station names and satellite PRNs) are read in from file(s), see step 11. Make sure that all satellite PRNs are listed in **satid2prn.m**.
11. Read 'Sat positions | Residuals' from file:
    - 'Open file' to select satellite positions (in *.aer format) or zero-difference residuals (ZDRs) in Napeos (*.ZDR) or in Bernese format (*.FRS). *The individual satellite data have to be provided for the same periods as the ZTD/ZWD/Gradients, or at least for parts of it, otherwise an error message will show up.**
    - 'Load' satellite positions | Residuals. Thereby, the time variables (start epoch and last epoch) are checked and re-computed if necessary, e.g. if the individual satellite data are provided for a limited time period only.
    - Select 'Output' option '**non-isotropic STD/SWD (+Gradients, +Res)**'. Otherwise, the individual satellite data from file will not be considered.
    - Parameters 'Elev' and 'Azi' have to be set to **'file'** (will be done automatically if satellite positions or residuals are loaded from file).
    - Parameter 'Res [mm]' can be set to '**file**' or any other value if a constant residual should be added to the slant delays. The same is also valid for 'GN [mm]' and 'GE [mm]' if individual, constant or no gradients should be considered.

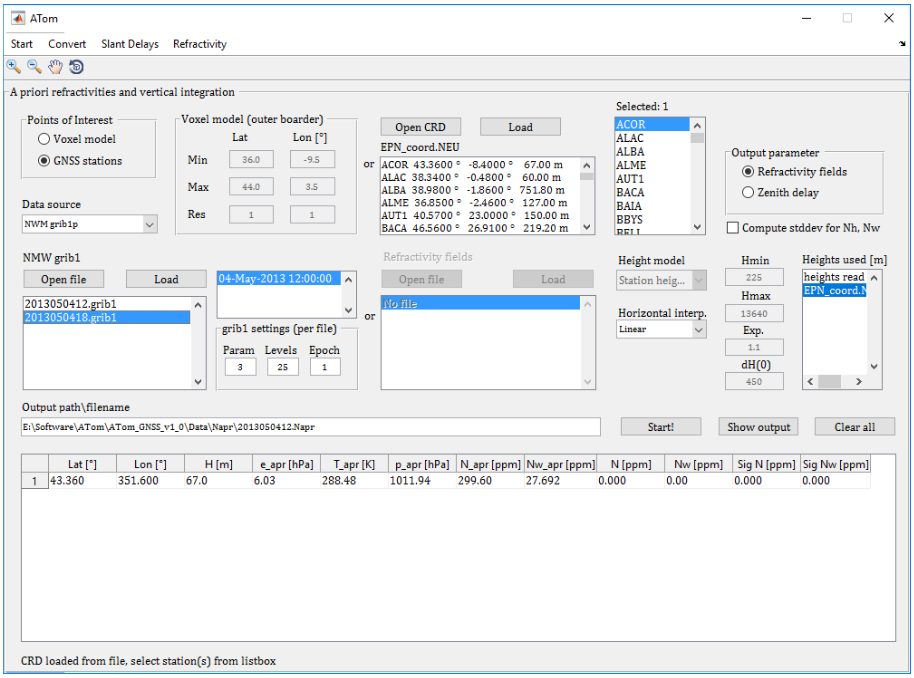
12. ‘Start!’ processing after all settings are made. First, a plausibility check is made and multiple entries in the ZTD/ZWD/Gradients time series are removed (so far, it keeps one entry per epoch, otherwise the interpolation or extrapolation would fail).
13. Tick ‘Show output’ to display output files. **Works only for ‘*.SWD’ and ‘*.STD’ files, ‘*.SNX’ files are not supported right now.**
14. ‘Clear all’ settings to start a new session from scratch.

Panel ‘Refractivity’ (ATom.m line 2819 – 5535)

Panel ‘Refractivity’ contains the two sub-panels ‘N (a priori) and ‘3D Tomography’.

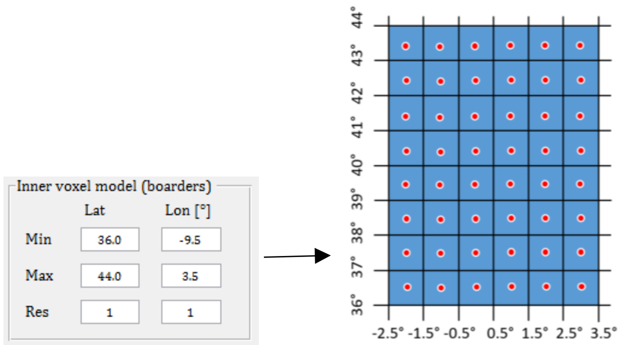
Sub-panel ‘N (a priori)’ (ATom.m line 2819 – 4324)

Sub-panel ‘N (a priori)’ is dedicated to the computation of a priori refractivity fields from standard atmosphere or numerical weather model (NWM) data. In addition, it allows for computation of zenith delays by vertical integration. Therefore, different input data like NWMs or refractivity fields obtained by GNSS tomography (see sub-panel ‘3D Tomography’) are used. The user decides whether the parameters of interest are computed for a voxel model or for specific GNSS sites – given in ellipsoidal coordinates. In the following, the processing steps for both, refractivity field and zenith delay calculation are detailed.



<u>How to compute a priori refractivity fields?</u>

1. Select ‘Points of Interest (POI)’, either ‘Voxel model’ if you would like to compute wet refractivity fields for a regular voxel model grid or ‘GNSS stations’ if you would like to compute wet refractivity for specific GNSS sites. According to you selection, different options in sub-panel ‘N (a priori)’ will be enabled or disabled in order to relieve the handling.
2. In case of option ‘Voxel model’ the voxel model shape, i.e. the regular voxel grid has to be defined. Therefore,
    - set the **outer boarder** of the voxel model and the spatial resolution (Lat, Lon, Res). **Be aware that the refractivities are not computed for the outer boarders but for the voxel center points, i.e the red dots [36.5° lat, -2° lon], … as indicated in the following plot.*



- Set voxel model **height layers** (see step 8)
3. In case ‘Points of Interest (POI)’ is set to ‘GNSS stations’, a coordinate file is requried. Therefore,
    - ‘Open CRD’ file with station coordinates in *.NEU format, ‘Load’ coordinate file and select station(s) of interest in listbox. Multiple selection is possible.
    - Set ‘Station heights’ in popup menu ‘Height model’ if not already set automatically. If the coordinate file was read in correctly, the name of the file will show up in the ‘Heights used [m]’ listbox, otherwise an error message will show up.
4. Set ‘Output parameter’ to ‘**Refractivity fields**’
5. Set ‘Data source’ to
    - **‘Standard atmosphere’** in order to use US standard atmosphere 1976 for computing refractivity fields. Therefore no further input data is necessary. Pressure, temperature and water vapour pressure is computed for each POI (voxel center points or GNSS stations) and is converted into total and wet refractivity.
    - **‘NWM grib1p’**, whereby ‘NWM’ stands for Numerical Weather Model, ‘grib1’ stands for the file format and ‘p’ for pressure level. Currently, global ECMWF pressure level data are supported as input data. In addition, ALARO or ALADIN data can be processed as well but only if they are provided in a similar structure than the ECMWF data. When reading in *.grib1 data, the following ‘grib1 settings (per file)’ have to be set beforehand: ‘Param’, ‘Levels’ and ‘Epoch’ (see step 6 for further details). **Minimum data required: latitude, longitude, temperature, specific humidity or relative humidity and geopotential on various pressure levels.** The input data is used to compute total and wet refractivity for each POI.
    - **‘Refractivity fields’**, in order to read in *.N files (see step 7), e.g. as generated in sub-panel ‘3D Tomography’. Hereby, only input data ‘N [ppm]’ and ‘Nw [ppm]’ are considered and linearly interpolated to the POI. **Be aware, no processing is possible for POIs outside the provided refractivity field (check if defined voxel model boarders or station coordinates are inside the refractivity field provided by *.N files, otherwise ‘NaN’ or an error message will show up as output).**
6. Read in ‘NWM grib1’ files. This is necessary if ‘NWM grib1p’ was selected as ‘Data source’.
    - Therefore, define ‘grib1 settings (per file)’ ‘Param’, ‘Levels’, ‘Epoch’:
      ‘Param’: The number of parameters available in the grib1 file, e.g. ‘3’ if temperature, humidity and geopotential is provided.
      ‘Levels’: The number of pressure levels available in the grib1 file, e.g. ‘25’.
      ‘Epoch’: The number of epochs stored in the grib1 file, e.g. ‘1’ if only one epoch is provided per file.
    - push ‘Open file’ button to select your grib1 file(s)
    - ‘Load’ grib1 data. In case multiple epochs are available, all available epochs will be listed. Select your epoch of interest from the listbox and ‘Load’ the data for this epoch. After the data is read in, a suggestion is provided for the output filename. It reflects the input filename but with file extension *.Napr.
7. Read ‘Refractivity fields’. This step is necessary if ‘Refractivity fields’ was selected as ‘Data source’
    - Therefore, push ‘Open file’ button to select *.N file(s)
    - ‘Load’ *.N data. **In case ‘Voxel model’ is selected as POI, it is checked whether the refractivity field covers the entire voxel grid, otherwise the voxel model boarders are adapted.** After the data is read in, a suggestion is provided for the output filename. It reflects the input filename but with a new file extension.
8. Set ‘Heigth model’:
    - **Perler (2011) height model**. This option requries the following input data:

'Hmin': Height of the lowest layer
'Hmax': Height of the upper layer
'Exp.': Exponent q for computing height differences $dH(i) = dH(0) \cdot q_h^i$ between two consequtive layers, whereby 'dH(0)' defines the height difference between the first two layers. The resulting heights are shown in the listbox below the headline 'Heights used [m]'. **This option is only available if 'Voxel model' is selected as POI.**

- Read **Height layers from** NWM *.grib1 **file** (in case 'NWM grib1p' was selected as 'Data source') or from *.N file (in case 'Refractivity fields' was selected as 'Data source'). In case of grib1, the heigth layers are derived from the geopotential values as orthometric heights. The resulting heights are shown in the listbox below headline 'Heights used [m]'. **This option is only available if 'Voxel model' is selected as POI.**
- Use **Station heights** as provided by *.NEU file. This option is only recommended if 'GNSS stations' is selected as POI and needs a coordinate file as input (see step 3). If the coordinate file was read in correctly, the name of the file will show up in the 'Heights used [m]' listbox, otherwise an error message will show up.

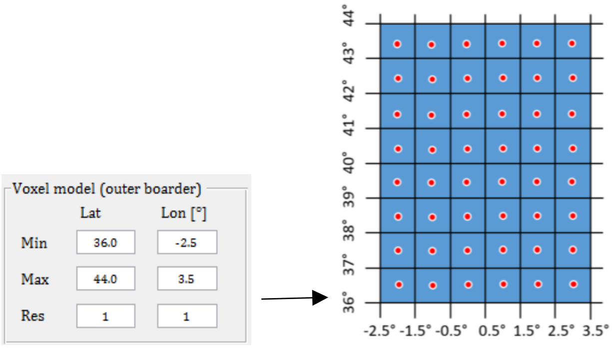
9. Set 'Horizontal interp.' option to:
   - **'Nearest'**: No horizontal interpolation will be carried out but the closest grid point wrt. the POI will be selected.
   - **'Linear'**: Bilinear interpolation will be carried out by selecting the four adjacent grid points in the surrounding of the POI (voxel model grid point or GNSS station). Beforehand, vertical interpolation will be carried out (either on meteo parameter level in case of *.grid1 data or on refractivity level in case of *.N data) to bring the input data on common height level(s).
   - **'Spline'**: A spline interpolation will be carried out by selecting the 16 adjacent grid points in the surrounding of the POI. Beforehand, vertical interpolation will be carried out (either on meteo parameter level in case of *.grid1 data or on refractivity level in case of *.N data) to bring the input data on common height level(s). **In case of standard atmosphere no horizontal interpolation method is applied.**

15. Tick option 'Add outer voxel model' to add an 5 degrees outer grid to the inner voxel model defined in step 2. **This option is only available if 'Voxel model' is set as POI and if 'Refractivity fields' is selected as output parameter. Be aware, that this option might lead to an error, e.g. if the *.grib1 or *.N data does not cover the outer voxel domain.**
16. Tick option 'Compute stddev for Nh, Nw' if you are interested in a priori standard deviations for N and Nw. These values are derived from a background table of typical standard deviations for pressure, temperature and specific humidity, see Steiner et al. (2006). **Be aware that this option (comp_stddev.m) makes processing rather low, use this option only if needed.**
17. 'Start!' processing after all settings are made. Output is a *.Napr file with total and wet refractivity for each POI (see format description)
18. Push button 'Show output' to display the output file. **Works for both '*.Napr' and '*.ZTD' files**
19. 'Clear all' settings to start a new session from scratch.

<u>How to compute zenith delays?</u>

1. Select 'Points of Interest (POI)', either 'Voxel model' if you would like to compute wet refractivity fields for a regular voxel model grid or 'GNSS stations' if you would like to compute wet refractivity for specific GNSS sites. According to you selection, different options in sub-panel 'N (a priori)' will be enabled or disabled in order to relieve the handling.
2. In case of option 'Voxel model' the regular ground voxel grid has to be defined. Therefore,

- set the **outer boarder** of the voxel model and the spatial resolution (Lat, Lon, Res). **Be aware that ZTDs are not computed for the outer boarders but for the voxel center points, i.e the red dots [36.5° lat, -2° lon], … as indicated in the following plot.*



- Set voxel model **height layers** (see step 8). **Be aware that only the first, i.e. the ground layer is considered as station height for zenith delay calculation, all upper layers will be discarded.**

3. In case 'Points of Interest (POI)' is set to 'GNSS stations', a coordinate file is requried. Therefore,
    - 'Open CRD' file with station coordinates in *.NEU format, 'Load' coordinate file and select station(s) of interest in listbox. Multiple selection is possible.
    - Set 'Station heights' in popup menu 'Height model' if not already set automatically. If the coordinate file was read in correctly, the name of the file will show up in the 'Heights used [m]' listbox, otherwise an error message will show up. **The zenith delays will be computed for the station heights set in the coordinate file.**
4. Set 'Output parameter' to '**Zenith delay**'
5. Set 'Data source' to
    - **'Standard atmosphere'** in order to use US standard atmosphere 1976 for computing zenith delays. Therefore no further input data is necessary. Pressure, temperature and water vapour pressure is computed for each POI (voxel center points or GNSS stations) from ground up to 136 km. Afterwards the meteo parameters are converted into total and wet refractivity. Therefrom, zenith wet and total delay is computed by vertical intregration.
    - **'NWM grib1p'**, whereby 'NWM' stands for Numerical Weather Model, 'grib1' stands for the file format and 'p' for pressure level. Currently, global ECMWF pressure level data are supported as input data. In addition, ALARO or ALADIN data can be processed as well, but only if they are provided in a similar structure than the ECMWF data. When reading in *.grib1 data, the following 'grib1 settings (per file)' have to be set beforehand: 'Param', 'Levels' and 'Epoch' (see step 6 for further details). **Minimum data required: latitude, longitude, temperature, specific humidity or relative humidity and geopotential on various pressure levels.** The input data is used to compute total and wet refractivity for each POI and all height layers defined in step 8. Beforehand, vertical interpolation is carried out up 136 km altitude. Therefrom, refractivity columns and in further consequence zenith wet and total delay is computed by vertical integration.
    - **'Refractivity fields'**, in order to read in *.N files (see step 7), e.g. as generated in sub-panel '3D Tomography'. Hereby, only input data 'N [ppm]' and 'Nw [ppm]' are considered and horizontally interpolated to the POI. **Be aware, no processing is possible for POIs outside the provided refractivity field (check if defined voxel model boarders or station coordinates are inside the refractivity field, otherwise 'NaN' or an error message will show up as output)*.* The zenith delays are computed only for the vertical range specified by the input data (station height or lowest layer up to the highest layer

provided in the *.N file). In case, the refractivity field is provided for the troposphere only, the zenith wet delay might be correct but the zenith total delay might be too small, since the remaining atmosphere above the troposphere is not considered.

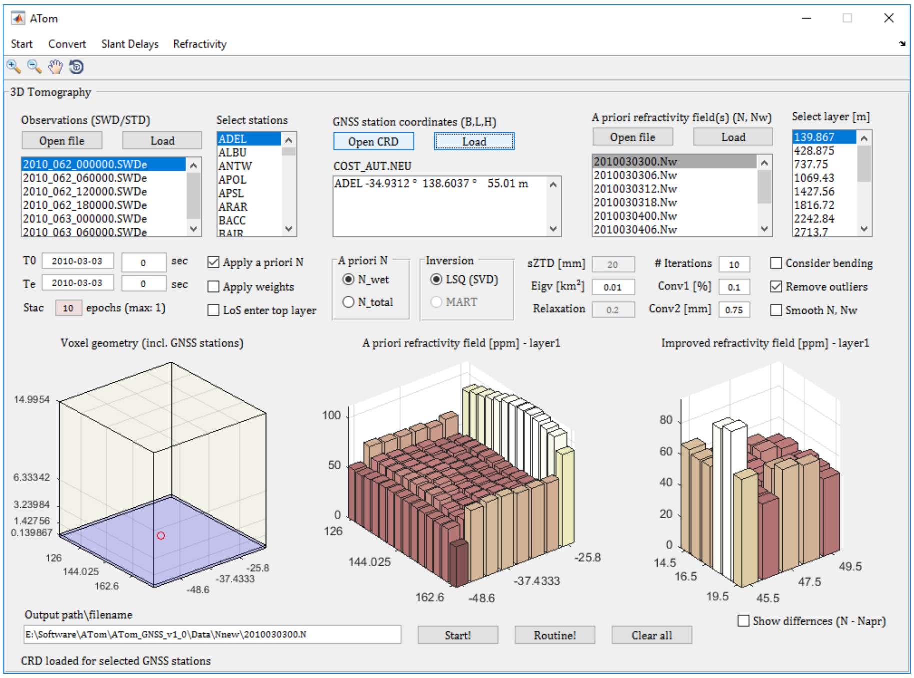
6. Read in ‘NWM grib1’ files. This is necessary if ‘NWM grib1p’ was selected as ‘Data source’.
   - Therefore, define ‘grib1 settings (per file)’ ‘Param’, ‘Levels’, ‘Epoch’:
     ‘Param’: The number of parameters available in the grib1 file, e.g. ‘3’ if temperature, humidity and geopotential is provided.
     ‘Levels’: The number of pressure levels available in the grib1 file, e.g. ‘25’.
     ‘Epoch’: The number of epochs stored in the grib1 file, e.g. ‘1’ if only one epoch is provided per file.
   - push ‘Open file’ button to select your grib1 file(s)
   - ‘Load’ grib1 data. In case multiple epochs are available, all available epochs will be listed. Select your epoch of interest from the listbox and ‘Load’ the data for this epoch. After the data is read in, a suggestion is provided for the output filename. It reflects the input filename but with file extension *.Napr.
7. Read ‘Refractivity fields’. This step is necessary if ‘Refractivity fields’ was selected as ‘Data source’
   - Therefore, push ‘Open file’ button to select *.N file(s)
   - ‘Load’ *.N data. **In case ‘Voxel model’ is selected as POI, it is checked whether the refractivity field covers the entire voxel grid, otherwise the voxel model boarders are adapted.** After the data is read in, a suggestion is provided for the output filename. It reflects the input filename but with a new file extension.
8. Set ‘Heigth model’:
   - **Perler (2011) height model**. This option requries the following input data:
     ‘Hmin’: Height of the lowest layer
     ‘Hmax’: Height of the upper layer
     ‘Exp.’: Exponent q for computing height differences $dH(i) = dH(0) \cdot q_h^i$ between two consequtive layers, whereby ‘dH(0)’ defines the height difference between the first two layers. The resulting heights are shown in the listbox below the headline ‘Heights used [m]’. *In case *‘Zenith delay’ is selected as ‘Output parameter’, only parameter ‘Hmin’ is relevant, i.e. set as station height’.**
   - Read **Height layers from** NWM *.grib1 **file** (in case ‘NWM grib1p’ was selected as ‘Data source’) or from *.N file (in case ‘Refractivity fields’ was selected as ‘Data source’). In case of grib1, the heigth layers are derived from the geopotential values as orthometric heights. The resulting heights are shown in the listbox below headline ‘Heights used [m]’. *In case *‘Zenith delay’ is selected as ‘Output parameter’, only the lowest height layer is relevant, i.e. set as station height’.**
   - Use **Station heights** as provided by *.NEU file. This option is only recommended if ‘GNSS stations’ is selected as POI and needs a coordinate file as input (see step 3). If the coordinate file was read in correctly, the name of the file will show up in the ‘Heights used [m]’ listbox, otherwise an error message will show up.
9. Set ‘Horizontal interp.’ option to:
   - **‘Nearest’**: No horizontal interpolation will be carried out but the closest grid point wrt. the POI will be selected.
   - **‘Linear’**: Bilinear interpolation will be carried out by selecting the four adjacent grid points in the surrounding of the POI (voxel model grid point or GNSS station). Beforehand, vertical interpolation will be carried out (either on meteo parameter level in case of *.grid1 data or on refractivity level in case of *.N data) to bring the input data on common height level(s).

- **'Spline'***:* A spline interpolation will be carried out by selecting the 16 adjacent grid points in the surrounding of the POI. Beforehand, vertical interpolation will be carried out (either on meteo parameter level in case of *.grid1 data or on refractivity level in case of *.N data) to bring the input data on common height level(s). **In case of standard atmosphere no horizontal interpolation method is applied.**

20. Option 'Compute stddev for Nh, Nw' is not relevant for zenith delay calculation.
21. 'Start!' processing after all settings are made. Output is a *.ZTD file with zenith wet and total delays for each POI (see format description below)
22. Push button 'Show output' to display output files. **Works for both '*.Napr' and '*.ZTD' files**
23. 'Clear all' settings to start a new session from scratch.

Sub-panel '3D Tomography' (ATom.m line 4352 – 5535)

Sub-panel '3D Tomography' is dedicated to the computation of wet or total refractivity fields from GNSS slant delays. Therefore, different input and parameter settings, but also different inversion strategies can be applied. In the following, the possible processing steps and options are described in more detailed.



<u>How to compute improved wet refractivity fields?</u>

1. 'Open file' to select SWD/STD input file(s). The following formats are supported:
   - Slant Wet Delays as computed in panel 'Slant Delays' and stored in *.SWD files
   - Slant Total Delays as computed in panel 'Slant Delays' and stored in *.STD files
   - Slant Wet Delays as provided in COST format (*.SWDe files)
2. 'Load' input file(s). Thereby, time variables (T0, Te, Stac) are derived from the input data:
   'T0' is the first epoch available in the input data
   'Te' is the last epoch available in the input data
   'Stac' is a parameter, which allows to specify epochs for processing, e.g. 'all' means all available epochs will be processed, '1' means only the first epoch will be processed, '5' means the first 5 available epochs will be processed, and so on. *The maximum number of

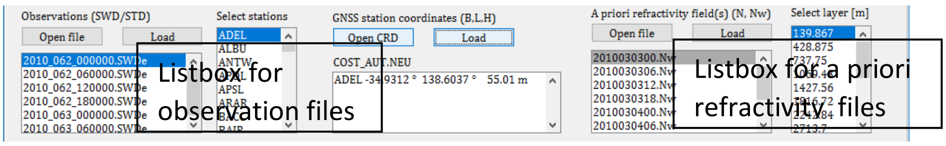
available epochs (e.g. 281) is computed when loading the input files and is highlighted in the GUI as follows: Stac [all] epochs (max: 281) *

3. 'Select stations' of interest from listbox. Multiple selection is possible. **Please make sure that all stations are located within the voxel boundaries, otherwise and error message will show up during processing.**
4. Open 'GNSS station coordinates (B,L,H)' in *.NEU format, i.e. lat, lon and height H. **Be aware that the GNSS station heights should be provided in the same height system as the a priori field (usually orthometric heights if derived from NWM data in panel 'N (a priori)').*
5. 'Load' coordinates from file: All stations with coordinates will be listed (check status line, in case not all stations are available in coordinate-file an error message will indicate the missing site)
6. 'Open file' to select 'A priori refractivity field (N, Nw)'. **This option is mandatory - even if the a priori refractivity field is not considered in processing.* T*he following formats are supported:
   - A priori refractivity files as computed in panel 'N (a priori)' and stored in *.Napr format
   - Refractivity fields from any previous tomography run in *.N format
   - A priori refractivity fields as provided in COST format (*.Nw)
7. 'Load' the file of a priori refractivities. Thereby, not only the a priori refractivities but also the shape of the voxel model, i.e. voxel center points for the inner and the outer voxel model (if provided) are read in. In addition, the available height layers will be listed in listbox 'Select layer [m]' and the voxel model is drawn in the lower left corner - including positions of the selected GNSS stations (if the coordinate file was already loaded). Dependent on the selected parameter ('N_wet' or 'N_total', see step 12), the a priori refractivity field is shown in the center plot 'A priori refractivity field [ppm]' – separately for each layer. **In order to highlight the a priori data of another layer, tick the height layer of interest in the listbox 'Select layer [m]'. The plots will update immediately.**
8. Select the period and epochs of interest (T0, Te, Stac, see step 2)
9. Tick option 'Apply a priori N' if the a priori refractivities should be considered in processing (recommended). Otherwise, the GNSS tomography solution is computed from slant delays only.
10. Tick option 'Apply weights' in order to set up a proper weighting matrix. In case this option is not set, the weighting matrix will be an identity matrix (equal weighting of all input data). Otherwise,
    - the weighting of the slant delays is computed from the standard deviation of the ZTDs (see step 14). Therefore, the standard deviation is mapped into direction of the satellite in view by sin(e)^2. **In case, elevation angles are not provided, the weighting matrix of the slant delays will be the identity matrix.**
    - the a priori sigmas of the refractivity field are read in from the a priori refractivity files (*.Napr or *.N). However, in case no a priori sigmas are provided, i.e. if all sigmas are zero or if the a priori refractivity field is read in from *.Nw files, the a priori sigmas are set to 10 % of the N (Nw). In case, single sigma values are zero, these values are replaced by '1' to avoid numerical problems.
11. Tick option 'LoS enter top layer' to consider only observations which enter the voxel model through the top layer and, in consequence discard observations which enter the voxel model through any lateral surface.
12. Define the refractivity field of interest with option 'A priori N': **Be aware that SWD files provide only SWDs and no STDs, thus total refractivities are probably not estimated correctly. So, select option 'N_total' only if STDs are provided.**
    - 'N_wet': Select this option to estimate wet refractivity fields
    - 'N_total': Select this option to estimate total refractivity fields.
13. Define the method for 'Inversion', either 'LSQ (SVD)' or 'MART'. In case of:
    - **LSQ (SVD)** the tomography equation system is solved by least squares adjustment, i.e. all selected observations are processed in one batch, whereby the refractivity in each voxel

is assumed as constant over time. Since matrix A is singular, singular value decomposition method is applied for inversion of A. Therefore, a threshold for the eigenvalues has to be defined (see step 15).

- **MART** is a special version of the algebraic reconstruction technic (ART). It allows to solve for refractivity iteratively, see Bender et al. (2011). Therefore, a relaxation factor has to be defined (see step 16). **Not fully implemented yet.**

14. Set standard deviation of the observations 'sZTD [mm]'. In processing this value is used to compute elevation-dependent weights for the slant delays. **Works only if option 'Apply weights' is active.**
15. The threshold for the eigenvalues 'Eigv [km^2]' is needed for singular value decomposition (see step 13). **The optimal value can be found by L-curve technique, see Möller (2017), p 100ff.**
16. The relaxation factor is an input parameter for the MART algorithm (see step 13). *This option is set inactive, since MART is not fully implemented yet.**
17. Define the maximum number of iterations '# Iterations'. ** This option works well only together with step 20, i.e. if outliers are removed. Otherwise, convergence criteria 1 (see step 18) is reached after two iterations.**
18. Define threshold for convergence (criteria 1). Thereby, the RMS of the weighted post-fit residuals of two consecutive solutions is compared with each other. If the RMS does not decrease more than the defined threshold, the processing will be stopped.
19. Define threshold for convergence (criteria 2). Thereby, the processing stops if the RMS of the weighted residuals is smaller than the predefined threshold.
20. Tick option 'Consider bending' to make use of the bended ray-tracer for reconstruction of the signal paths. **This option is recommended if slant delays below 10 degrees elevation angle enter the tomography solution, see Möller and Landskron (2018) for further details.**
21. Tick option 'Remove outliers' to check the postfit residuals. Slant delays with residuals larger than **120 times** the RMS of the post-fit residuals (see ATom.m Line 5392) are removed from processing. The processing is repeated with the remaining observations until the convergence criteria is fulfilled or until the maximum number of iteration steps is reached.
22. Tick option 'Smooth N, Nw' in order to apply an interpolation method to the improved refractivities. This option allows for computation of improved refractivities for voxels which are not traversed by any observation. **This option is not implemented yet but is recommended if the signal delays should be determined from the improved refractivity fields.**
23. 'Start!' processing after all settings are made. Output is a *.N file with improved wet or total refractivities and standard deviations for each voxel center point. In addition, the obtained refractivities are highlighted in the lower right plot. Tick 'Show differences (N-Napr)' to highlight the differences between a priori and improved refractivities for each layer.
24. Tick 'Routine!' to process multiple sessions. Beforehand, make sure that the same number of observation and a priori refractivity files are available in the listboxes (see figure below).



25. 'Clear all' settings to start a new session from scratch.

Formats

Navigation Message file format for GPS (*.YYn) and GLONASS (*.YYg)

ftp://igs.org/pub/data/format/rinex211.txt

ftp://igs.org/pub/data/format/rinex303.pdf

IGS SINEX Tropo format *.zpd:

ftp://igs.org/pub/data/format/sinex_tropo.txt

New SINEX Tropo format *.SNX:

The new SINEX tropo format description is not available yet, but will be provided with the COST final report end of 2018. Thus, this format is not fully implemented yet.

Bernese troposphere file format *.TRP

http://www.bernese.unibe.ch/docs/DOCU52.pdf, section 24.8.1 on page 751ff

Bernese residual file format *.FRS

http://www.bernese.unibe.ch/docs/DOCU52.pdf, section 24.11.9. on page 768ff

Napeos zero difference residual file format *.ZDR

This format is created by res2xyz.exe, a Fortran script provided with Napeos for the conversion of binary residual files (*.res) into ASCII files (*.ZDR). In order to run the program, copy res2xyz.exe into the folder with binary residual files and execute the following command:

./res2xyz.exe ${FILE01} ALL ALL 18 > ${FILE02}

whereby ${FILE01} is the name of the input file and ${FILE02} the name of the output file with extension *.ZDR. The format of the *.ZDR file reads as follows:

56417.00000 ROET GPS-36 145.7366 73.9806   0.9542

- 01 MJD
- 02 Station name
- 03 Satellite ID
- 04 Azimuth angle in degrees
- 05 Elevation angle in degrees
- 06 Zero difference residual in m

COST synoptic data format *.syn

2013-05-01 00:00 1027.9   4.6   3.4   91 -999

format: (%4f-%2f-%2f %2f:%2f %f %f %f %f %f)

- 01 Date (YYYY-MM-DD)
- 02 Time (HH:MM)
- 03 Pressure in hPa
- 04 Temperature in °C
- 05 Dry temperature in °C
- 06 Relative humidity in %
- 07 Rain/hour in mm

COST Slant Wet Delay format *.SWDe:

The content of the *.SWDe files is the following (with 17 columns)

ALBU 146.915557 -36.077536 197.5702 -4324312.544 2817311.048 -3735264.846 -8994895.522 -13722905.430 -21276124.528 3 136.173382 14.479369 00 00 00 0.496

format: (%4s %11.6lf %11.6lf %9.4lf %16.3lf %16.3lf %16.3lf %16.3lf %16.3lf %16.3lf %2d %10.6lf %9.6lf %02d %02d %02d %7.3lf)

- 01 Station name
- 02 Longitude
- 03 Latitude
- 04 Altitude
- 05 Station X-coordinate in m
- 06 Station Y-coordinate in m
- 07 Station Z-coordinate in m
- 08 Satellite X-coordinate in m
- 09 Satellite Y-coordinate in m
- 10 Satellite Z-coordinate in m
- 11 PRN
- 12 Azimuth angle in degrees
- 13 Elevation angle in degrees
- 14 Hour
- 15 Minute
- 16 Second
- 17 SWD in m

COST a priori refractivity format *.Nw:

The content of Nw/WVdens files is the following (with 4 columns)

126.000 -48.600000 139.8670 51.72928

format: (%7.3lf %10.6lf %10.4lf %10.5lf)

- 01 Longitude in degrees
- 02 Latitude in degrees
- 03 Altitude in m
- 04 Wet refractivity in ppm

TAWES synoptic data format *.dat

Data of the ‚Teilautomatisches-Wetter-Erfassungs-System‘, i.e. from the meteorological network of synoptic stations in Austria. This data is provided by ZAMG on a routine basis to TU Wien in the following format:

20180101   10   11001   60   9364   71

- 01 Date (YYYYMMDD)
- 02 Time (*HH*MM)
- 03 Site ID
- 04 Temperature in 0.1 °C
- 05 Pressure in 0.1 hPa
- 06 Relative humidity in %

ATOM satellite coordinate file format *.XYZ:

2013 125   900 R01 -15873114.304 -10599206.606 -16930267.563

- 01 Year
- 02 Day of Year
- 03 Second of Day
- 04 PRN
- 04 ECEF X-coordinate in m
- 05 ECEF Y-coordinate in m
- 06 ECEF Z-coordinate in m

ATOM satellite direction file format *.AER:

2013 312 3900 AFAL R01   344.7105 5.0098 24168655.5334

- 01 Year
- 02 Day of Year
- 03 Second of Day
- 04 Station name
- 05 PRN
- 06 Azimuth angle in degrees
- 07 Elevation angle in degrees
- 08 Distance in m

ATOM station coordinate file format *.NEU:

AFAL   46.527144   12.174517 2284.096

- 01 Station name
- 02 Latitude in degrees
- 03 Longitude in degrees
- 04 Height in m

ATOM Zenith Wet Delay file format *.ZWD:

54754.00000 ANZA   2.4055   0.2278   0.000   0.000 956.50   0.0   0.00 M001

- 01 ... MJD
- 02 ... Station name
- 03 ... ZTD in m
- 04 ... ZWD in m
- 05 ... North Gradient in mm
- 06 ... East Gradient in mm
- 07 ... Pressure in hPa
- 08 ... Temperature in °C
- 09 ... Water vapor pressure in hPa
- 10 ... In-situ station name

ATOM Zenith Total Delay format *.ZTD:

ALST   48.71577   15.32971   543.1 2.1769 0.1208 2.1763

- 01 ... Station name
- 02 ... Latitude in degrees
- 03 ... Longitude in degrees
- 04 ... Height in m
- 05 ... ZHD in m
- 06 ... ZWD in m

The date and time is taken from filename (YYYYMMDDHHxx.ZTD) whereby, YYYY is Year, MM is Month, DD is day of month, HH is hour and xx is a wildcard for any further information like minute.

ATOM Slant Wet Delay format *.SWD:

56413.00000 JENB G06   0.0992 81.1661 142.1293

- 01 ... MJD
- 02 ... Station name
- 03 ... PRN
- 04 ... SWD in m
- 05 … Elevation angle in degrees
- 06 … Azimuth angle in degrees

ATOM Slant Total Delay format *.STD:

56413.00000 JENB G06   2.0656 81.1661 142.1293

- 01 ... MJD
- 02 ... Station name
- 03 ... PRN
- 04 ... STD in m

- 05 … Elevation angle in degrees
- 06 … Azimuth angle in degrees

ATOM a priori refractivity format *.Napr (new since August 2018):

36.50000   1.00000   225.0 14.223 286.34 994.32 334.585 66.273   0.000   0.000 5.156 5.068

- 01 ... Latitude in degrees
- 02 ... Longitude in degrees
- 03 ... Height in m
- 04 … Water vapor pressure in hPa
- 05 … Temperature in K
- 06 … Pressure in hPa
- 07 … A priori total refractivity in ppm
- 08 … A priori wet refractivity in ppm
- 09 … Total refractivity in ppm (reserved for tomography results, i.e. mostly zero)
- 10 … Wet refractivity in ppm (reserved for tomography results, i.e. mostly zero)
- 11 … Standard deviation for 07 (or 09 if provided)
- 12 … Standard deviation for 08 (or 10 if provided)

ATOM refractivity format *.N (new since August 2018):

This format is identical with the Napr format. In case, tomography processing is carried out, columns 09 and 10 are used to output the improved refractivity fields (either N or Nw).

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