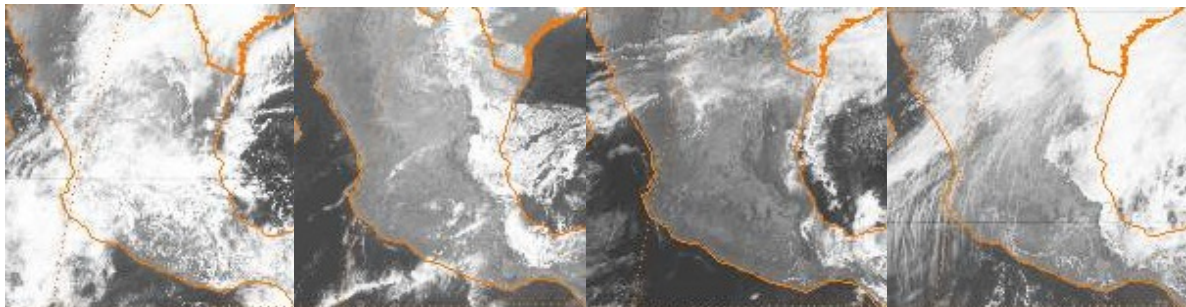# - TRAIN -

Toolbox for Reducing Atmospheric InSAR Noise
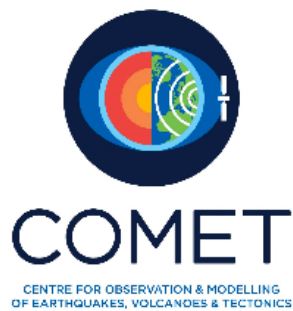

(Visible spectrum images at a geostationary orbit over Mexico, copyright NOAA)

David Bekaert

Version 2beta

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COMET

CENTRE FOR OBSERVATION & MODELLING
OF EARTHQUAKES, VOLCANOES & TECTONICS

1   Introduction

The Toolbox for Reducing Atmospheric InSAR Noise – **TRAIN** – is developed in an effort to include current state of the art tropospheric correction methods into the default InSAR processing chain. Initial development was performed at the University of Leeds. We request **TRAIN** users to reference our publication of **TRAIN**:

> *Bekaert, D.P.S., Walters, R.J., Wright, T.J., Hooper, A.J., and Parker, D.J. (2015c), Statistical comparison of InSAR tropospheric correction techniques, Remote Sensing of Environment, doi: 10.1016/j.rse.2015.08.035*

In addition, also cite the original methods where needed. E.g. for our power-law method this is:

> *Bekaert, D.P.S., Hooper, A.J., and Wright, T.J. (2015a), A spatially-variable power-law tropospheric correction technique for InSAR data, JGR, doi:10.1029/2014JB011558*

I would like to acknowledge the contribution and help of Richard J. Walters, Hannes Bathke, and Simran Sangha, and the support of Tim J. Wright, Andy J. Hooper, and Doug J. Parker. In addition, I would like to thank Zhenhong Li, the Leeds InSAR group, as well as other COMET members for their feedback

TRAIN is distributed under a GNU GPL licence. The toolbox consists of a combination of command line scripts, shell scripts, and matlab scripts. More information on software is provided in Chapter 3. **TRAIN** is independent of the used InSAR processor, as long as the data convention is followed. The toolbox is compatible with the StaMPS software. Further initial efforts have been put to include **TRAIN** into the default Π-rate processing chain.

The manual provided with this toolbox is undergoing continuous development. Any feedback is welcomed. Post questions and comments to the TRAIN help forum. In order to post to the forum you will need to subscribe and provide a small description. The latter is only used to separate spam from actual users. You can search for answered questions without being a member of the group. https://groups.google.com/forum/?hl=en#!forum/TRAIN_support

Throughout this manual command line commands are indicated in blue. Matlab commands are indicated to be in the matlab environment, i.e. command is proceeded by >>. Red refers to inputs that need to be set by the user. Description of the matlab functions can be obtained by typing help and the function name in matlab e.g. >> help function_name. In matlab all the processing parameters are contained in the parms_aps.mat file. Parameter values can be retrieved by >> getparm_aps for the full list or through >> getparm_aps('parameter_name') for the

parameter_name parameter. On the other hand parameters can be changed by the user by using the > setparm_aps('parameter_name',new_value). At the first run the default parameters will be loaded. To reset at any time on of the parameters to the default value do:

> setparm_aps ('parameter_name', NaN)

TRAIN includes:

Weather balloon sounding delays:
- Balloon sounding download script
- Balloon sounding delay estimation tool (station location only)

Tropospheric correction techniques for InSAR:
- Phase-based - Power-law correction
    - Input parameters can be estimated from sounding data
    - Option to have variable power-law coefficients between interferograms
    - Fixed windows generation of using mountain ridge information
- Phase-based - Linear correction
    - Full interferogram or non-deforming region
- Spectrometer - MERIS correction *(currently only Envisat support)*
    - Input parameters can be estimated from sounding data
    - Option to vary conversion coefficients for each SAR date
    - Auto re-projection to geo-coordinates
- Spectrometer - MODIS correction
    - Input parameters can be estimated from sounding data
    - Option to vary conversion coefficients for each SAR date
    - Auto download and merging using OSCAR service
    - Re-calibration option of MODIS PWV with respect to MERIS PWV
- Weather model correction
    - Download of weather model data
    - ERA-I from the BADC and ECMWF data servers
    - MERRA and MERRA2
- Weather model – Weather Research and Forecasting Model (WRF) correction
    - Including download script of weather model data
    - WRF input file generation

The table below gives an overview of the different components estimated in each technique

Techniques	*Hydrostatic delay*	*Wet delay*
MERIS (Spectrometer)	**NO***	**YES – Including turbulent**
MODIS (Spectrometer)	**NO***	**YES – Including turbulent**
WRF (Weather model)	**YES**	**YES – Including turbulent**
ERA (weather model)	**YES**	**YES – Including turbulent**
MERRA/MERRA2 (weather model)	**YES**	**YES – Including turbulent**
Linear correction (uniform troposphere)	**Yes - Combined (no turbulence).**	
Power-law correction (spatially-varying troposphere)	**Yes - Combined (no turbulence).**	

*A comparison can be made with other techniques when adding the hydrostatic component from e.g. a weather model.

2 Contents

3   Configuration

To set up the required variables source the appropriate file for your shell. If you are using a csh like shell, run:

> source APS_CONFIG.tcsh

Or, if you are using a bash like shell:

> source APS_CONFIG.sh

If you unsure of which shell you are using, you should be able to find out by running the command:

> echo $SHELL

Edit the APS_CONFIG file and update the path of the APS_toolbox to the location where you have downloaded it to. The configure file needs to be sourced on each shell start-up. It is recommended to add the sourcing command to your .bashrc or .tcshrc file

Below a list is provided with external software's that are used within this toolbox. All of them are freely available except Matlab. Not all of them are required when running specific parts of the toolbox.

3.1   Matlab

The main software used throughout this toolbox. The development of the toolbox has been done using Matlab 2012 and 2013. While not tested it is expected to run without large problems with older versions.

3.2   Beam

Free downloadable software from ESA, http://www.brockmann-consult.de/cms/web/beam/, which allows you to load satellite data and perform image operation like re-projection to WGS84 format. The Beam (VISAT) software is only used for the MERIS correction part of the toolbox. Note that other software might be able to do a re-projection as well.

3.3   NCL

Free downloadable software from http://www.ncl.ucar.edu/index.shtml, which is used to convert GRIB1 and GRIB2 reanalysis date into netcdf format. This software will be needed when using weather model data from the US.

3.4 GMT

GMT is an open source software that can be downloaded for free and which is for the auxilary tropospheric correction methods. TRAIN has been tested for GMT version prior to version 5. Download from http://gmt.soest.hawaii.edu/gmt/gmt_download.html.

3.5 Python

Python is used to automate some routines, which can also be completed manually. E.g. this includes the batch ordering and download of ERA-I data from the ECMWF website, and the automatically batch re-projection of the MERIS coordinate system. When using the automated options one will also need to add the PYTHONPATH with the location of the packages in the APS_CONFIG file.

3.6 OSCAR JPL – MODIS service

For the MODIS spectrometer estimate, the downloading and cropping relies on the OSCAR JPL online service. Data fetching and downloading can be done using their provided Python scripts. Download these at http://oscar.jpl.nasa.gov and update the location of the get_modis.py in your APS_CONFIG.sh or APS_CONFIG.tcsh file. Note OSCAR server includes MODIS data till 2013 only.

3.7 ECMWF WEBAPI

The ECMWF webapi can be used to batch order and download the ERA-I from the ECMWF website. Download the package and follow the guidelines as given at:

https://software.ecmwf.int/wiki/display/WEBAPI/Accessing+ECMWF+data+servers+in+batch.

The python package can be installed in the Python folder of the APS toolbox, which will be automatically sourced in the APS_CONFIG file. Installing the package at another location will require you to update the APS_CONFIG file such the package is added to the PYTHONPATH. To run the API, a username and password from ECMWF are required, and a WEBAPI password will need to be requested linked to your account. Once given, put your account information in the hidden ~/.ecmwfapirc file as instructed on the ECMWF website.

3.8 StaMPS

Users which are using this toolbox as a plug-in to StaMPS can use ps_plot of the StaMPS Matlab toolbox to visualise their tropospheric correction results. TRAIN has been integrated with StaMPS and recognises the StaMPS structure. For the power-law tropospheric correction a lot of the required processing parameters are automatically extracted based on the StaMPS files. Note that for non-processed StaMPS data, the plotting will fail, unless all the required files are provided in the StaMPS format. For interested users see: http://homepages.see.leeds.ac.uk/~earahoo/stamps/.

3.9 WRF

The Weather research and Forecasting (WRF) model, used to run your own local weather model at a high resolution, can be downloaded at http://www2.mmm.ucar.edu/wrf/users/downloads.html. You will need to install two components of the software, WPS and WRF.

As different libraries and packages are required, it might be useful to follow the compilation tutorial step by step. http://www2.mmm.ucar.edu/wrf/OnLineTutorial/compilation_tutorial.php. It will help you to first make sure your system is set up correctly, and then will help you to install libraries, netcdf, mpich, and to make sure that everything is compatible. It will then help you to install WRFV3 and WPS. For WRF installation related questions please contact WRF support.

4 Preparing your data for processing with TRAIN

TRAIN assumes the interferometric phase, height, and date information to be stored in a specific formation. Below it is elaborated how to set this structure up. StaMPs users can skip this step, as the toolbox will be automatically set the paths to the correct variables in the parameter file.

In the following n_p, refers to the number of points, while n_ifgs will refer to the number of interferograms.

Tip: When you have a different selection of points for each interferogram you can include NaN's in the phase matrix for those pixels.

To save you data do something like:

>> save('hgt.mat', 'hgt')

---

hgt_matfile = [pwd 'hgt.mat']	Topography, stored in a column vector of size [n_points 1] in meter units as variable "hgt". **This is needed for the phase-based correction methods only.**
phuw_matfile = [pwd 'phuw.mat']	Unwrapped interferograms, stored as a matrix of size [n_points n_ifgs] in radian units, as variable "phuw". **This is needed for the phase-based correction methods only.**
ll_matfile = [pwd 'll.mat']	Geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude, specified as degrees, as variable "lonlat". **Needed for all correction methods**.
ifgday_matfile = [pwd 'ifgday.mat']	Interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format, and as variable "ifgday". **Needed for all correction methods.**

UTC_sat = ['HH:MM']	UTC time of the satellite pass over your study area. It is specified as a string in a two-digit hour and two-digit minute string format "HH:MM". A colon needs to be included in between! **Needed for all weather model and MODIS correction methods.**
look_angle = 21/180*pi or path to file	The look angle [rad] is used to projection from zenith to the radar line of sight. By default this is set to 21 degrees. Alternative a file can be specified in which the look angle for each point can be given. This needs to be a column vector of size [n_points 1] with the angle in radians saved as "la" variable. **Needed for all correction methods except phase-based correction and MERIS.**
demfile = [pwd 'dummy.dem'] or = [pwd 'dummy.grd']	The path to the DEM_file. Few options are included: 1) using a ".grd" file, 2) a DEM_file with corresponding DEM_file.rsc file. For option 2 the DEM_file.rsc should contain the associated WIDTH, LENGTH, X_STEP (resolution), Y_STEP(-1*resolution), X_FIRST and Y_FIRST (upper left corner of the DEM), and optional the FORMAT. X and Y refer to longitude and latitude. You can use construct_dem.sh to make you DEM file. **Needed for all weather model correction methods**.

5   Downloading of sounding data

This step is not required for the linear topography-phase correction. Optional it can be used for the spectrometer (MERIS/MODIS) and power-law correction to get an estimate for the scaling coefficients of the correction techniques. In case no sounding data is downloaded the default values will be loaded for those techniques instead. The user can manually change the values as well.

Sounding data can give a good indication on how delays vary within your region of interest. However, note that sounding delays are often acquired at fixed times of 00 UTC and 12 UTC and thus there might be an offset between your radar acquisition over which the atmospheric conditions might have been changed. Retrieve those sounding acquisitions the closest to your SAR acquisition.

5.1   Download

Below the instructions are provided on how to automatically download balloon sounding from the University of Wyoming (please acknowledge the source data in your work).

cp $APS_toolbox_scripts/sounding_download .

Edit the parameters in sounding_download to your region of interest and run sounding_download from the command line.

Parameter name	Description
station	The station number of the sounding station the closest to your region of interest. To identify the station number consult the sounding map at http://weather.uwyo.edu/upperair/sounding.html
region	This is the regions where your souding station is located. This is either "eu" for Europe, "na" for North America, "af" for Africa. When going to the website you can find the region of the station within the URL.
year	The years of sounding data that needs to be downloaded e.g. "2010 2011 2012".
month	The months of the year that needs to be downloaded e.g. "01 02 03" for January till March.
day	The days of the month that needs to be downloaded e.g . "28 29 30 31".
savepath	The full path where the sounding data needs to be saved to.

The data will be downloaded when available and saved as a YYYYMMDD_HR.txt files following the region/station_nr/YYYYMMDD_HR.txt directory structure.

5.2   Loading in Matlab and saving into .mat files

Next all the ".txt" files are loaded into Matlab and saved as ".mat" files with the atmospheric variables (P,T,h, and RH) stored as assumed by other routines in this toolbox. Launch matlab and set the sounding data location using setparm_aps:

Parameter and default value	Description
sounding_dir = [pwd '/sounding_data']	Directory string where the sounding data is downloaded to. Use full path.

Now load the sounding data into matlab by running:

>> load_sounding

6 Computation of sounding profile delays

This Matlab script allows for the computation of the sounding delays. Go directly to the power-law or MERIS/MODIS chapter when you want to use sounding data to estimate the input coefficients of the correction method.

6.1 Sounding data format

No modification of the file structure is needed when the sounding data has been loaded using the load_sounding script as elaborated in Chapter 5. When done so this step can be skipped.

All the sounding data should be loaded into Matlab and saved into the date 'YYYYMMDD' and UTC 'HR' format as "YYYYMMDD_HR.mat" files. The variables within this mat files are the 'P' pressure (hPa), 'T' the temperature (degrees), 'RH' the relative humidity (%) and 'h' the heights in (m). After having constructed vectors for each of these variables, of the same length, do the following to save them:

>> save('YYYYMMDD_HR.mat', 'P', 'T', 'RH', 'h')

6.2 Computation of sounding delays

The sounding program computes the refractivity, the mean LOS delay (phase [rad] and displacement [m]), the corresponding heights and appends this information to the existing "YYYYMMDD_HR.mat" files. In addition, a single estimate for the power law coefficients will be given as output based on the full sounding period. It can be neglected when not needed. More sophisticated power-law and spectrometer coefficient estimation, including seasonal variation and SAR date specific estimates, are contained in the chapter of the power-law and MERIS correction.

Delays are computed based on the user processing parameters, given below and which can be retrieved using the >> getparm_aps and modified using the >> setparm_aps functions.

To compute the delays, type:

>> sounding

Parameter and default value	Description
sounding_dir = [pwd '/sounding_data']	Directory string where the sounding data is downloaded to. Use full path.
sounding_time_stamp = ['00' ; '12']	The UTC acquisition times of the sounding data to be used into the computation. By default this is set to 00 and 12 UTC. Needs to be specified as a column vector string.
sounding_start_date = []	Start date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. By default [], the earliest date is used.
sounding_end_date = []	End date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. By default [], the latest date is used.
sounding_h0 = 0	The height in km units till which the delays are computed. When set to 0 sounding_h0 is computed to the height at which the net delay is approximately 0. Note for individual delays you might want to increase this value.
sounding_errror_promp = 'n'	Crashes are suppressed (default). Instead error message are outputted and data is patched with NaN when set to 'n'.
look_angle = 21/180*pi or path to file	The look angle [rad] used in the projection to the line of sight. By default this is set to 21 degrees. Alternative a file can be specified in which the look angle for each pixel or PS can be given. This needs to be a column vector of size [n_points 1] with the angle in [rad].
lambda	The radar wavelength of the SAR satellite in m. This is used to convert the delay towards a phase delay. By default lambda is set to be 0,0562 m.

7   Phase-based - Linear tropospheric correction

A linear tropospheric correction can be computed based on the phase and topographic information by typing:

> >> aps_linear

Output is saved into a "tca2.mat" or "tca_sb2.mat" as the "ph_tropo_linear" variable.

The relation can either be estimated based on the full interferogram or for a selected non-deforming region. Support it included for interferograms with varying pixel selection in time, by introducing them as NaN in those interferograms where the pixel is not included. The parameters which are used in aps_linear are:

Parameter and default value	Description
hgt_matfile = [pwd 'hgt.mat']	Full file path containing the topography, stored in a column vector of size [n_points 1].
phuw_matfile = [pwd 'phuw.mat']	Full file path of the unwrapped interferograms, stored as a matrix of size [n_points n_ifgs].
ll_matfile = [pwd 'll.mat']	Full file path of the geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude.
non_defo_flag = 'n'	By default the correction is performed based on the full interferogram. Put to 'y' to use the non-deforming estimation.

7.1   Full interferogram based

By default the 'non_defo_flag' is set to 'n', which will force the computation of the tropospheric relation between phase and topography based on the whole interferogram.

7.2   Non-deforming region

To use the non-deforming region turn the 'non_defo_flag' in the parms_aps list on by typing:

> >> setparm_aps('non_defo_flag','y')

Note that turning this functionality on, requires you to have a file "non_defo.mat" with in it a variable "poly", being a matrix with in its columns the longitude and latitude of the non-deforming region. To save such a variable do: >> save('non_defo.mat', 'poly').

8 Phase-based - Powerlaw correction

This technique is contained in Bekaert et. al. (2015a, 2015b). An expansion of the powerlaw method using the ridge approach, comparing it with the other tropospheric correction methods in TRAIN over multiple regions is documented in Bekaert et al. (2015c). The following section describes the processing steps together with the required input parameters for each step. Output is saved into a "tca2.mat" or "tca_sb2.mat" as the "ph_tropo_powerlaw" variable.

The program can be called by >> aps_powerlaw for which all processing steps will be run. Individual steps can be run by:

>> aps_powerlaw(start_step,end_step)

Optional steps:

Below the different steps are elaborated. Step 0 (ridge definition) and step 1 (coefficient estimation from sounding data) are optional steps:

In step 0 the user can use the DEM information to define the individual regions in which the powerlaw relationship is estimated. By default (powerlaw_ridge_constraint = 'n') this step is skipped, with the different regions defined by approximately square windows, where the user controls the number of windows (powerlaw_n_patches) and the percentage overlap (path_overlap).

In step 1 the power-law decay coefficient and height at which the net delays have reduced to approximately zero is estimated from the sounding data. By default and in case no sounding data is available ('sounding_data flag is set 'n') this step is skipped, and the default or user-defined coefficients will be loaded. For more information on how to obtain sounding data and the required data structure see Chapter 5 of the manual.

> The **selection of a non-contaminated frequency band is not automated**. You will need to know which frequency band to use in advance, or by validation with another independent technique, e.g. MERIS, ERA, etc. Beside the tectonic deformation also other signals can bias specific frequency bands like for example the higher spatial frequencies in case of atmospheric turbulence.
>
> Alternatively, the user can assume one of the other techniques as reference, and evaluate the RMSE of the different power-law bands with respect to it. By comparing the average RMSE between the power-law bands and the reference one might get an idea which band might be best to continue with. This is included in step 5 and currently only supported for StaMPS users. In future this will be generalized for other InSAR processing methods, but for not one could opt to make a visual comparison to find a suitable band.

8.1   Step 0: Defining mountain ridges

This step is optional. You can decide either to have your region to be split into multiple approximately square windows [Bekaert et.al., 2015a], or you can choose the windows to follow mountain ridges as boundary [Bekaert et al., 2015c]. Choosing for the ridge approach can be enabled by using >> setparm_aps('powerlaw_ridge_constraint','y')

Parameter and default value	Description
powerlaw_ridge_constraint = 'n'	When set to 'y' windows/ patches are defined based on mountain ridges. Note that when 'y' powerlaw_n_patches and patch_overlap will not be used.

To run this step type:

>> aps_powerlaw(0,0)

Next follow the instructions as given in the screen. You will need to click on the topography map to define your ridges. Once you have finished a ridge press the "enter" button. You will be asked if the ridge is a hard ridge or not.

The definition of a hard ridge becomes important once the estimated relation between phase and topography from the different windows is used to extrapolate the estimate to a given location (pixel) within the study region. Only windows not blocked by a hard ridge will contribute to the weighted estimate of an individual point location. Soft ridges can be used to split a region into multiple windows.

> **Note**: Defined ridges need to extend slightly outside the red polynomial (InSAR convex hull). Depending on your InSAR dataset, this polynomial could cover no data regions. The intersection between ridges and the red polynomial is used to define sub-regions. Only InSAR observations within a sub-region will contribute to the sub-region estimate.

8.2   Step 1: Estimate power-law coefficient from sounding data

This step is optional and will use default values when skipped. To enable this method sounding data needs to be downloaded according to Chapter 5.

>> setparm_aps('sounding_data','y')

>> setparm_aps('sounding_dir',string_with_your_path)

Two options exist for the coefficient estimation. By default a mean value will be estimated for the power-law coefficients using the full sounding date range ('sounding_sensitivity' = 'n'). However, this can be changed such the power-law coefficients are estimated for each specific SAR data, after which the mean is taken to estimate the power-law coefficients for each individual interferogram. In addition, there is the option to make a sensitivity analysis of the power-law coefficients. Below the different option are summarised together with their specific parameters. Modify these using the setparm_aps function.

Estimation option	Description of parameters controlling option
A mean coefficient for all interferograms (default option)	'sounding_sensitivity' is 'n'. This method is not recommended for large sounding periods. It is recommended instead to use the sensitivity analysis and manually set a mean value.
Individual coefficients for each interferogram	'sounding_sensitivity' and 'sounding_ifg_dates' are both 'y'. In total 15 days before and after the SAR date are used to compute the mean delay.
Sensitivity analysis	'sounding_sensitivity' is set to 'y', while 'sounding_ifg_dates' is set to 'n'. The number of months over which the mean delay is computed is given by 'sounding_months'. The latter is by default 1 month.

Both h_0 and α are estimated from the sounding data. h_0 corresponds to height at which the tropospheric net delays have reduced to approximately zero. It is estimated by making many net-delay combinations and requires sounding_h0 to be set to zero.

>> setparm_aps('sounding_h0', 0)

α corresponds to the power-law decay coefficient and is defined as the slope of the mean delay versus height curve in the log-log domain. It is estimated from zero elevation up to sounding_h_alpha_thres (km units).

>> setparm_aps('sounding_h_alpha_thres', 4)

Below all remaining parameters used for this step are summarized. To run the estimation of the sounding data coefficients type:

>> aps_powerlaw(1,1)

Parameter and default value	Description
sounding_time_stamp = ['00' ; '12']	The UTC acquisition times of the sounding data to be used into the computation. By default this is set to 00 and 12 UTC. Needs to be specified as a column vector string.
sounding_start_date = []	Start date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_end_date = []	End date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_h0 = 0	The height in km units till which the delays are computed. When set to 0 sounding_h0 is computed to the height at which the net delay is approximately 0.
sounding_h_alpha_thres = 4	Lower range of sounding heights in km, for which the power-law decay coefficient alpha is estimated. It is recommended to have this value around or a bit a larger than the maximum topography.
sounding_errror_promp = 'n'	Crashes are suppressed (default). Instead error message are outputted and data is patched with NaN when set to 'n'.

Obtained results can be re-processed or displayed by re-running this step: >> aps_powerlaw(1,1)

8.3   Step 2: Rotate and interpolate to a regular grid together with power-law scaling

To minimize band-filtering effects, the InSAR data is rotated over the heading angle to decrease white space around the InSAR track, see *Figure 1*. In order to perform the Fourier transform the data is interpolated to a regular grid with the sampling controlled by powerlaw_xy_res. The sampling should not be made bigger than the resolution of you InSAR data. Next, the topography is scaled according to the power-law relationship. An overview of the used input parameters is given below.

Note that NaN values are ignored when interpolating to a regular grid. While not done by default, at this stage one can opt to crop out part of the data by changing >> setparm_aps('crop_flag', 'y'). As wrongly unwrapped regions bias the filtering and thus the tropospheric estimation, it is advised to use this option to crop out those specific areas.

To run this step type:

>> aps_powerlaw(2,2)
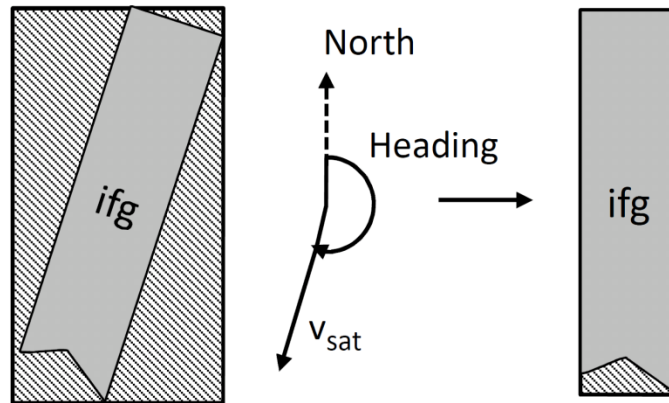
Figure 1: Rotate over the satellite heading to minimize the bounding box around the data.

Parameter and default value	Description
heading = [] or from StaMPs file	The rotation angle in deg over which the InSAR data needs to be rotated to minimize the bounding box. The satellite heading is a good approximation.
powerlaw_xy_res = [30 30]	The regular grid resolution [x y] in m, to which the data will be interpolated. This resolution should not be better (smaller) than the data resolution, i.e. powerlaw_xy_res >= data_res.
powerlaw_h0 = 10 or from step 1	The height [km] at which the tropospheric net delays have approximately reduced to zero. By default this value is set to be 10 km. When running step 1 this value is automatically updated. This can also be a vector with a value for each interferogram.

powerlaw_alpha = 1.6 or from step 1	The power-law decay coefficient. By default this value is set to be 1.6. When running step 1 this value is automatically updated. This can also be a vector with a value for each interferogram.
powerlaw_DEM_corr = 'n'	For time-series interferograms the input phase used for the tropospheric estimation can be corrected for the DEM associated error (correlated with baseline). By default this is not done. It is not recommended to perform this correction when having less than 5 interferograms. Supported for StaMPS users only.

Tip: In case of memory issues, it might be worth checking if the "powerlaw_xy_res" resolution is set too low. All InSAR data is interpolated to a regular grid to perform filtering in the frequency domain. Depending on the size of your InSAR region this can become intensive. In regards to the next step, the area around your InSAR dataset will be mirrored by half the largest bandwidth.

Tip: If your study area is irregular shaped, there can be a better rotation angle than the heading to minimize the white space around the InSAR data.

8.4   Step 3: 1D and or 2D Fourier band filtering

At this stage the scaled topography and phase is filtered in different bands. By default, it is opted to perform a 2D Fourier band filter. However, in those cases where the percentage of the largest filter dimension with respect to the smallest dimension is bigger than 10%, then the filtering is switched automatically to a 1D Fourier filtering in the largest dimension only. The different spatial band filters are contained in 'powerlaw_spatial_bands'. It is advised not to make your spatial band filters much bigger than your maximum dimension, as this would introduce filtering effects. The data is mirrored to reduce edge effects, which also increased the memory need.

To run this step type:

>> aps_powerlaw(3,3)

Parameter and default value	Description

powerlaw_spatial_bands =
 	
[2000   4000
  4000   8000
  8000 16000
16000 32000
32000 64000
64000 128000];
	Spatial filter band given in meters as a two column matrix [lower_band higher_band]. It is recommended not to make you filter magnitude smaller that the twice the spatial resolution of the dataset (Nyquist frequency) and larger than the spatial extend of your dataset.

Tip: Do not make your band-filters smaller than two times the grid resolution (Nyquist principle). Make sure the band-filter is reasonable. i.e. do not make it larger than your InSAR region, as this will cause filtering effects to propagate in the APS estimation, and allow for some difference between the lower and higher extend of the band-filter.

8.5   Step 4: Computation of the tropospheric delays

In this step the tropospheric delays are estimated. This is done over multiple sub-windows (patches) in the spatial frequency bands you filtered before. Currently a mean is selected from the indicated frequency bands, so it is important to exclude those bands that are contaminated by other signals than the atmosphere.

In case you do not know which band is not contaminated, you can compare each estimated tropospheric band correction with a reference technique. Care should be given as the reference tropospheric correction method can have a different sensitivity to the tropospheric delay (e.g. topographically-correlated versus turbulent). By default the estimated delay for each individual band is stored (powerlaw_all_bands = 'y') in the variable tca_bands_sb2.mat or tca_bands2.mat. Once you have identified the band you want to keep you can replace update the original estimated powerlaw delay with that of your preferred band (band_number) using:

>> setparm_aps('powerlaw_kept', band_number)

For StaMPS users the comparison with a reference technique and the band updating is supported through step 5.

To estimate the delays type:

>> aps_powerlaw(4,4)

Parameter and default value	Description
powerlaw_h0 = 10 or from step 1	The height in km at which the tropospheric net delays have approximately reduced to zero. By default this value is set to be 10 km. When running step 1 this value is automatically updated. Do not modify this or one will need to re-run from step 2 onwards.
powerlaw_alpha = 1.6 or from step 1	The power-law decay coefficient. By default this value is set to be 1.6. When running step 1 this value is automatically updated. Do not modify this parameter or one will need to re-run from step 2 onwards.

powerlaw_spatial_bands =
 	
[2000   4000
  4000   8000
  8000 16000
16000 32000
32000 64000
64000 128000];
	Spatial filter band given in meters as a two column matrix [lower_band higher_band]. It is recommended not to make you filter magnitude smaller that the twice the spatial resolution of the dataset (Nyquist frequency) and larger than the spatial extend of your dataset. Do not modify this parameter, or one will need to re-run from step 3 onwards.

powerlaw_ridge_constraint = 'n'	When set to 'y' windows/ patches are defined based on mountain ridges. This flag supersedes the powerlaw_n_patches. i.e. when 'y' the windows defined in step 0 are used.
powerlaw_n_patches = 50	Number of patches using this value is adapted such approximately square patches are generated. When a single patch is preferred, put to 0. Note that this parameter is not used when powerlaw_ridge_constraint = 'y'.
patch_overlap = 50	Percentage of the patch overlap. Note that this parameter is not used when powerlaw_ridge_constraint = 'y'.

8.6   Step 5: Selection of the Power-law bands by comparing RMSE to another technique

Currently this step is only included for StaMPS. An example of the approach is contained in [Bekaert et al.,2015c]. When running step 5 the user will be prompt which technique he/she want to use as reference in the RMSE computation of the bands. The reference technique should be one of the techniques that have been processed before. Care needs to be taken when using original phase as input, as this will have a superposition of different signals. Also one should note that the power-law has a wet and hydrostatic component estimated. While often small, it is better to add a hydrostatic component to the spectrometer data to ensure that the same part of the tropospheric delay is being observed. An overview of the different components is contained in the introduction table.

To estimate this comparison type:

>> aps_powerlaw(5,5)

9 Spectrometer - MODIS correction

MODIS data (spectrometer) is acquired on the Aqua and Terra satellites, and can be used for the estimation of an atmospheric delay map for any platform, but limited to day-light conditions. The success rate of this is strongly depending on the daily cloud cover. The service used to download and mosaic the MODIS data is provided by JPL through the Online Services for Correcting Atmosphere in Radar (OSCAR). Only wet delay is provided when using spectrometer data.

The MODIS delay estimation is controlled by >> aps_modis, which runs all processing steps. Individual steps can be run by:

>> aps_modis(start_step,end_step)

Output is saved into a "tca2.mat" or "tca_sb2.mat" as the "ph_tropo_modis" and "ph_tropo_modis_no_interp" variables. The latter contains the non-interpolated but cloud masked MODIS delay estimates.

Note that the integrated water vapour conversion parameter estimation (step 1) is optional.

9.1 Downloading and cropping of MODIS data

The MODIS data is downloaded using the OSCAR service provided by JPL. Make sure the software is set-up accordingly. Data is provided free of charge. The service consists out MODIS granule identification covering your area, interpolated space and time of the MODIS data, and the cropping of the data.

To run this step type:

>> aps_modis(0,0)

The program will automatically set up the directory structure PATH/MODIS/ within this folder the YYYYMMDD/MODIS*.grd files. The following inputs control the download:

Parameter and default value	Description
modis_datapath	The full path to your MODIS processing folder.
region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the

	interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

9.2   Step 1: Spectrometer conversion parameter estimation from sounding data

This step is optional and is the same for both spectrometers (MERIS and MODIS). Unless already ran when using the MERIS correction, the default value is used for the PI-conversion factor. (Walters, et al., 2013) showed the sensitivity of these parameters not to be significant in affecting the estimated delay map. To run this step you will need to have the balloon sounding data downloaded. Information on how to do this is documented in Chapter 5.

The constants can be estimated by running:

>> aps_modis(1,1)

The PI_factor is appended to each ".mat" file of the sounding data, and the spectrometer_PIconversion is updated automatically in parameter list. You can either estimate it for each SAR date or use an average value.

Estimation option	Description of parameters controlling option
A mean coefficient for all interferograms (default option)	This method is not recommended for large sounding periods. It is recommended instead to have SAR date varying conversion factors.
Individual coefficients for each interferogram	Put 'sounding_ifg_dates' to 'y'. In total 15 days before and after the SAR date is used to compute the coefficient on each day. In case the actual day does not have a sounding, the mean over this period is used instead. In case this does not lead to an estimate, the average for all SAR dates is used to fill in the gaps.

The following parameters control the conversion factor estimation:

Parameter and default value	Description
sounding_dir = [pwd '/sounding_data']	Directory string where the sounding data is downloaded. Use full path.
sounding_time_stamp = ['00' ; '12']	The UTC acquisition times of the sounding data to be used into the computation. By default this is set to 00 and 12 UTC. Needs to be specified as a column vector string.
sounding_start_date = []	Start date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_end_date = []	End date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_errror_promp = 'n'	Crashes are suppressed (default). Instead error message are outputted and data is patched with NaN when set to 'n'.
'sounding_ifg_dates' = 'n'	By default conversion factors are estimated as the mean of the sounding period. Putting this flag to 'y' will allow to compute the conversion factor for each SAR date.

The time-series of coefficients is saved in the sounding directory within the spectrometer folder. The mean of the time-series coefficients is automatically set to be the new coefficient in aps parameter file.

9.3   Step 2: Computing the individual SAR delays

Next, an individual delay map is computed for each of the MODIS dates, by running

>> aps_modis (2,2)

When not existing a file "MODIS_batch_file.txt" is generated containing the full paths to the downloaded MODIS files. The first line of the file should read "files". All specified file are processed individually.

MODIS is know to overestimate Percipitable Water Vapour (PWV), this is accounted for through the calibration factor which is defined as PWV$_{calibrated}$ = calibration*PWV$_{MODIS}$. While this calibration factor varies in time, Li Z. et al. (2009) found an average bias of 0.95. Alternatively, MERIS has been validated without bias with respect to GPS estimates, and thus when having MERIS observations MODIS data can be calibrated with respect to MERIS [Bekaert et al., in prep]. To opt for this latter option, first continue with Chapter 11, and set the modis_recalibrated flag to 'y'.

Update the following input parameters to your region of interest using the setparm_aps function. Note that the DEM information will be required to be updated.

Parameter and default value	Description
modis_datapath	The full path to your MODIS processing folder.
spectrometer_PIconversion = 6.2 or from step 1	PI conversion [-] factor. Can be estimated from step 1.
region_res = 0.00833	The output resolution in degrees
region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region
modis_calibration=0.95	MODIS calibration factor. On average MODIS over-estimates by 5% (Z. Li et al., 2009). This value is ignored when using recalibrated MODIS data.
modis_recalibrated = 'n'	By default it is assumed that the data has not been re-calibrated with respect to MERIS. You can opt for this after completion of Chapter 11, and by setting this flag to 'y'. When 'y' the value of modis_calibration will be ignored and re-calibrated MODIS data will be used directly.

> **TIP:** When having problems, the first thing to check is that you have the files set-up correctly, i.e. in a data folder structure with a file name of the MODIS*YYYYMMDD.grd data. Next you can check if the DEM is loaded properly. You can check this by turning the fig_test flag to 1 in the aps_modis_SAR script. When running the script a plot of the resampled DEM will be made.

9.4   Step 3: Computing the MODIS tropospheric InSAR delays

Note that in the estimation of a SAR delay a exponential decay has been assumed for the pressure for estimating the dry component. For an interferometric delay this will cancel out when assuming identical ground pressures, reducing the estimated interferometric delay to a wet delay only. To compute the interferometric MODIS delay type:

>>   aps_modis(3,3)

The following parameters are used to calculate the interferometric phase delays

Parameter and default value	Description
meris_perc_coverage = 80	Percentage of points that need to have MODIS coverage (cloud free). In case this is not met the MODIS date is rejected.
lambda	The radar wavelength of the SAR satellite in m. This is used to convert the delay towards a phase delay. By default lambda is set to be 0,0562 m.
ll_matfile = [pwd 'll.mat']	Full file path of the geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude.
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

10 Spectrometer - MERIS correction (Envisat only)

Both the ASAR and spectrometer instrument, MERIS, have been operated simultaneous on-board Envisat, which allows for the estimation of an atmospheric delay map from the MERIS data for each specific descending (day-time) ASAR acquisition. However the success rate of this is strongly depending on the daily cloud cover. e.g. (Walters, et al., 2014). Only wet delay is provided when using spectrometer data.

The MERIS delay estimation is controlled by >> aps_meris, which runs all processing steps. Individual steps can be run by:

>> aps_meris(start_step,end_step)

Output is saved into a "tca2.mat" or "tca_sb2.mat" as the "ph_tropo_meris" and "ph_tropo_meris_no_interp" variables. The latter contains the non-interpolated but cloud masked MERIS delay estimates.

Below additional information is provided regarding the free MERIS data download, the projection to the WGS84 reference frame, the MERIS conversion parameter estimation using sounding data, the delay map computation for the different SAR acquisitions and as last the interferometric delay computation. Note that the MERIS conversion parameter estimation is optional.

10.1 Downloading of MERIS data

MERIS data "MER_RR_2P" can be obtained from ESA Earthnet Online website under the free-distributed ESA policy (https://earth.esa.int/web/guest/pi-community). A user id is required, which can be requested by contacting ESA. Next follow the information on how to download the data as send by email.

Alternatively, once you have received your password and user id to access the MERCI server, you can use the 'meris_download.ftp' script in the TRAIN bin folder to automatically download all the data. You will need to edit this script file and specify your user id, password, Envisat track number, and a link to a file containing the dates in YYYYMMDD format that need to be downloaded. As the SAR data is acquired simultaneous with the MERIS data, no UTC time stamp is required.

> ls -ld [1-2]* > MERIS_dates.txt

> vim $TRAIN_software/bin/meris_download_ftp   *(edit the file)*

> meris_download_ftp

10.2 Projecting the MERIS data to WGS 84

The MERIS data is provided in its image format with equal spaced points and needs to be re-projected to WGS 84. This is done here using the free Beam (VISAT) software from ESA (see section 3.2). You can either do it by hand or using the command line in batch process.

To re-project automatically from command line, make sure the bin of the Beam software is sourced such it finds the "gpt.sh" script. Next continue with the next section (setting up the directory structure) and turn the re-projection flag to 1. When doing so the whole track will be re-projected. See the tip section in case you want to project for a smaller subset.

To do the re-projection manually, load each MERIS data file, by opening it in beam. Re-project the data by going to "tools" tab > "Reprojection". Next change the projection to "Geographic Lat/Lon (WGS 84)" under the "reprojection parameters" tab. Make sure to change the save format to a "GeoTIFF". Note that re-projection filenames should be kept as default (e.g. MER_RR__2P*.N1_reprojected.tif).

10.3 Setting the directory structure

It is recommended to make symbolic links of your raw and re-projected data to avoid loss of data. Both the raw and re-projected data needs to be organised in a date structure as YYYYMMDD/MER_RR_2P*. When not done, all files should be placed in the same folder and the link_raw_meris script will set-up the structure prior to making the symbolic links. To run the script type:

> link_raw_meris Rawdata_PATH [Processing_PATH reprojection_flag date_file](optional)

With the Rawdata_PATH the full path to downloaded MERIS data, Processing_PATH the full path to your processing directory, reprojection_flag a flag set to 1 to auto re-project using beam command line, and date_file the path to a file containing the dates folders to be linked (specified as rows in YYYYMMDD format). The latter three are optional fields. It is recommended to set your Processing_PATH to a dedicated MERIS folder, which can be at the same level of your InSAR processing directory. For example PATH/MERIS/ within this folder the YYYYMMDD/MER_RR_2P* structure needs to be followed.

TIP: BEAM might give output that looks like an error message, but might not be. Easiest to see if the projection worked is to check the re-projected file sizes. In case the re-projection fails it could be that some extreme values at the edge of the projection is causing issues. You can re-projection locally over you study region by calling link_raw_meris with the reprojection_flag set to 2, which will call reproject_params_subset.xml instead of reproject_params.xml. Note you will need to edit POLYGON((LAT1 LON1, LAT2 LON2, LAT3 LON3, LAT4 LON4)), where LAT and LON are the corners of your study region, in:

> vim $APS_toolbox/scripts/reproject_params_subset.

10.4 Step 1: MERIS conversion parameter estimation from sounding data

This step is optional and is the same for both spectrometers (MERIS and MODIS). Unless already ran when using the MODIS correction, the default value is used for the PI-conversion factor. (Walters, et al., 2013) showed showed the sensitivity of these parameters not to be significant in affecting the estimated delay map. To run this step you will need to have the balloon sounding data downloaded. Information on how to do this is documented in Chapter 5.

The constants can be estimated by running:

>> aps_meris(1,1)

The PI_factor is appended to each ".mat" file of the sounding data, and the spectrometer_PIconversion is updated automatically in parameter list. You can either estimate it for each SAR date or use an average value.

Estimation option	Description of parameters controlling option
A mean coefficient for all interferograms (default option)	This method is not recommended for large sounding periods. It is recommended instead to have SAR date varying conversion factors.
Individual coefficients for each interferogram	Put 'sounding_ifg_dates' to 'y'. In total 15 days before and after the SAR date are used to compute the coefficient on each day. In case the actual day does not have a sounding, the mean over this period is used instead. In case this does not lead to an estimate, the average for all SAR dates is used to fill in the gaps.

The following parameters control the conversion factor estimation:

Parameter and default value	Description
sounding_dir = [pwd '/sounding_data']	Directory string where the sounding data is downloaded. Use full path.
sounding_time_stamp = ['00' ; '12']	The UTC acquisition times of the sounding data to be used into the computation. By default this is set to 00 and 12 UTC. Needs to be specified as a column vector string.

sounding_start_date = []	Start date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_end_date = []	End date of the sounding data to be used into the computation, specified as a string in 'yyyymmdd' format. Note, unlike for the sounding delay chapter, a date needs to be specified!
sounding_errror_promp = 'n'	Crashes are suppressed (default). Instead error message are outputted and data is patched with NaN when set to 'n'.
'sounding_ifg_dates' = 'n'	By default conversion factors are estimated as the mean of the sounding period. Putting this flag to 'y' will allow to compute the conversion factor for each SAR date.

The time-series of coefficients is saved in the sounding directory within the meris folder. The mean of the time-series coefficients is automatically set to be the new coefficient in aps parameter file.

10.5 Step 2: Computing the individual SAR delays

Next, an individual delay map is computed for each of the MERIS dates, by running

>> aps_meris (2,2)

When not existing a file "MERIS_batch_file.txt" is generated containing the full paths to the re-projected MERIS files. The first line of the file should read "files". All specified file are processed individually.

Update the following input parameters to your region of interest using the setparm_aps function.

Parameter and default value	Description
meris_datapath	The full path to your MERIS processing folder.
spectrometer_PIconversion = 6.2 or from step 1	PI conversion [-] factor. Can be estimated from step 1.
region_res = 0.00833	The output resolution in degrees

region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region

TIP: When having problems, the first thing to check is that you have the files set-up correctly, i.e. in a data folder structure with a file name of the meris data ending with _reprojected.tif. Next you can check if the dem is loaded properly. You can check this by turning the fig_test flag to 1 in the aps_meris_SAR script. When running the script a plot of the resampled dem will be made.

10.6 Step 3: Computing the MERIS tropospheric InSAR delays

Note that in the estimation of a SAR delay a exponential decay has been assumed for the pressure for estimating the dry component. For an interferometric delay this will cancel out when assuming identical ground pressures, reducing the estimated interferometric delay to a wet delay only. To compute the interferometric MERIS delay type:

>> aps_meris(3,3)

The following parameters are used to calculate the interferometric phase delays

Parameter and default value	Description
meris_perc_coverage = 80	Percentage of points that need to have MERIS coverage (cloud free). In case this is not met the MERIS date is rejected.
lambda	The radar wavelength of the SAR satellite in m. This is used to convert the delay towards a phase delay. By default lambda is set to be 0,0562 m.

ll_matfile = [pwd 'll.mat']	Full file path of the geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude.
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

11 Spectrometer - MODIS PWV calibration

MODIS on average over-estimates Precipitable Water Vapour (PWV). There is some variation around this calibration factor. In Bekaert et al. (In prep) we investigated into this variation. On average confirmed the 5% over-estimation, but also found variations up to 15%. This chapter describes how to re-calibrate the MODIS PWV with respect to that of MERIS, when both data sources are available. This can be done by typing:

>> aps_spectrometer_PVW_comparison(start_step,end_step)

Where start_step and end_step describes the start and end step of the processing.

11.1 Load and save PWV of MODIS and MERIS

In step 1 the PWV of both MODIS and MERIS is loaded, masked for clouds and stored again. Depending if you downloaded the whole track this can take some processing time. This step only needs to be done once.

>> aps_spectrometer_PVW_comparison(1,1)

11.2 Computation of the MODIS PWV re-calibration factors

Step 2 does the actual estimation of the calibration factor between MERIS and MODIS as $PWV_{calibrated}$ = calibration$*PWV_{MODIS}$ +PWV_0. This is done by estimating a linear relation. A correlation threshold and a 10% minimal percentage of mutual pixels is used as a quantitive measure to decide if the estimate should be kept or not. Those SAR dates missing data for either MERIS or MODIS are patched with the mean estimated value. All this information and flags are outputted to the screen and stored in the MODIS data directory.

>> aps_spectrometer_PVW_comparison(2,2)

11.3 Re-calibrate MODIS PWV data

Step 3 does the calbibration of the MODIS PWV and writes new files with the suffix "_recalibrated" in the MODIS data directory. At the end you can set modis_recalibrated to 'y' and compute the delays for the recalibrated data by running Chapter 9.

>> aps_spectrometer_PVW_comparison(3,3)

12 Weather model - ERA-I/MERRA/MERRA-2 corrections

The weather model corrections are controlled by aps_weather_model, where model_type is a string with one of the available models: 'era', 'merra', or 'merra2':

>> aps_weather_model(model_type,start_step,end_step)

The start_step and end_step control the weather model delay computation steps. After completion the final output is saved into a "tca2.mat" or "tcasb2.mat" file as a "ph_tropo_model_type" variable.

The following parameters are specific depending on the model_type, and are used in all the following steps. You can modify them using the setparm_aps function

Parameter and default value	Description
era_datapath = []	The full path to your ERA-I processing folder.
era_data_type = 'ECMWF'	The data website that will be used to download the ECMWF data. By default this is set to ECMWF, alternatively set to BADC.
merra_datapath = []	The full path to your MERRA/MERRA2 processing folder.

Discontinued MERRA model: the merra model has been discontinued since February 2016, and replaced with merra2. The merra2 model covers the complete historic period of merra. Therefore, it is recommended to user MERRA-2 model.

Free access to MERRA and MERRA2: Both the MERRA and MERRA-2 model are available without any data account from NASA Goddard Space Flight Center.

Access to ERA-I model: For ECMWF an account is needed (https://apps.ecmwf.int/auth/login/ both GRIP and netcdf files support included). If you use the automatic download you need to python and the ECMWF API, see software's. Also BADC (http://badc.nerc.ac.uk/home/) support is included (netcdf) for which an account is needed as well.

Model background:
- ERA-Interim by ECMWF, outputted at 00, 06, 12 & 18 UTC with a 2-month lag.
- MERRA/MERRA-2 by NASA Goddard, outputted at 00, 06, 12 & 18 UTC, with a 5-week lag.

12.1 Step 0: Overview of required weather model data files

This step is optional and provides an overview the files which need to be downloaded. Run in the InSAR directory

>> aps_weather_model(model_type,0,0)

This will generate a file "model_type_files.txt". The parameters used in this function are:

Parameter and default value	Description
UTC_sat = ['HH:MM']	The UTC time of the satellite pass over your study area. It is specified as a string in a two digit hour and two digit minute format. A colon needs to be included in between!
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

12.2 Step 1: Download of weather model data

In this step the weather model data is downloaded. A data selection will be made depending on your area of interest. Note, a different approach needed for the ERA-I BADC option (see section below).

>> aps_weather_model(model_type,1,1)

The following parameters control this step:

Parameter and default value	Description
region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region
UTC_sat = ['HH:MM']	The UTC time of the satellite pass over your study area. It is specified as a string in a two digit hour and two digit minute format "HH:MM". A colon needs to be included in between!

12.2.1 ERA-I using BADC option

To download the BADC data to your current location type:

> get_ecmwf password username file_list

Where you replace password with your password, username with your BADC username and file_list with the full path to the file containing the files to be downloaded.

Manual downloading of data: Alternatively, the user can download the data manually. Note that the APS toolbox assumes a fixed format.

- ERA-I: ggapYYYYMMDDHHMM.nc stored in YYYYMMDD folders at era_datapath.
- MERRA: MERRA_YYYYMMDD_HH.hdf stored in YYYYMMDD folder at merra_datapath.
- MERRA2: MERRA2_YYYYMMDD_HH.nc4 stored in YYYYMMDD folder at merra_datapath.

12.3 Step 2: Computing individual SAR delays (zenith)

In this step the zenith tropospheric dry and wet delays are computed for each of the SAR dates:

>> aps_weather_model(model_type,2,2)

The following input parameters are used

Parameter and default value	Description
UTC_sat = ['HH:MM']	The UTC time of the satellite pass over your study area. It is specified as a string in a two digit hour and two digit minute format. A colon needs to be included in between!
demfile = [pwd 'dummy.dem'] or = [pwd 'dummy.grd']	The path to the DEM_file. Few options are included: 1) using a ".grd" file, 2) a DEM_file with corresponding DEM_file.rsc file. For option 2 the DEM_file.rsc should contain the associated WIDTH, LENGTH, X_STEP (resolution), Y_STEP(-1*resolution), X_FIRST and Y_FIRST (upper left corner of the DEM), and optional the FORMAT. X and Y refer to longitude and latitude. You can use construct_dem.sh to make you DEM file.
region_res = 0.00833	The output resolution in degrees
region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region

12.4 Step 3: Computing tropospheric InSAR delays

To compute the interferometric weather model delays type:

>> aps_weather_model(model_type,3,3)

The following parameters are used to calculate the interferometric phase delays. Make sure the default values are updated to your region.

Parameter and default value	Description
lambda = 0.0562	The radar wavelength of the SAR satellite in m. This is used to convert the delay towards a phase delay. By default lambda is set to be 0,0562 m.
ll_matfile = [pwd 'll.mat']	Full file path of the geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude.
look_angle = 21/180*pi or path to file	The look angle [rad] used in the projection to the line of sight. By default this is set to 21 degrees. Alternative a file can be specified in which the look angle for each pixel or PS can be given. This needs to be a column vector of size [n_points 1] with the angle in [rad] saved as "la" variable.
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

13 Weather model - Weather Research and Forecasting model

This part of the toolbox gives support to run and compute the delays using the Weather Research and Forecast (WRF) model. Currently only support scripts are included using Global Forecast System (GFS) input data. An account (free) is required in order to download the GFS data from CISL Research data Archive (http://rda.ucar.edu/datasets/ds335.0/#!description).

13.1 Required files and generation of the WPS and WRF input files

Once the path has been set-up. Step 0 can be run in order to get a list of the required files. Simultaneous input files are generated for the WPS and WRF software. For these input files the domains need to be set-up. To do so edit the top lines of the aps_wrf_files.m function, by typing:

>> edit aps_wrf_files.m

> **TIP:** The set-up of the domains is specific to your own application. aps_wrf_files.m contains an example for a larger (100*500 km) and smaller (100*100 km) InSAR area, which are both nested to a spatial resolution of 5 km. You can use this example set-up over you study region by changing "stand_lon" and "ref_lon" to the centre longitude of your study regions, and "ref_lat" to the centre latitude of your region. Next you can decide for the large or smaller WRF domain set-up. If decided for the smaller area, comment the 4 lines of code after "% larger 500 km track".

Next run:

>> aps_wrf(0,0)

Update the following input parameters to your region of interest using the setparm_aps function.

Parameter and default value	Description
wrf_datapath = []	The full path to your WRF processing/data folder.
UTC_sat = ['HH:MM']	The UTC time of the satellite pass over your study area. It is specified as a string in a two digit hour and two digit minute format "HH:MM". A colon needs to be included in between!

ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

WPS and WRF input files will be generated such that the model has at least a 12 hr spin-up time, based on a 6 hr interval renewal of the nested boundaries, and output the weather model simulation at the time of the SAR acquisition. The domain information is set automatically as well as the required outputs needed to computed the tropospheric delays.

13.2 Downloading the CFSR and GFS data and directory set-up

Once the CFSR and/or GFS lists with the required files have been generated, the files can be downloaded automatically from the CISL website to your current folder. You will need to have an account generated with CISL at https://rda.ucar.edu/index.html?hash=data_user&action=register. As no GFS data exist prior to 1 November 2006, all SAR dates before this date will use CFSR data to run WRF. To download the GFS file type on the command line:

> cd wrf_datapath

> get_GFS.csh passwd email filelist

Where you replace wrf_datapath with the path of your wrf data, passwd with your password, email with your email address and filelist with the full path to GFS_files.txt.

Similar, you can download the CFSR data using:

> get_CFSR.csh passwd email filelist

Where filelist now is the full path to CFSR_files.txt.

After download has been completed, the downloaded files can be organised in the date folder structure YYYYMMDD by running in your InSAR directory:

>> aps_wrf(0.1,0.1)

13.3 Running of the WRF software

Once all the data has been downloaded and the directory structure has been set-up the WRF software can be run for all the different SAR dates by executing:

> wrf_runfile datelist

Where datelist is the path to a file containing all the date folders (YYYYMMDD format) to be processed. Within the wrf_runfile also additional input needs to be modified including the WRF data_dir and the path to the WPS software. This can be done by typing:

> vim $APS_toolbox/bin/wrf_runfile

13.4 Step 1: Computing individual SAR delays (zenith)

In this step the zenith tropospheric dry and wet delays are computed for each of the SAR dates by running

>> aps_wrf(1,1)

Update the following input parameters to your region of interest using the setparm_aps function. Note that the DEM information will be required to be updated.

Parameter and default value	Description
demfile = [pwd 'dummy.dem'] or = [pwd 'dummy.grd']	The path to the DEM_file. Few options are included: 1) using a ".grd" file, 2) a DEM_file with corresponding DEM_file.rsc file. For option 2 the DEM_file.rsc should contain the associated WIDTH, LENGTH, X_STEP (resolution), Y_STEP(-1*resolution), X_FIRST and Y_FIRST (upper left corner of the DEM), and optional the FORMAT. X and Y refer to longitude and latitude. You can use construct_dem.sh to make you DEM file.
region_res = 0.00833	The output resolution in degrees
region_lon_range = []	The longitude crop in degrees. Make this slightly bigger than your InSAR region
region_lat_range =[]	The latitude crop in degrees. Make this slightly bigger than your InSAR region

13.5 Step 2: Computing the WRF tropospheric InSAR delays

To compute the interferometric WRF delays type:

>> aps_wrf(2,2)

The following parameters are used to calculate the interferometric phase delays. Make sure the default values are updated to your region.

Parameter and default value	Description
lambda = 0.0562	The radar wavelength of the SAR satellite in m. This is used to convert the delay towards a phase delay. By default lambda is set to be 0,0562 m.
ll_matfile = [pwd 'll.mat']	Full file path of the geo-coordinates, stored in a matrix with size [n_points 2] and in its columns the longitude and latitude.
look_angle = 21/180*pi or path to file	The look angle [rad] used in the projection to the line of sight. By default this is set to 21 degrees. Alternative a file can be specified in which the look angle for each pixel or PS can be given. This needs to be a column vector of size [n_points 1] with the angle in [rad] saved as "la" variable..
ifgday_matfile = [pwd 'ifgday.mat']	Full file path to the mat file containing the interferogram dates stored as a matrix with name ifgday and size [n_ifgs 2]. The master image is in the first and slave in the second column respectively. Specify dates a numeric value in YYYYMMDD format.

14 Plotting results

Results can be plotted in StaMPS using the conventional ps_plot function. In case the data has not been processed in StaMPS one can load the tropospheric corrections from the tca_sb2.mat or tca2.mat files, and plot you own plotting tools. The data is stored in the same format as the definition of the input interferogram, i.e. as a matrix with an interferogram in each column.

14.1 StaMPS plotting

> **NOTE**: The current version of StaMPS does not include the latest support for the TRAIN toolbox. A patch is provided online, which will allow users to use the plotting options provided below.
>
> **NOTE**: In future there will be an update towards the stamps plotting routine to allow support for different atmospheric correction methods which have a similar short notation. Short notation will be replaced with full name of methods: e.g. 'a_m' will be replaced with 'a_meris' and 'a_merra' etc.

To plot only atmosphere, the same convention is used as for the phase, where 'a' refers to single master, and 'asb' to small baselines. In addition, you will need to specify the correction method. Depending on the chosen processing type use for the following different correction techniques:

'a_e', 'a_w'	wet+hydro of ERA, WRF
'a_eh', 'a_wh'	hydro of ERA, WRF
'a_ew', 'a_ww'	wet of ERA, WRF

'a_l'	wet+hydro of linear
'a_p'	wet+hydro of powerlaw
'a_m', 'a_M'	wet of MERIS, MODIS

Examples for the hydrostatic WRF delays for small baselines and single master respectively:

>> ps_plot('asb','a_wh',2)   >> ps_plot('asb','a_wh',2)

The location of the processing type (e.g. 'a_wh') does not matter with respect to the other input arguments of ps_plot. The other ps_plot flag remain valid, e.g. following is identical as above:

>> ps_plot('asb',2,0,'a_wh')   >> ps_plot('asb',2,0,'a_wh')

In StaMPS you can conventionally remove DEM errors, master atmosphere, and ramps by adding respectively 'd', 'm', and 'o' as a minus argument to the phase 'u' and 'usb', or the velocity 'v' and 'V'. Likewise, you can do the same for the tropospheric signal as estimated using TRAIN, by stating 'a' as a minus argument. Examples for the WRF delay removed from the velocity.

>> ps_plot('v-da','a_w')   >> ps_plot('v-dao','a_w')   for help >> help ps_plot

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15 Version changes

15.1 Version 1beta: released version

- Initial version of the toolbox
- Updates to the initial chapters add info on installation
- Significant updating on the MERIS and power law chapters. MERIS codes have been updated to be included on the toolbox.
- Incorporate ERA-I correction technique
- Incorporate processing structure different from StaMPS for MERIS and ERA-I. ERA-I script adapted from Richard Walters.
- Incorporate WRF processing functionality
- Include submissions by Hannes Bathke to include ERA-I ECMWF website data support. This includes file generation, fetching data and data reading.
- Expand the manual and clean it up. Incorporate more compatibility with non-stamps processing. Include ridges based approach for power-law.
- Include MODIS tropospheric correction. This is based on the JPL OSCAR service for downloading and cropping of MODIS data.
- Include varying conversion factors for each SAR date for the spectrometer options. Re-name variables to be more generic for spectrometers.
- Expand the StaMPS plotting chapter with examples and options.

15.2 Version 1: released version

- Fix errors in the manual
- Expand manual: include WRF software installation,
- Add missing scripts: local2llh.m
- Include support from the OSCAR online retrieval, allows for *.grd files in aps_modis
- Bug fixes: aps_wrf calls non existing function
- Include ftp download for MERIS data and local re-projection to WGS84
- Remove hydrostatic computation with scale height from spectrometer methods.

15.3 Version 2beta: released version

- Including powerlaw-band comparison with a reference technique (MERIS, ERA-I, WRF, unwrapped phase).
- Include the option to re-calibrate the MODIS PWV wrt MERIS PWV.
- Add chapter on PWV recalibration in manual.
- Include powerlaw ridge approach
- Include powerlaw and linear method support for varying interferogram pixel selection
- Isolate DEM loading module.

- Auto-format recognition for DEM, adapted from Hua Wang contribution
- Include ".grd" file support for DEM
- Matlab multi-core support included for WRF and weather models.
- Plotting of sounding sensitivity for spectrometer and powerlaw method.
- Add more tip and tricks based on issues on TRAIN forum
- Integrate all weather model approaches together into modular approach
- Include MERRA and MERRA2 weather model support with automatic download and integration into the weather model routine
- Automated error catching.
- Attempt to autocorrect issues for GMT usage of MAC and Linux users
- Update manual on weather model correction routine
- aps_erra.m, aps_era_sar.m and aps_era_insar are discontinued and integrated in aps_weather_model.m module.
- Incorporate function which patches no-date pixels for weather models.
- Redefine hydrostatic delay based on surface pressure for aps_wrf and aps_weather_model functions.