Practical Exercise:

Glacier Surface Elevation Change and Mass Balance by means of InSAR-DEM Differencing

Prepared by Helmut Rott & Stefan Scheiblauer, ENVEO IT, Innsbruck, Austria

Geodetic Method for Retrieving Glacier Volume Change and Mass Balance:

DEM differencing is a powerful method for measuring surface elevation change of glaciers and ice sheets. The change of glacier surface topography (dh/dt) over a time interval is computed by differencing DEMs acquired on different dates (Cogley, 2009). The annual mass balance of a glacier is an essential climate parameter, so that the preferred time spans for DEM differencing are annual or multi-annual time intervals. For converting volume change into mass change, an estimate for density of the added or depleted volume is needed. The resulting change of ice mass in time (the total net mass balance B_n) is:

$$B_n(\Delta t) = \int_S \rho \Delta h(s) dS$$

Δh is the change in surface height during the time interval Δt. S is the glacier area. The density ρ refers to the mean density of the snow or ice column. It needs to account for changes in the vertical density profile over Δt. If a density profile does not change in time, the density of ice can be used.

Single-pass interferometry for surface topography:

Single pass interferometry (SP-InSAR) offers excellent capabilities for precise mapping of surface topography and elevation change: SP-InSAR is not affected by temporal decorrelation (a problem for repeat-pass SAR over snow and ice) and does not require any surface features (a problem for optical sensors in glacier accumulation areas).

There are specific issues to be considered for generating InSAR DEMs and performing DEM differencing over ice bodies:

Radar imaging geometry: Radar shadow and InSAR phase ambiguities on steep slopes perpendicular to radar line-of-sight (LOS) due to layer and foreshortening. These slopes need to be masked out.

Radar signal penetration: The SAR derived elevation refers to the position of the scattering phase centre in the snow and ice volume. In X-band the penetration bias in dry snow and firn may be up to a few metres. For wet snow the X-band SAR return signal is reflected from the surface. For DEM differencing the impact of changes in radar penetration can be minimized by using data from acquisition dates of the same season and with the same snow and ice conditions. This can be checked by comparing the backscatter signatures. Furthermore, it is recommended to use DEMs generated for SAR data of similar observation geometry (same look angle), so that the refraction into the snow volume is similar. If these requirements are fulfilled very high accuracy can be achieved for surface elevation change on glaciers (SEC). (See comparison of TanDEM-X and NASA IceBridge airborne lidar SEC in Rott et al., 2018).

Study Site:

Drygalski Glacier, Antarctic Peninsula

The Larsen A Ice Shelf in front of Drygalski Glacier disintegrated in January 1995 (Rott et al., 1996). This triggered near-immediate acceleration of the outlet glaciers previously feeding the ice shelves, resulting in major mass losses due to increased ice discharge which is still going on (Rott et al., 2002; Rott et al., 2014; 2018). SEC is dominated by dynamic downwasting; the losses by surface melt are insignificant.

References:

Cogley, J.G. 2009. Geodetic and direct mass-balance measurements: comparison and joint analysis. Ann. Glaciol., 50, 96-100.

Cook, A. J., Murray, T., Luckman, A., Vaughan, D. G., and Barrand, N. E. 2012. A new 100-m digital elevation model of the Antarctic Peninsula derived from ASTER Global DEM: Methods and accuracy assessment, Earth Syst. Sci. Data, 4, 129–142, doi:10.5194/essd-4-129-2012.

Rott, H., Skvarca, P., and Nagler, T. 1996. Rapid collapse of Northern Larsen Ice Shelf, Antarctica, Science, 271, 788–792.

Rott, H., Rack, W., Skvarca, P., and De Angelis, H. 2002: Northern Larsen Ice Shelf, Antarctica: Further retreat after collapse, Ann. Glaciol., 34, 277– 282.

Rott, H., Floricioiu, D., Wuite, J., Scheiblauer, S., Nagler, T., and Kern, M. 2014. Mass changes of outlet glaciers along the Nordensjköld Coast, northern Antarctic Peninsula, based on TanDEM-X satellite measurements, Geophys. Res. Lett., 41, doi:10.1002/2014GL061613, 2014.

Rott, H., Abdel Jaber, W., Wuite, J., Scheiblauer, S., Floricioiu, D., et al. 2018. Changing pattern of ice flow and mass balance for glaciers discharging into the Larsen A and B embayments, Antarctic Peninsula, 2011 to 2016. The Cryosphere, 12,1273-1291, https://doi.org/10.5194/tc-12-1273-2018.

Main tasks:

- Getting acquainted with specific features of the SAR data and InSAR DEMs
- Generating a map of surface elevation change (SEC) of Drygalski Glacier by differencing single-pass InSAR DEMs
- Accounting / correcting for effects of SAR imaging geometry and phase noise
- Deriving SEC and mass balance of the glacier and analysing the elevation dependence of these parameters.

Input Data

TanDEM-X based geocoded products

The DEM files and associated SAR products include a sub-section (covering Drygalski Glacier) of larger DEMs. The surface elevation refers to the ellipsoid. Use for display in QGIS: "*Antarctic Polar Stereographic (EPSG:3031)*"

Specifications of SAR CoSSC images used for DEM production:

Date: 20-06-2013: HoA = -56.7 m; inc. angle = 40.6 deg.

Date: 27-07-2016: HoA = -29.1 m; inc. angle = 40.6 deg.

- ***TanDEM-X Raw DEMs from 20 June 2013 and 27 July 2016***
  - tdm0_w061d70s63d77_33358_20130620T082327_004_DEM.tif
  - tdm0_w061d69s63d78_50559_20160727T082344_004_DEM.tif

The Raw DEMs were processed and co-registered with the DLR Integrated TanDEM-X Processor (ITP) (W. Abdel Jaber, DLR Remote Sensing Technology Institute). The global TanDEM-X DEM was used as background for supporting phase unwrapping and the absolute phase estimation of the Raw DEMs. DEM pixels size 12 m x 12 m.

- ***SAR Backscatter Images*** (calibrated σ°hh in dB)
  - tdm0_w061d70s63d77_33358_20130620T082327_004_BKS
  - tdm0_w061d69s63d78_50559_20160727T082344_004_BKS

- ***SAR Coherence Images***
  Normalized coherence ($0 \leq \gamma \leq 1$) scaled to 8 bit (0 to 255)
  - tdm0_w061d70s63d77_33358_20130620T082327_004_COH
  - tdm0_w061d69s63d78_50559_20160727T082344_004_COH

<u>Auxiliary Data</u>

- **Landsat image**
  Landsat-8, 19 March 2016, band 3, 4, 5 (true colour)
  - LC08_L1GT_217105_20160319_LarsenTrue_Color
- ***Glacier outline***
  - G298872E64662S_DrygalskiGlacier (shape file)
- ***Background DEM***
  - AP100DEM_Drygalski.tif

  This is a sub-section of the ASTER-based Antarctic Peninsula DEM, 100 m grid-size, produced by Cook et al. (2012). This DEM is used for generating the mask of elevation zones. Recently the TanDEM-X global DEM at 90 m grid size became freely available.
- ***Flag Mask for Phase Noise and Layover***
  - Flag_Mask_SEC_processing.tif

  This is a geocoded mask (raster file) indicating where shadow and layover regions are located, as well as areas with phase-unwrapping problems. This information is based on analysis of radar LOS vs. the reference DEM. The mask provided for the exerciseis derived from the FLM product (output of the ITP) which provides detailed quality indicators on product generation and phase unwrapping. We merged the different layers of the FLM file into a binary layer and applied a low-pass filter.
- ***Outlines of 50 m elevation zones***
  - G298872E64662S_DrygalskiGlacier_ElevationBands50m (shape file)

  The file contains the boundaries of the elevation zones in 50 m steps: 0 up to ≤+50 m above sea level, >50 m up to ≤100 m.. etc. ...., >2000 m up to ≤2050 m.

<u>TanDEM-X Interferograms in SAR Geometry</u>

Interferograms (colour coded images of the topographic phase, cyclic in 2π; here shown as quick-looks) are intermediate products before phase unwrapping, geocoding and conversion of interferometric phase into absolute height. The flat Earth phase has been subtracted. These processing steps have been performed at DLR with the ITP. In this exercise the interferograms are included for visualization and for checking potential problem areas (mainly on fore-slopes) which need to be masked out in the DEMs.

- PHASE_flat_Earth_20160620.png
- PHASE_flat_Earth_20160727.png

<u>Workflow:</u>

Tool for data analysis and visualisation: **QGIS version 2.10 or later** (https://www.qgis.org). The extension Zonal statistics plugin is required. For a quick check of the data the Value Tool extension and the Profile tool extension are helpful. For 3D rendering use the plug in Qgis2threejs.

Task 1: Get acquainted with the study area in optical and SAR imagery; check backscatter signatures

1.1 Try to identify characteristic glacier zones and their relation to topography in the optical satellite image; e.g. ice plateau, escarpment (steep ice and rocks cliffs), nunataks, main glacier terminus, calving front.

QGIS: Load and display Landsat image (raster layer) and glacier outlines (shape file, vector layer) *Tool: "Add Layer".*

Zoom into the Drygalski Glacier area.

Add the background DEM (raster layer) and check typical altitudes of different glacier sections. "*Value Tool*"

1.2 Check characteristic backscatter coefficients (σ°) for different glacier sections and try to explain reasons for striking differences in various glacier zones (hint: σ° in dry snow and firn is mainly driven by volume scattering properties). Try to find out the direction of radar illumination (line-of-sight). Slopes close to specular reflection show high backscatter.

QGIS: Load and display the two backscatter images (raster layer) in a new project. Check numerical values of σ° at different locations. "*Value Tool*"

1.3 Check for agreement/differences in σ° of the two dates. This is of relevance for assessing the possibility of shifts in the scattering phase centre which may cause biases in retrieving elevation change. This is also relevant for estimating uncertainty of SEC.

QGIS: Subtract one backscatter image from the other and store the result in new layer. Display the new layer. *Tool: "Raster calculator"*. Use the "*Value Tool*" for checking Δσ° values.

Task 2: Derive a map of surface elevation change (SEC) by differencing the TanDEM DEMs. Browse for SEC over various locations in the map in order to get some insight into the magnitude of changes.

2.1 Load the two TDM DEMs. Use the Tool *"Raster calculator":* Specify a new output layer (e.g. SEC_M20160727_SL20130620) subtract the DEM of 20130620 from the DEM of 20160727 (*Tool: "Raster calculator")* The results are stored in the output layer.

2.2 Display and enhance the SEC map.

QGIS: Add glacier outlines (shape file, vector layer) and DEM (raster layer) in order to support the interpretation. Enhance the grey scale of the SEC map for visualisation.

2.3 Browse the SEC map, display elevation data along profiles.

QGIS: Use "Value tool" for checking SEC data at various points and the tool "Terrain Profile" for extracting and displaying SEC along lines selected with the cursor.

Task 3: Check potential areas with interferometric phase uncertainties and phase noise in the quick look interferograms. Load the SEC map and the Flag Mask and compute the final SEC map.

3.1 Load and display the two topographic interferograms (quick-looks) using an image graphic tool. Zoom into the Drygalski area. Try to localize (visually) areas with phase noise and possible phase discontinuities. Explain the different spacing of fringes between the two interferograms.

3.2 Load and visualize the SEC map and the Flag Mask. The areas with flagged "1" will be used for final SEC analysis over the glacier. SEC data of the areas with flag "0" (mostly locate on steep slopes) will not be used. Compute the final SEC map.

QGIS: Load the SEC map and the Flag_Mask_SEC (raster). Use the Tool *"Raster calculator"* for computing the final SEC map. Specify a new output layer (e.g. SEC_M20160727_SL20130620_final) and multiply the SEC map with the Flag Mask. In the new SEC map the areas flagged out get the label "NaN".

Task 4: Derive mean annual rates of SEC, volume change and net mass balance for the elevation zones and the total glacier. Export the numerical values for computations and for graphical visualisation.

4.1 Retrieve the SEC and volume change for the elevation zones, store the numerical values, and export the data.

QGIS: Load the *final* SEC map and the outlines of the elevation zones (shape file). Use the Raster tool "*Zonal statistics*" for extracting the mean SEC per elevation zone. For computing the volume change open the "*Attribute Table*" of the shape file (accessible at right click of layer).

Input selection for Zonal Statistics

- Raster layer: *final* SECmap specify "file-name"
- Polygon layer: G298872E64662S_DrygalskiGlacier_ElevationBands50m
- Statistics to calculate: count, mean, standard deviation, max, min

Open the Attribute Table to check the file. Clic the polygon layer, select "*Save as* " with format **csv** and disable **"**add saved file to map**"** in order to get the table in txt format.

4.2 Compute the total volume change and mass balance (annual rates) for Drygalski Glacier (e.g. importing csv file into excel). Multiply the count (Nr. of pixels) with pixel size 12 m x 12 m and the mean elevation to get the volume change per elevation zone (m^3). Compute the total volume change (sum of elevation zones) and compute the annular rate of volume change (km^3/yr) (total time span 1133 days, 3.10 years).

Compute the mean annual SEC for the total glacier basin (dividing the volume change by basin area: 998 km^2 in 2016). It can be assumed that the mean surface elevation of the areas flagged out is stable because these areas are located on ice and rock cliffs that are not affected by dynamic downwasting (zero SEC on steep slopes). Generate a diagram on elevation dependence of SEC and speculate about the driving mechanisms for the elevation dependence of mass depletion.