C. Offset tracking

With offset tracking the registration offsets of two SAR images in both slant-range (i.e. in the line-of-sight of the satellite) and azimuth (i.e. along the orbit of the satellite) directions are generated. Applications requiring offset information can be classed into those that require only a global offset function, such as interferometry, multitemporal studies, and change detection, and those that require localized individual measurements, such as radar stereo and deformation mapping. Here we describe the use of offset-tracking for the estimation of surface displacement.

The offset fields are generated with a normalized cross-correlation of image patches of detected real-valued SAR intensity images. The location of the peak of the two-dimensional cross-correlation function yields the image offset. The successful estimation of the local image offsets depends on the presence of nearly identical features in the two SAR images at the scale of the employed patches. If coherence is retained the speckle pattern of the two images is correlated and tracking with small image patches can be performed to remarkable accuracy. In order to increase the estimation accuracy, oversampling rates are applied to the image patches and a two-dimensional regression fit to model the correlation function around the peak is determined with interpolation. The confidence level of each offset is estimated by comparing the height of the correlation peak relative to the average level of the correlation function to determine an effective cross-correlation value for the patch. Coarse information on the slant-range and azimuth offsets is used to guide the search of the cross-correlation maximum. The estimated offsets are unambiguous values, which means that there is no need for phase unwrapping.

The image offsets in the slant-range and azimuth directions are related, in the absence of stereo offsets due to substantial topography and large orbit separation, to the different satellite orbit configurations of the two SAR images, the displacement occurring between the acquisition time interval of the image pair, and potential ionospheric effects. The estimation of surface motion requires the separation of these effects. The orbital offsets are determined \by fitting a bilinear polynomial function to offset fields computed globally from the SAR images assuming no displacement for most parts of the image. Detected ionospheric streaks on the azimuth offset maps may be high-pass filtered along the range direction.

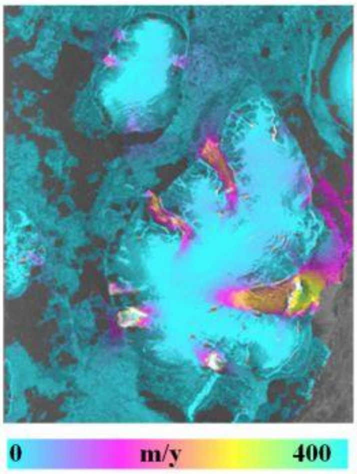

Figure C1. Horizontal displacement for Wilczek Land in Franz-Josef Land from JERS offset tracking between SAR images of January 6 and February 19, 1998 with a perpendicular baseline of 190 m. Image width is ~80 km.

Offset tracking consists of three processing steps

- Determination of the bilinear polynomial function
- Precise estimation of the offsets
- Computation of the displacement

The first step in offset tracking is the determination of the orbital offset between the two SLC images. The offset can be determined either by cross correlation of the real valued image intensity or by optimization of the fringe visibility globally from the SAR data assuming no displacement for large parts of the image. Polynomial coefficients for offsets in both range and azimuth direction over the whole image are determined.

Once the bilinear polynomial function is determined, many offsets are estimated in the area of interest. Recent developments were mainly dedicated to the image intensity cross-correlation algorithm, but the fringe visibility approach may be also applied. The bilinear polynomial function serves as indication for the positions where to precisely estimate the offsets. Typical size of the patch for offsets estimation is 64 x 256 SLC pixels, roughly corresponding to 1 km in ground range and azimuth with ERS or JERS SAR data.

The offsets estimated in range and azimuth direction are then transformed to displacements. The bilinear polynomial function determined all over the image is used for the separation of the orbital offsets from those of the area concerned with displacement. The displacement in the SAR geometry may be expressed in the range-azimuth or in the ground range-azimuth coordinate systems. Geocoding of the results is performed with the DIFF&GEO software module.

Below a processing example for measuring from the offsets the displacements of a glacier is given. For the processing two SLC images and the corresponding ISP SLC parameter files are needed. The ISP SLC parameter file can be obtained as described in Section 3. For a practical example see Example A, Sections 1 and 2. In this example we will use two images acquired by PALSAR on 20061206 and 20070211 separated by 46 days over a glacier on the island of Novaya Zemlya, Russia. The images are in SLC format and represent a subset of the original SLCs which have been obtained through JAXA's AO P1750001. For processing the image acquired on 20061206 will be used as reference. The dates of acquisition will be used as file identifiers. For self-processing the two SLCs and the corresponding ISP SLC parameter files have been provided on the DEMO CD-ROM.

C.1. Determination of the bilinear polynomial function

To compute the offsets between SLC, the first step consists of creating the ISP processing/offset parameter file using the program ***create_offset***. This file contains information used in the interferometric processing, such as file dimensions, geometric parameters, and the registration offset polynomials:

```
create_offset 20061206.slc.par 20070121.slc.par 20061206_20070121.off 1
```

The last input variable indicates the registration algorithm that will be used (1 for registration based on image intensity cross-correlation, 2 for fringe visibility method). The user can select number and size of the image chips that will be used when estimating the local offsets with the programs offset_pwr / offset_SLC (see Table on next page for some reference values). For this example with accept the default values suggested by the program.

Initial range and azimuth offsets between the two SLC images are estimated either manually by the operator (To do this the operator is supported with the SLC image display program ***disSLC***) or automatically using the programs ***init_offset_orbit*** and ***init_offset***. With ***init_offset_orbit*** a first guess of the offsets can be obtained based on orbital information. This first guess can then be improved with ***init_offset*** which determines the initial offsets based on the cross-correlation function of the image intensities. In order to avoid ambiguity problems and still to achieve an accurate estimates ***init_offset*** may first be run with multi-looking, followed by a second run at single look resolution. Each time the initial offset estimates are written to *.off file and are then used in following run as initial guess. The user can specify position and size of the area used to compute the cross-correlation between images, from which the initial estimate of the offsets will be derived. The user can also set the threshold on the cross-correlation value for accepting/rejecting the offset estimates. As default the subset is put in the middle of the image with a dimension of 1024x1024 pixels. If the cross-correlation value is below the threshold, the estimated offsets are not written to the ISP offset parameter file. It is possible that by changing position and/or size of the subset, an estimate corresponding to a cross-correlation value above the threshold is obtained. To identify the location of the subset, it is suggested to look at one of the SLCs and look for areas with contrast (e.g. topography, urban areas, fields).

In this example we consider the use of ***init_offset_orbit*** only since PALSAR orbital data should be precise enough to provide a satisfactory initial estimate of the offsets. The command line looks as follows

```
init_offset_orbit 20061206.slc.par 20070121.slc.par 20061206_20070121.off
```

To obtain more precise range and azimuth offsets two methods can be pursued.

The first method is based on the image intensity and is implemented in the program ***offset_pwr***. For a large number of image segments this method searches for the range and azimuth offsets resulting in the maximum level of intensity correlation. The method requires at least a minimum of image contrast. It does not depend on the level of coherence between the two SLC images and is computationally efficient. The more important parameters for the search are number and size of the offset estimation windows in range and azimuth, and the offset estimation threshold. In the example we report some general values.

ISP processing parameter:	**Example for appropriate values for use of offset_pwr**
offset_estimation_range_samples:	32
offset_estimation_azimuth_samples:	32
offset_estimation_window_width:	64
offset_estimation_window_height:	64
offset_estimation_threshold::	0.15

The second method is based on the complex valued data and is implemented in the program ***offset_SLC***. For a large number of image segments this method searches for the range and azimuth offsets resulting in the maximum level of coherence. The method requires at least for a number of locations in the image a sufficient level of coherence between the two SLC. The method also works for very low image contrast. Appropriate values for the more important parameters for this search are:

ISP processing parameter:	Example for appropriate values for use of offset_SLC
offset_estimation_range_samples:	16
offset_estimation_azimuth_samples:	16
offset_estimation_window_width:	16
offset_estimation_window_height:	16
offset_estimation_threshold::	0.1

Both approaches determine a field of registration offsets (file *.offs) and a corresponding quality measure field (*.ccp). The *.offs file is in FCOMPLEX format, the real and the imaginary part expressing for each image chip the range and the azimuth offset. Offsets can also be saved as text file for further analysis (file *.offsets).

If very few or even no estimates with good quality are achieved the registration will fail. This may be a result of

- poor initial estimate of the offsets
- too little contrast in the image (*for offset_pwr*)
- too large baseline (*for offset_SLC*)
- too much change (water, forest, high vegetation, long acquisition time interval)

In this example we use ***offset_pwr*** as follows

```
offset_pwr  20061206.slc  20070121.slc  20061206.slc.par  20070121.slc.par
20061206_20070121.off offs ccp 128 128 offsets 2 24 24
```

Here we decided to use image chips being 128 pixels wide and long and accepted all other default values. The list of offsets is written to the binary file offs as well as to the text file offsets whereas the list of cross-correlation values is written to the binary file ccp.

Based on the field of registration offsets and the quality measure of the offsets, the bilinear registration offset polynomial is then determined using a least squares error method. This is implemented in the program ***offset_fit***. In this example the command line looks as follows:

```
offset_fit offs ccp 20061206_20070121.off coffs coffsets
```

The binary files offs and ccp are read and the resulting registration offset polynomials for range and azimuth offset are written to the ISP offset parameter file. The user can judge the quality of the registration between the images by looking at the estimated standard deviation of the offsets in range and azimuth. The offsets actually used for generating the registration polynomial are saved to the binary file coffs and the corresponding file in text version coffsets.

The procedure of estimating the offsets polynomials can be repeated to refine the polynomial. The offsets computed during the first run are used to guide the estimation procedure. In addition the user can choose whether to use a different number of image chips, their size and the cross-correlation threshold. In this example we simply repeat the offset_pwr / offset_fit sequence used before:

```
offset_pwr  20061206.slc  20070121.slc  20061206.slc.par  20070121.slc.par
20061206_20070121.off offs ccp 128 128 offsets 2 24 24

offset_fit offs ccp 20061206_20070121.off coffs coffsets
```

C.2. Precise estimation of the offsets

Once the bilinear polynomial function is known, many offsets are estimated in the area of interest, again based on the image intensity cross-correlation or on the fringe visibility. If precise estimates shall be determined with the image intensity cross-correlation, use the program ***offset_pwr_tracking***. The method based on fringe visibility is supported by the program ***offset_SLC_tracking***.

The selection of one of the two supported methods (image intensity cross-correlation or fringe visibility) depends on the level of coherence between the two SLC images and on the image contrast, on one side, and on the computing time, accuracy and displacement velocity, on the other hand. For identical search windows, ***offset_SLC_tracking*** takes significantly longer to execute than ***offset_pwr_tracking***, but has the advantage that the offset is actually based on the interferometric phase coherence. Another advantage is that the program will find offsets in areas with essentially no features at all. If the displacement is very large, than ***offset_SLC_tracking*** may failed because of lack of coherence and ***offest_pwr_tracking*** is the only available source of information.

In both cases the bilinear polynomial function obtained at the previous stage serves as indication for the position where to estimate the precise offsets. The field of registration offsets here obtained is stored in a new FCOMPLEX file *.offs, where the real part corresponds to the offsets in range and the imaginary part to the offsets in azimuth. The corresponding quality measure field is stored in a new file *.ccp.

If using ***offset_pwr_tracking*** a search window size of 64x256 pixels is appropriate for most of the cases. Oversampling rates of 1, 2 and 4 are supported, 2 is generally a good trade-off between accuracy and efficiency. For tracking the displacement of a glacier, a low cross-correlation threshold is preferred in order to obtain as many estimates as possible. If the noise is too high, estimates with somewhat larger cross-correlation values can be rejected in the computation of the displacement (see Section C.3). The area where the offsets are to be estimated and the number of estimates can be specified on the command line.

For our example the command line looks as follows:

```
offset_pwr_tracking 20061206.slc 20070121.slc 20061206.slc.par
20070121.slc.par 20061206_20070121.off offsN ccpN 64 192 offsetsN 2 0.1 12
36 1 2496 1 5976
```

The two SLCs, the corresponding parameter files and the ISP offset parameter file *.off area read, from which offset estimates in binary format (offsN), in text format (offsetsN) and offset estimation cross-correlation in binary format (ccpN) are obtained. The search region size has been set to 64 pixels in range and 192 in azimuth. In this way an almost squared area is considered. The quality threshold for the offset estimate is set to 0.1. Steps in range pixels are 12 pixels in range and 36 pixels in azimuth to reflect the ratio 1:3 of PALSAR pixel size in range and azimuth. The computation is limited to 2496 columns which corresponds to the rounded value of the width of the image (2500 pixels) divided by the multi-look factor in range (12). Similarly the computation is limited to 5976 lines, corresponding to the rounded value of the length of the image divided by the multi-look in azimuth (36). In this way the image of the offsets will match with the MLI obtained from the SLC using 12 and 36 as multi-look factors. This is of advantage when geocoding the maps of offsets since they are in the same geometry of the MLI image of the reference SAR image (see also Section C.4).

Because of the dense sampling used in this example the program takes several minutes for generating the grid of offsets.

If using ***offset_SLC_tracking*** the search window size must be entered as a power of 2 (8, 16 or 32 are recommended). Oversampling rates of 1 (no oversampling), 2, 4, 8, and 16 are supported. The search chip interferogram size in non-oversampled pixels is set by default to 16. For tracking the displacement of a glacier, a low cross-correlation threshold is preferred in order to obtain as many estimates as possible. If the noise is too high, estimates with cross-correlation slightly higher than the initial threshold can be rejected in the computation of the displacement (see Section C.3). The area where the offsets are to be estimated and the number of estimates can be specified on the command line. The selection of the search window size, the oversampling factor, the search chip interferogram size and the cross-correlation level depends on the size of the area of interest, on the number of estimates, and on the expected accuracy. Large oversampling factors (e.g., 4) with a relatively large search window size (e.g. 16) make the computation very slow and are not suitable for the determination of many offsets. If a large number of offsets have to be estimated, then it is preferred to reduce the search window size and/or the oversampling factor at cost of a reduced accuracy.

C.3. Computation of the range and azimuth displacements

The offsets estimated in range and azimuth direction are then transformed to displacements.

The bilinear polynomial function determined all over the image and stored in the *.off file is used for the separation of the orbital offsets from those of the area concerned with displacement. The range and azimuth offsets generated by ***offset_pwr_tracking*** or ***offset_SLC_tracking*** are transformed in range and azimuth displacements by means of the program ***offset_tracking***. The command line in this example looks as follows:

```
offset_tracking offsN ccpN 20061206.slc.par 20061206_20070121.off coffsN
coffsetsN 2 0.1 1
```

The output displacements are written to the binary file coffsN in FCOMPLEX format and (optionally) to a text file, which in this case is called coffsetsN. The displacements can be computed in range and azimuth directions in pixels or meters or in ground-range and azimuth directions (horizontal geometry) in meters. Points can be rejected based on a cross-correlation thresholding. Offset estimates with a cross-correlation value below the indicated threshold are not considered. In this case it was chosen to express the displacement in meters in ground range and azimuth direction (mode parameter set to 2), the cross-correlation threshold to accept offset value was set to 0.1 and it was chosen to subtract the polynomial trend from offset data (poly_flag parameter set to 1). If generated, the displacements for each image chip can be found in the last two columns of the displacements file in text format, i.e. in this example the file coffsetsN, respectively for the range and the azimuth direction.

C.4. Display of results

The MLI image is obtained with the program ***multi_look*** as follows

```
multi_look 20061206.slc 20061206.slc.par 20061206.mli 20061206.mli.par 12
36
```

The MLI image is 208 pixels wide and 166 pixels long. The ISP MLI parameter file can be used for geocoding the MLI and all offset tracking products in the same geometry.

The DISP program ***raspwr*** can be used to generate a SUNraster/bmp version of the multi-look intensity image.

```
raspwr 20061206.mli 208 - - 1 1 - - - 20061206.mli.ras
```

The multi-look image is displayed in Figure C2.

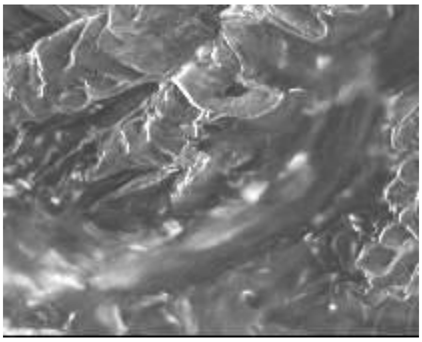

Figure C2. Multi-look image of 20061206.slc (208 pixels wide, 166 pixels long, pixel size approximately 120 m in both directions).The glacier of interest is located in the central part of the image along the valley stretching from the top right corner of the image to the bottom left corner.

The output file containing the displacements in FCOMPLEX format can be transformed in files of float with the program ***cpx_to_real*** (DISP module) in order to obtain the real or imaginary parts only (i.e. the range and azimuth displacements) or the maximal intensity or phase (i.e. direction) of the displacement. These files can be represented with the DISP programs ***dishgt*** or can be saved to a SUNraster / bmp image file with ***rashgt***.

In our example computation and display of the real and imaginary parts of the displacements file (i.e. range and azimuth displacements) are done as follows. At first the range and the azimuth component of the displacement are saved to separate files and then they are saved together with the SAR intensity image to two SUNraster files.

```
cpx_to_real coffsN coffsN_real 208 0

cpx_to_real coffsN coffsN_ima 208 1

rashgt coffsN_real 20061206.mli 208 1 1 0 1 1 30. 1. .35 1 coffsN_real.ras

rashgt coffsN_ima 20061206.mli 208 1 1 0 1 1 30. 1. .35 1 coffsN_ima.ras
```

Figure C3 shows these two components. The figures show the clear displacement of the glacier along both the ground range direction (i.e. horizontally) and the azimuth direction (i.e. vertically).

Computation and display of the maximal intensity of the displacement is achieved as follows. With ***cpx_to_real*** the magnitude of the complex file coffsN is obtained. With the DISP program ***rasdt_pwr24*** it is then possible to generate a 24-bit SUNraster/bmp file of float parameter (e.g. deformation) + intensity image:

```
cpx_to_real coffsN coffsN_mag 208 3

rasdt_pwr24  coffsN_mag  20061206.mli  208  1  1  0  1  1  30.  1.  .35  1
coffsN_mag.ras
```

Figure C4 shows the intensity of the displacement. The displacement of the glacier is clearly visible.

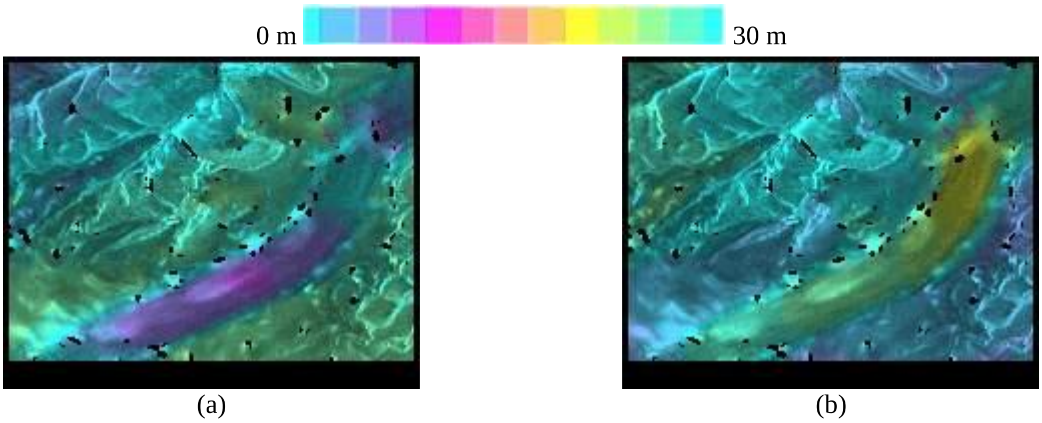

Figure C3. Real (a) and imaginary (b) component of the FCOMPLEX displacement file with SAR intensity of reference image in the background. The two images indicate respectively displacement in the ground range and the azimuth direction.

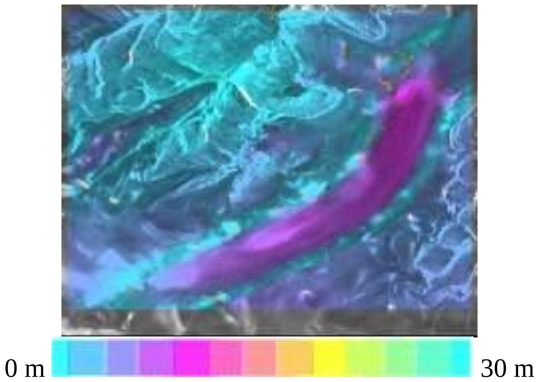

Figure C4. Intensity of displacement obtained from offset tracking file with SAR intensity of reference image in the background.

Further refinement is possible with filtering of noise and azimuth streaks (see Pritchard et al., 2005 and Wegmüller et al., 2006).

The MLI parameter file obtained with multi_look can now be used for setting up the geocoding lookup table so that data can be put into a specific map projection. Instructions for geocoding of SAR images can be found in the DIFF&GEO User's Guide on Geocoding and Image Registration.

C.5. Relevant publications on offset tracking processing

Pritchard, H., Murray, T., Luckman, A., Strozzi, T. and Barr, S., Glacier surge dynamics of Sortebræ, east Greenland, from synthetic aperture radar feature tracking, Journal of Geophysical Research, 110(F03005), doi:10.1029/2004JF000233, 2005.

Strozzi, T., Luckman, A., Murray, T., Wegmüller, U. and Werner, C., Glacier motion estimation using SAR offset-tracking procedures, IEEE Transactions on Geoscience and Remote Sensing, 40, 11, pp. 2384-2391, 2002.

Strozzi, T., Kouraev, A., Wiesmann, A., Sharov, A., Wegmüller, U. and Werner, C., Estimation of Arctic glacier motion with satellite L-band SAR data, Proceedings of IGARSS 2006, Denver, 31 July – 4 August, 2006.

Wegmüller U., Werner, C., Strozzi T., and Wiesmann, A., Automated and precise image registration procedures, in “Analysis of multi-temporal remote sensing images”, Bruzzone and Smits (ed.), Series in Remote Sensing, Vol. 2, World Scientific (ISBN 981-02-4955-1), pp. 37-49, 2002.

Wegmüller, U., Werner, C., Strozzi, T., and Wiesmann, A., Ionospheric electron concentration effects on SAR and INSAR, Proceedings of IGARSS 2006, Denver, 31 July – 4 August, 2006.

Werner C., Strozzi, T., Wiesmann, A., Wegmüller, U., Murray, T., Pritchard H. and Luckman, A., Complimentary measurement of geophysical deformation using repeat-pass SAR, Proceedings of IGARSS 2001, Sydney, 9-13 July, 2001.

Werner C., Wegmüller, U., Strozzi T., and Wiesmann, A., Precision estimation of local offsets between SAR SLCs and detected SAR images, Proceedings of IGARSS 2005, Seoul, 25-29 July, 2005.