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# Sentinel-1 InSAR Phase Unwrapping using S1TBX and SNAPHU

Adapted from the European Space Agency's <u>STEP</u> community platform

#### In this document you will find:

- A. System Requirements
- B. Background Information
- C. Materials List
- D. Pre-Unwrapping Steps
- E. Install a Linux Virtual Machine (VM)
- F. Unwrapping with SNAPHU
- G. Post-Unwrapping Steps
- H. Sample Images
- I. Extended Reading List

# A) System Requirements

Many of the steps take a very long time to process. We recommend the following:

- At least 16GB memory (RAM)
- Close other applications if possible while using S1TBX
- Do not use the computer while a product is being processed

# **B)** Background

This data recipe is a continuation from ASF's <u>Sentinel-1 InSAR Processing</u> recipe. It provides the 'unwrapping' of the interferogram generated in that recipe, which in turn allows height values to be derived from the product. Phase unwrapping is the most complicated stage of interferometric data processing.

Here, we will be using SNAPHU, which is a two-dimensional phase unwrapping algorithm proposed by Chen and Zebker (<u>see Section H</u>). The software is written in C and should run on most Unix/Linux platforms, and it is freely available to the public.



The interferometric phase is ambiguous and only known within  $2\pi$ . In order to be able to relate the interferometric phase to the topographic height, the phase must first be unwrapped. The altitude of ambiguity  $h_a$  is defined as the altitude difference that generates an interferometric phase change of  $2\pi$  after interferogram flattening.

Phase unwrapping solves this ambiguity by integrating phase difference between neighboring pixels. After deleting any integer number of altitudes of ambiguity (equivalent to an integer number of  $2\pi$  phase cycles), the phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation.

# C) Materials List

Linux Virtual Machine

Windows users have several options to access a Linux machine:

- Download a virtual machine (VM) software such as <u>VirtualBox</u> or <u>VMware</u>.
- Download a Operating System such as LinuxMint.
- Launching an <u>Amazon EC2 Linux Instance</u> through Amazon Web Services (AWS).
- <u>Sentinel-1 Toolbox</u> (S1TBX).
- SNAPHU Algorithm for Phase Unwrapping (See Step 3)
- InSAR Data (continuation from the <u>InSAR data recipe</u>), including the coherence band for your interferogram.

# D) Pre-Unwrapping Steps

This data recipe assumes that you have already generated an interferogram, if not the graph below shows the pre-unwrapping steps.



Figure 1: Pre-unwrapping Interferogram Formation steps.

For optimal unwrapping results it is recommended to multi-look (i.e., square) and phasefilter (i.e. increase signal-to-noise and smooth) the interferogram. **Note that when performing the multi-look process for data that will be used for phase unwrapping, the coherence band (coh) must be included along with the "i" and "q" bands.** 

The quality and reliability of unwrapped results strongly depends on the input coherence. Reliable results can only be expected in areas with high coherence.

## Step 1 - Open Your Interferogram in S1TBX

- Use the **Open Product** button to open your interferogram
- You will see the opened product in the Product Explorer
- Double-click on the opened product to view the product bands
- Double-click on the Phase band to view your interferogram
- Zoom in using the mouse wheel and dragging the left mouse button

## Step 2 - Create a Subset (Optional)

To reduce the amount of processing needed, you may create a subset of the particular area in which you are interested.

Once you have zoomed and panned to your area of interest, right click on the image and select **Spatial Subset from View** in the context menu.

Geometry from WKT WKT from Geometry Export Transect Pixels Export Mask Pixels Export View as Google Earth KMZ Export View as Image Export Colour Palette as File Export Colour Legend as Image Spatial Subset from View... Copy Pixel-Info to Clipboard

The subset dialog box will automatically select the area you were viewing. To adjust the extent of your subset image, you may drag the bounding box, enter the pixel coordinates, or add geo coordinates (Figure 2).

atial Subset Band Subset T	e-Point Grid Subset Metadata Subse	t
	<ul> <li>Pixel Coordinates Geo Coordin</li> <li>Scene start X:</li> <li>Scene start Y:</li> <li>Scene end X:</li> <li>Scene end Y:</li> <li>Scene step X:</li> <li>Scene step Y:</li> <li>Subset scene width:</li> <li>Subset scene height:</li> <li>Source scene height:</li> <li>Source scene height:</li> <li>Use Preview</li> </ul>	nates 0 ↓ 1112 ↓ 20,662 ↓ 7784 ↓ 1 ↓ 20663.0 6673.0 20663 16250 Fix full width Fix full height
	Es	timated, raw storage size: 394.4

Figure 2: Specifying a Product Subset

Press **OK** to create the subset.

*Note:* By default, all bands will be included in the subset. For phase unwrapping, it is required that you keep both the **phase** and **coherence** bands.

When the new subset product appears in the products view:

- Right-click on the product
- Select Save Product in the context menu
- Select Yes to convert the product to the BEAM-DIMAP format

#### Step 3 - Export to SNAPHU

Export your interferogram from S1TBX

- Select the product from the **Product Explorer** tab
- Navigate to: Radar > Interferometric > Unwrapping > SNAPHU Export
- In the SNAPHU Export tab type in the folder directory in the Target Folder box
  - We recommend creating a separate folder for this step (Figure 3)



- Select **DEFO** for deformation mapping
- To speed up the unwrapping process, you may increase the number of processors (this depends on the CPU you have)
- Click Run to create SNAPHU export folder

Target folder:	C:\Users\kjaustin\Desktop\PhaseUnwrap\Export	]
Statistical-cost mode:	DEFO	~
Initial method:	MCF	~
Number of Tile Rows:		20
Number of Tile Columns:		20
Number of Processors:		4
Row Overlap:		0
Column Overlap:		0
		500
He Cost Threshold:		
Tile Cost Threshold:		
The Cost Threshold:		

Figure 3: SNAPHU Export

## E) Install and open a Virtual Machine (VM)

### Step 4 - Install and open a Linux VM

If you do not have a Linux OS, you will need to install a Linux VM to operate SNAPHU (see Section C: Materials List).

#### **Step 5 - Transfer in the SNAPHU Export files**

Zip the newly generated SNAPHU Export files and move them to a shared folder so it is accessible in your VM for unwrapping. Approaches include:

- Place files in Google Drive or Dropbox on your PC, and download them in your VM.
- Email the files to yourself and retrieve them in your VM.

# F) Unwrapping with SNAPHU

<u>SNAPHU</u> is a Statistical-cost, Network-flow Algorithm for Phase Unwrapping developed at Stanford University by Curtis Chen and Howard Zebker, and is available for Linux only. VM users need to start their Linux VM and open the command line in that environment. Linux users simply need to open a command line and follow the steps. Run the following commands from each step:

#### **Step 6 - Install SNAPHU**

Install the software by typing the following command in the command line and hit Enter:



apt-get install snaphu

Figure 4. At the Linux command line, install SNAPHU.

If a user is not granted root access (the *install snaphu* command results in an Access error), use the following command, which will then prompt for the user's password for Linux (or the Linux VM) and allow the user the elevated privileges required for installing the software:

## sudo apt-get install snaphu

## Step 7 - Display the SNAPHU config file

\*\*Make sure you are in the same directory as the 'snaphu.conf' file\*\*

- Open or <cd> to the SNAPHU Export data folder you created in Step 3
- Use the following command or use a text-only editor of your choice to open the configuration file located inside the export folder (snaphu.conf):

nano snaphu.conf

kjaustin@vbox4~/Desktop/subset_0_of_S1A_IW_SLC_1SSV_20160408T091355_20160408 - + × File Edit View Search Terminal Help
<pre>kjaustin@vbox4 ~ \$ cd Desktop kjaustin@vbox4 ~/Desktop \$ ls subset_0_of_S1A_IW_SLC1SSV_20160408T091355_20160408T091430_010728_01001F_83EB_ Orb_Stack_ifg_deb_flt kjaustin@vbox4 ~/Desktop \$ cd subset_0_of_S1A_IW_SLC1SSV_20160408T091355_20160 408T091430_010728_01001F_83EB_Orb_Stack_ifg_deb_flt/ kjaustin@vbox4 ~/Desktop/subset_0_of_S1A_IW_SLC1SSV_20160408T091355_20160408T0 91430_010728_01001F_83EB_Orb_Stack_ifg_deb_flt \$ nano_snaphu.conf</pre>

Figure 5. Display the SNAHPU config file

Step 8 – Obtain the Call to Command SNAHPU within the config file

Highlight and copy the Command to call snaphu, to exit the config file type Crtl^X

snaphu -f snaphu.conf YOUR\_PHASE\_BAND.snaphu.img XXXX

kjaustin@vbox	x4 ~/Desktop/subset_0_of_S1A_IW_SLC_1SSV_20160408T091355_20160408T0914 - + ×
File Edit View Sea	arch Terminal Help
GNU nano 2.5.3	3 File: snaphu.conf
# CONFIG FOR SNA #	арни
# Created by SNA	AP software on: 15:44:06 15/10/2018
# # Command to cal #	ll snaphu:
# snaphu -	-f snaphu.conf Phase_ifg_IW1_VV_08Apr2016_20Apr2016.snaphu.img 20663
######################################	######################################
STATCOSTMODE INITMETHOD VERBOSE	DEFO MCF TRUE
######################################	
^G Get Help   ^O ^X Exit     ^R	O Write Out AW Where Is AK Cut Text AJ Justify AC Cur Pos R Read File AN Replace AU Uncut Text AT To Spell A Go To Line



27 September 2017 v.5 | 7

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### **Step 9 - Run the Command:**

Paste the command into the command terminal and hit Enter:

kjaustin@vbox4 ~/Desktop/subset_0_of_S1A_IW_SLC_1SSV_20160408T091355_20160408T091430 - + X
File Edit View Search Terminal Help
kjaustin@vbox4 ~ \$ cd Desktop kjaustin@vbox4 ~/Desktop \$ ls subset_0 of SlA_IW_SLC_1SSV_20160408T091355_20160408T091430_010728_01001F_83EB_0rb_St ack_ifg_deb_flt kjaustin@vbox4 ~/Desktop \$ cd subset_0 of_SLA_IW_SLC_1SSV_20160408T091355_20160408T091 1430_010728_01001F_83EB_0rb_Stack_ifg_deb_flt7 kjaustin@vbox4 ~/Desktop/subset_0 of_SLA_IW_SLC_1SSV_20160408T091355_20160408T091430_ 010728_01001F_83EB_0rb_Stack_ifg_deb_flt \$ nano Snaphu.conf kjaustin@vbox4 ~/Desktop/subset_0_of_SLA_IW_SLC_1SSV_20160408T091355_20160408T091430_ 010728_01001F_83EB_0rb_Stack_ifg_deb_flt \$ snaphu.conf kjaustin@vbox4 ~/Desktop/subset_0_of_SLA_IW_SLC_1SSV_20160408T091355_20160408T091430_ 010728_01001F_83EB_0rb_Stack_ifg_deb_flt \$ snaphu .conf kjaustin@vbox4 ~/Desktop/subset_0_of_SLA_IW_SLC_1SSV_20160408T091355_20160408T091430_ 010728_01001F_83EB_0rb_Stack_ifg_deb_flt \$ snaphu .f snaphu.conf Pase_ifg_IW_IVV_08Ap_IVIVVV_08Ap_IVIVV_08Ap_IVIVV_08Ap_IVIVV_08Ap_IVIVV_08Ap_IVIVVV_08Ap_IVIVVV_08Ap_IVIVV_08Ap_IVIVVV_08Ap_IVIVVV_08Ap_IVIVVV_08Ap_IVIVVV000Ap_IVIVVV00Ap_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IVIVVV00AP_IV
snaphu v1.4.2 27 parameters input from file snaphu.conf (84 lines total) Logging run-time parameters to file snaphu.log Creating temporary directory snaphu tiles_2509 Unwrapping tile at row 0, column 0 (pid 2510) Unwrapping tile at row 0, column 1 (pid 2511) Unwrapping tile at row 0, column 2 (pid 2512) Unwrapping tile at row 0, column 3 (pid 2513)

Figure 7: SNAPHU Output

**Note:** Execution time depends on the size of the interferogram. Unwrapping can use a lot of memory. If the unwrapping fails due to insufficient memory, you may wish to create a subset of your area of interest (<u>see Step 2</u>) and try it again.

## Step 10 – Make output files available to S1TBX

Zip and move the files from the VM to your PC, then download them so they are accessible to S1TBX.

- On your desktop, check the .hdr and .img filenames for a possible mismatch
  - A bug may cause a filename and contents mismatch between the .hdr and .img files
  - Mismatched filenames and contents will cause recipe failure
  - If this happens see the Defect Warning and Work around section below

#### **Optional - Defect Warning and Work around**

**Work around:** If the polarization in the .hdr filename does not match the .img filename, edit the .hdr filename and contents to match the .img filename and contents polarization. Example below:

• Edit the .hdr filename polarization to match the .img filename polarization:

UnwPhase\_ifg\_IW1\_VH\_20Jul2015\_01Aug2015.snaphu.hdr

• To match the .img file name:

UnwPhase\_ifg\_IW1\_VV\_20Jul2015\_01Aug2015.snaphu.img

• To get this:

UnwPhase\_ifg\_IW1\_VV\_20Jul2015\_01Aug2015.snaphu.hdr

• Edit the .hdr contents polarization to match the polarization of the .img file.



Figure 8. Edit the .hdr file polarization (VH) to match the .img polarization (VV).

# G) Post-Unwrapping Steps

This section assumes you have your interferogram from Section D, <u>Step 3</u> still open in S1TBX. If you do not, please open your product before proceeding.

#### Step 11 – SNAPHU Import

Navigate to Radar > Interferometric > Unwrapping > Snaphu Import

In the SNAPHU Import window (Figure 6):

- In the Read Phase tab: Select the interferogram product
- In the Read Unwrapped Phase tab: Navigate to your SNAPHU export folder and select the UnwPhase.hdr file



• In the **SNAPHU Import** tab:

OPTIONAL: To create a separate file, check the **Do NOT save Wrapped** interferogram in the target product option

	Shaph					
	1-Read-Ph	ase 2-Read-Unwrapped-Phase 3-SnaphuImport 4-Write				
	Source Pr	roduct				
	Name:					
	UnwPha	ise_itg_IW1_VV_08Apr2016_20Apr2016.snaphu v				
	Data Fo	rmat: Any Format 🗸				
elect Sourc	e Product	×				
Look in	: subset_0	_of_S1A_IW_SLC1SSV_20160408T091355_20160408T091430_010728_01001F_83EB_Orb_Stack_ifg_deb_fit 🗸 🗈 📸 📰 •				
<u></u>	snaphu_t	iles_2697				
	L] c					
ent Items	Coh_IW1_	The coh_W1_VV_08Apr2016_20Apr2016.snaphu				
	Coh_IW1_	VV_UBApr2016_20Apr2016.snaphu				
	Bhase_ing	vvuoAppzulo_zOAppzulosinaphu				
and the set	spaphu c	ranbu conf				
esktop	snaphu					
_	UnwPhas	se ifa IW1 VV 08Apr2016 20Apr2016.snaphu				
	UnwPhas	se_ifg_IW1_VV_08Apr2016_20Apr2016.snaphu				
cuments						
his PC						
1	File name:	UnwPhase ifa 1W1 VV 08Apr2016 20Apr2016.snaphu.hdr Select				
	Files of type:	Al Elec				
etwork		All Files				

Figure 9: SNAPHU Import – Select Unwrapped Phase Product

27 September 2017 v.5 |

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#### Step 12 – Geocoding

At this point, you may view your Unwrapped Phase product (Figure 10). However, you will notice that areas of no-elevation incorrectly appear as having data in the Unwrapped Phase image. To fix this, we will terrain correct and geocode the data.



Figure 10: Unwrapped and Wrapped Phase

Navigate to Radar > Geometric > Terrain Correction > Range-Doppler Terrain Correction



In the **Range-Doppler Terrain Correction** window (Figure 11), select the Unwrapped Phase product you just imported from SNAPHU.

📀 Range Doppler Terrain Correctio	on X			
File Help				
I/O Parameters Processing Parameters				
Source Bands:	Unw_Phase_ifg_08Apr2016_20Apr2016			
Digital Elevation Model:	SRTM 3Sec (Auto Download) 🗸 🗸			
DEM Resampling Method:	BILINEAR_INTERPOLATION V			
Image Resampling Method:	BILINEAR_INTERPOLATION V			
Source GR Pixel Spacings (az x rg):	13.97(m) x 4.18(m)			
Pixel Spacing (m):	13.97			
Pixel Spacing (deg):	1.2549464519149715E-4			
Map Projection:	WGS84(DD)			
Mask out areas without elevation Output complex data				
Output bands for:				
Selected source band	DEM Latitude & Longitude			
Incidence angle from ellipsoid	Local incidence angle Projected local incidence angle			
Apply radiometric normalization				
Save Sigma0 band	Use projected local incidence angle from DEM $$			
Save Gamma0 band	Use projected local incidence angle from DEM $$			
Save Beta0 band				
Auxiliary File (ASAR only):	Latest Auxiliary File 🗸 🗸			
	Run Close			

Figure 11: Range Doppler Terrain Correction

In the **Processing Parameters** tab:

- Select the option to Mask out areas with no elevation, of desired
- Change pixel spacing, if desired
- Leave all other parameters as default
- Click **Run** to geocode your data

The resulting product name is appended with  $\_\textbf{TC}.$ 

See Figure 12 below for the resulting geocoded wrapped and unwrapped interferograms.



Figure 12: Geocoded Wrapped and Unwrapped Phase

#### Step 12 – Export Data

The final geocoded data can be exported from S1TBX in a variety of formats.

To export you may either **right-click** on your product in the product view or navigate to *File > Export* 

In addition to GeoTIFF and HDF5 formats, KMZ and various specialty formats are supported. Figure 13 shows a KMZ-formatted unwrapped interferogram in Google Earth.





Figure 13: Geocoded Kumamoto Unwrapped Phase projected onto Google Earth. Contains modified Copernicus Sentinel data (2016) processed by ESA

#### Interferogram Interpretation

The interferometric phase carries a wealth of information about surface deformation (strength and direction of motion) and the location of the surface rupture. The phase map is also a proxy for other earthquake-related parameters such as the energy released during an event and the amount of shaking experienced across the affected area.

Unwrapped results should be interpreted as a relative height/displacement between two pixels. To obtain absolute estimates, a tie point can be used in the unwrapped phase to height operation.



# I) Extended Reading List

- Akerson, J. J., Yang, Y. C. E., Hara, Y., Wu, B. I. and Kong, J. A., 2000. Automatic phase unwrapping algorithms in Synthetic Aperture Radar (SAR) Interferometry. *IEICE Transactions on Electronics*, **E83C** (12) :1896-1904.
- Chen, C. W. and Zebker, H. A., 2001. Two-dimensional phase unwrapping with use of statistical models for cost functions in nonlinear optimization. *Journal of The Optical Society of America A-Optics Image Science and Vision*, **18** (2) :338-351.
- Chen, C. W. and Zebker, H. A., 2002. Phase unwrapping for large SAR interferograms: Statistical segmentation and generalized network models. *IEEE Transactions on Geoscience and Remote Sensing*, **40** (8) :1709-1719.
- Costantini, M., Farina, A. and Zirilli, F., 1999. A fast phase unwrapping algorithm for SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, **37** (1) :452-460.
- Davidson, G. W. and Bamler, R., 1999. Multiresolution phase unwrapping for SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, **37** (1) :163-174.
- Egidi, N. and Maponi, P., 2004. A comparative study of two fast phase unwrapping algorithms. *Applied Mathematics and Computation*, **148** (3) :599-629.
- Flynn, T. J., 1997. Two-dimensional phase unwrapping with minimum weighted discontinuity. *Journal of the Optical Society of America A-Optics Image Science and Vision*, **14** (10) :2692-2701.
- Fornaro, G., Franceschetti, G., Lanari, R., Sansosti, E. and Tesauro, M., 1997. Global and local phase-unwrapping techniques: a comparison. *Journal of the Optical Society of America A-Optics Image Science and Vision*, **14** (10) :2702-2708.
- Fu, S. H., Long, X. J. and Yang, X., 2010. Coherence estimation method and its application to phase unwrapping. *Journal of Applied Remote Sensing*, **4** (5) .
- Gang, Li, Jia, Xu, Ying-Ning, Peng and Xiang-Gen, Xia, 2007. An efficient implementation of a robust phase-unwrapping algorithm. *IEEE Signal Processing Letters*, **14** (6) :393-6.

- Gens, R., 2003. Two-dimensional phase unwrapping for radar interferometry: developments and new challenges. *International Journal of Remote Sensing*, **24** (4) :703-710.
- Ghiglia, Dennis C. and Pritt, Mark D., 1998. Two-dimensional phase unwrapping : theory, algorithms, and software. *International Journal of Remote Sensing*, **24** (4) :xiv, 493 p.
- Ghiglia, D. C. and Romero, L. A., 1994. Robust 2-Dimensional Weighted and Unweighted Phase Unwrapping That Uses Fast Transforms and Iterative Methods. *Journal of The Optical Society of America A-Optics Image Science and Vision*, **11** (1) :107-117.
- Ghiglia, D. C. and Romero, L. A., 1996. Minimum L(p)-norm two-dimensional phase unwrapping. *Journal of The Optical Society of America A-Optics Image Science and Vision*, **13** (10) :1999-2013.
- Goldstein, R. M. and Werner, C. L., 1998. Radar interferogram filtering for geophysical applications. *Geophysical Research Letters*, **25** (21) :4035-4038.
- Goldstein, R. M., Zebker, H. A. and Werner, C. L., 1988. Satellite Radar Interferometry -Two-Dimensional Phase Unwrapping. *Radio Science*, **23** (4) :713-720.
- Guarnieri, A. M., 2003. Using topography statistics to help phase unwrapping. *IEEE Proceedings-Radar Sonar and Navigation*, **150** (3) :144-151.
- Hooper, A. and Zebker, H. A., 2007. Phase unwrapping in three dimensions with application to InSAR time series. *Journal of The Optical Society of America A-Optics Image Science and Vision*, **24** (26):2737-2747.
- Li, Z. F., Bao, Z. and Suo, Z. Y., 2007. A joint image co-registration, phase noise suppression, and phase unwrapping method based on subspace projection for multi-baseline InSAR systems. *IEEE Transactions on Geoscience and Remote Sensing*, **45** (3) :584-591.
- Lin, Q., Vesecky, J. F. and Zebker, H. A., 1992. New Approaches In Interferometric Sar Data-Processing. *IEEE Transactions on Geoscience and Remote* Sensing, **30** (3) :560-567.

- Lin, Q., Vesecky, J. F. and Zebker, H. A., 1994. Phase Unwrapping Through Fringe-Line Detection In Synthetic-Aperture Radar Interferometry. *Applied Optics*, **33** (2) :201-208.
- Lyuboshenko, I. V., Maitre, H. and Maruani, A., 2002. Least-mean-squares phase unwrapping by use of an incomplete set of residue branch cuts. *Applied Optics*, **41** (11) :2129-2148.

Nico, G., Palubinskas, G. and Datcu, M., 2000. Bayesian approaches to phase unwrapping: Theoretical study. *IEEE Transactions on Signal Processing*, **48** (9) :2545-2556.

- Sandwell, D. T. and Price, E. J., 1998. Phase gradient approach to stacking interferograms. *Journal of Geophysical Research-Solid Earth*, **103** (B12) :30183-30204.
- Shanker, A. P. and Zebker, H., 2010. Edgelist phase unwrapping algorithm for time series InSAR analysis. *Journal of The Optical Society of America A-Optics Image Science and Vision*, **27** (3) :605-612.

Shanker, A. P. and Zebker, H. A., 2009. Sparse Two-Dimensional Phase Unwrapping Using Regular Grid Methods. *IEEE Geoscience and Remote Sensing Letters*, 6 (3) :519-522.

Spagnolini, U., 1993. 2-D Phase Unwrapping And Phase Aliasing. *Geophysics*, **58** (9) :1324-1334.

- Wei, Z. Q., Xu, F. and Jin, Y. Q., 2008. Phase unwrapping for SAR interferometry based on an ant colony optimization algorithm. *International Journal of Remote Sensing*, **29** (3) :711-725.
- Yang, Lei, Liu, Wei and Zhao, Yong-jun, 2007. Branch cut strategy analyses in phase unwrapping algorithm for interferometric SAR. *Science of Surveying and Mapping*, **37** (1) :75-7.
- Zakharova, L. N. and Zakharov, A. I., 2003. Comparison of some modern phase unwrapping methods in radar interferometry. *Journal of Communications Technology and Electronics*, **48** (10) :1108-1112.