ESA STUDY CONTRACT REPORT

WiMCA Executive Summary

ESA CONTRACT No 21319/07/NL/HE	**SUBJECT** A novel approach for Wide-Band SAR Interferometry		**CONTRACTOR** CNR-ISSIA
ESA CR( )No	**STAR CODE**	**No of volumes** **This is the Volume No**	**CONTRACTORS REFERENCE**

ABSTRACT:

The present document constitutes the executive summary of the ESA WiMCA research project which is addressed to a systematization of the technical aspects related to the innovative multi-chromatic analysis (MCA) in terms of theoretical formulation, implementation and validation.

WiMCA

Wide-Band Multi-Chromatic Assessment

ESA ITT ref. AO/1-5509/07/NL/HE, issued on 31 July 2007,
entitled “A novel approach for Wide-Band SAR Interferometry”

Executive Summary

Document History		
Doc. Name: Executive Summary	**Version:** First release	**Date:** September, 2010
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Reference Documents

[RD1] S. N. Madsen and H. A. Zebker, Automated Absolute Phase Retrieval in Across-Track Interferometry, Proc. IGARSS'92, vol. II, pp. 1582–1584, 1992.

[RD2] N. Veneziani, F. Bovenga, A. Refice, A wide-band approach to absolute phase retrieval in SAR interferometry, Multidimensional Systems and Signal Processing, MULT vol. 14(1-2), pp. 183-205, Kluwer Academic Publisher, 2003.

[RD3] V. M. Giacovazzo, A. Refice, F. Bovenga, N. Veneziani, "Identification of coherent scatterers: spectral correlation vs. Multi-Chromatic Phase Analysis ", *Proceedings of IGARSS 2008*, Boston, Massachusetts, USA, July 6-11, 2008.

[RD4] F. Bovenga, V. M. Giacovazzo, A. Refice, N. Veneziani, R. Vitulli, "First validation experiment for a multi-chromatic analysis (MCA) of SAR data starting from SLC images", *Proceedings of IGARSS 2009*, Cape Town, South Africa, July 13-17, 2009.

[RD5] F. Bovenga, V. M. Giacovazzo, A. Refice, N. Veneziani, R. Vitulli, "Multi-Chromatic Analysis of InSAR data: validation and potential", *Proceedings of FRINGE 2009*, ESRIN, Frascati, Italy, Nov.30 – Dec. 4, 2009.

[RD6] D. Derauw, A. Orban and C. Barbier, "Wide band SAR sub-band splitting and inter-band coherence measurements", *Remote Sensing Letters*, 1: 3, 133 — 140, First published on: 08 March 2010

Applicable Documents

[AD1] Wide-Band Multi-Chromatic Assessment, CSL Proposal to ISSIA - University Bari (Italy) in response of the ESA ITT ref. AO/I-5509/07/NL/HE, issued on 31 July 2007, titled "A novel approach for Wide-Band SAR Interferometry", Doc CSL-OFF-ESA-07074, October 26, 2007.

[AD2] WiMCA Deliverable 1: "Technical note on the algorithm" (WIMCA_D1_Draft_v2.doc), October 10, 2008

[AD3] WiMCA Deliverable 2: "Data Sets description" (WIMCA_D2.doc), July 07, 2008

[AD4] Deliverable 3-4: "Technical note on the algorithm performance and limitation", November, 11, 2009.

[AD5] Deliverable 5-6 "Technical note on Atmospheric effects estimation and on PS detection and comparison with PSI technique", June, 2010.

[AD6] Deliverable 7-10 "WiMCA Final Report, conclusions and recommendations", July, 2010.

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I. Executive Summary

Recent investigations have shown that extending the diversity of imaging radar surface observations to the dimension given by the incident radiation carrier frequency may spawn new investigation and application potential. The novel processing concept introduced by Madsen and Zebker [RD1] and further developed by Veneziani, Bovenga and Refice [RD2], led to the the so-called multi-chromatic InSAR processing approach.

The method involves computing a set of equal-resolution interferograms of the same scene, from SAR images focused by using portions of the available processing bandwidth, centred at different carrier frequencies. The complex signal of each image pixel is then studied as a function of the carrier frequency.

If the attention is focused on single targets presenting stable phase behaviour along the frequency range, the phase of suitable frequency-coherent scatterers evolves linearly with the central wavelength, the slope being proportional to the absolute optical path difference. Multi-chromatic InSAR then potentially allows to retrieve unambiguous height information, without requirement of spatial phase unwrapping (PU), which is needed in the standard monochromatic processing.

The WiMCA research project is addressed to a systematization of the technical aspects related to the innovative multi-chromatic analysis (MCA) in terms of theoretical formulation, implementation and validation. In particular, the activities carried out in this framework concern:

- Definition of the state of the art of the research subject.
- SAR wide-band data selection.
- Algorithms specification and prototyping: in particular two specific applications of MCA are investigated concerning the absolute height retrieval and an advanced coregistration procedure.
- Algorithm tuning and validation.
- Coding in C language of the algorithms prototypes.
- Innovative aspects investigation: i) comparison between the frequency-persistent scatterers (PS_{fd}) and the Persistent Scatterers (PS), ii) inter-band coherence: model and validation.

Concerning the algorithm development, the equivalence between MCA performed starting from Level 0 and Level 1 data has been proven and the first implementation of the MCA processing chain on Level 1 data has been developed.

Moreover, the impact of the SAR images coregistration within the MCA processing chain has been investigated in detail. The possibility has been proven of performing this processing step once, operating on the full-band images before sub-looks generation, in order to save processing time.

Through a parametric analysis, we obtained a first evaluation of the impact of the MCA processing parameters on the height estimation performances. Results show that the estimation is improved by using wider bandwidths of the sub-look images and by increasing the number of sub-looks. It is worthwhile to stress this last point since it concerns the main difference between the proposed MCA and the original concept introduced in [RD1], which involves the processing of only two sub-band images.

Moreover, this analysis shows that MCA results are effective if proper bandwidth is available. In particular, a value of 100 MHz seems to be inadequate for a reliable application of MCA for absolute difference path retrieval as well as for fringe classification, while a bandwidth of at least 300 MHz seems to be required to provide reliable results.

Figure 1 shows the expected standard deviation (STD) on the integer number of k values which are related to the integer number of 2π needed to compute the absolute interferometric phase. These STD values have been evaluated theoretically for different values of the available full bandwidth (B), and for different number sub-band images (N_f) and sub-bandwidth values (B_p). The condition for proper k value determination is $\sigma_k < 0.5$, which is satisfied for $B > 300$ MHz.

This theoretical figure was validated by processing a SAR interferometric pair of images acquired simultaneously by the AES-1 airborne sensor: this dataset is well-suited for MCA in terms of both available bandwidth and phase coherence, and confirmed the indications derived by the theoretical analysis. Figure 2 shows the k values computed through MCA analysis by using different bandwidths (400, 300, 200 and 100 MHz). The k values are related to the interferometric fringes pattern of the full band interferogram. It can be noted that the k values map obtained by processing a bandwidth of 400 MHz reproduces properly the fringe pattern. It is worthwhile to point out that the k values map is computed on a pixel by pixel basis without any spatial integration of the information. This means that the number of k value classes can be inferred by the difference between the k values computed on two pixels PS_{fd} located at near and far range respectively.

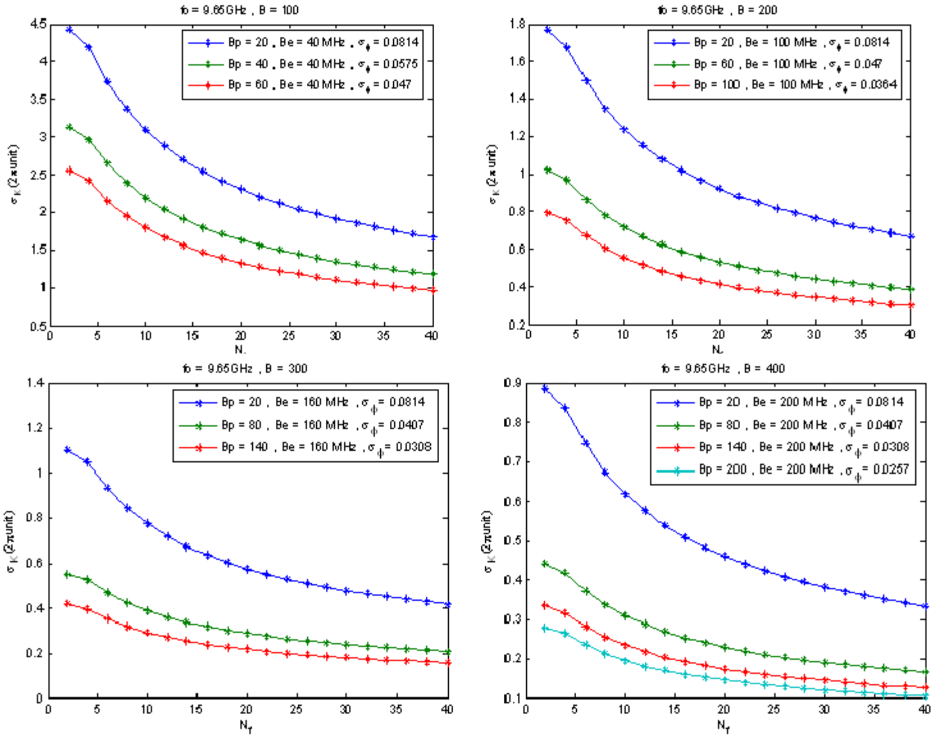

Figure 1. σ_k trends as a function of N_f, for B_p ranging from 20 to 200 MHz and for different bandwidth B = 100 MHz (top left), 200 MHz (top right), 300 MHz (bottom left), 400 MHz (bottom right).

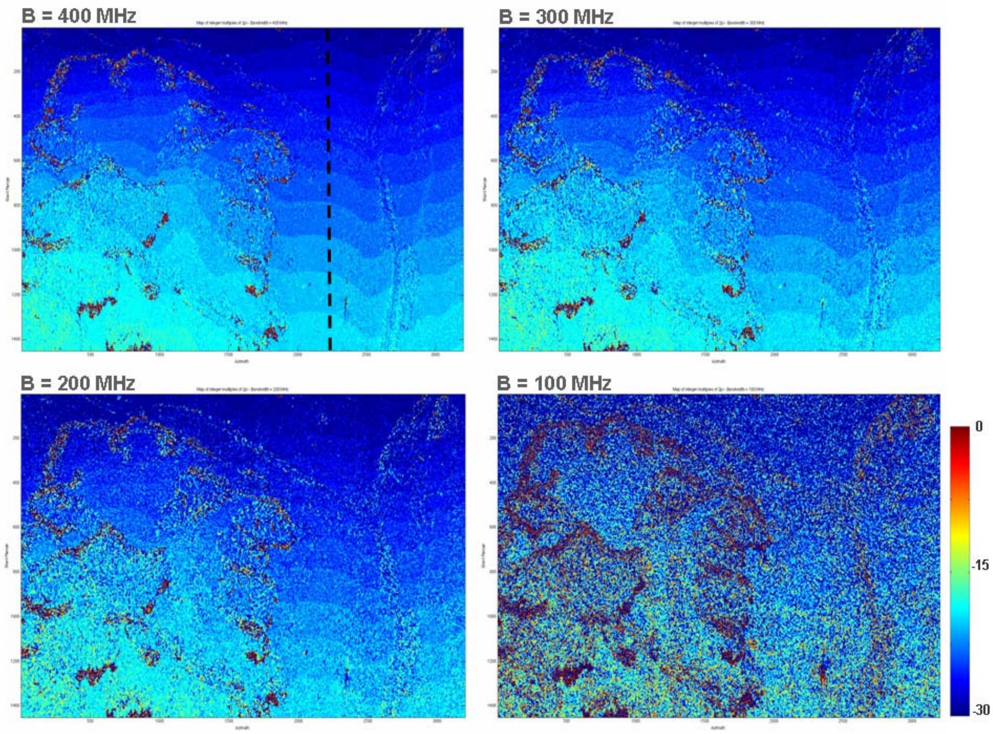

Figure 2. *k* values maps computed through MCA analysis by using different bandwidths (400, 300, 200 and 100 MHz, resp.). The *k* values are related to the fringe pattern since each fringe corresponds to a *k* value. It can be noted as the *k* values distribution obtained by processing a bandwidth of 400 MHz reproduces properly the fringe pattern. As the bandwidth decreases the fringe classification appears noisier. In particular it is evident that for *B* = 100 MHz, which is the standard available bandwidth for the TerraSAR-X spaceborne sensor in Stripmap mode, the fringe pattern disappears.

The constraints on the bandwidth represented the main critical aspect in the project implementation. The investigation of interesting innovative aspects, such as atmospheric component estimation and PS_{fd} vs PS comparison, was hindered by the lack of proper SAR data. Different spaceborne datasets acquired by both TerraSAR-X and COSMO-SkyMed were used to test and validate the developed procedures, even though the available bandwidths were mostly inappropriate. Only one TerraSAR-X experimental Spotlight interferometric dataset acquired on the deserted area of Ayers Rock (Australia) resulted promising for a full implementation of the project objectives. Although the MCA processor was not developed to perform precise InSAR processing of spotlight acquisitions, a validation of the MCA was possible and interesting results where achieved.

In particular, the validation activities were devoted to the following possible applications of MCA:

- the use of MCA for performing PU;
- the use of MCA for absolute height measurement on a pixel by pixel basis;
- the use of MCA to support and improve standard PU procedures;
- the use of MCA to support SAR images coregistration.

In figure 3 the flow chart of the experiments is sketched.

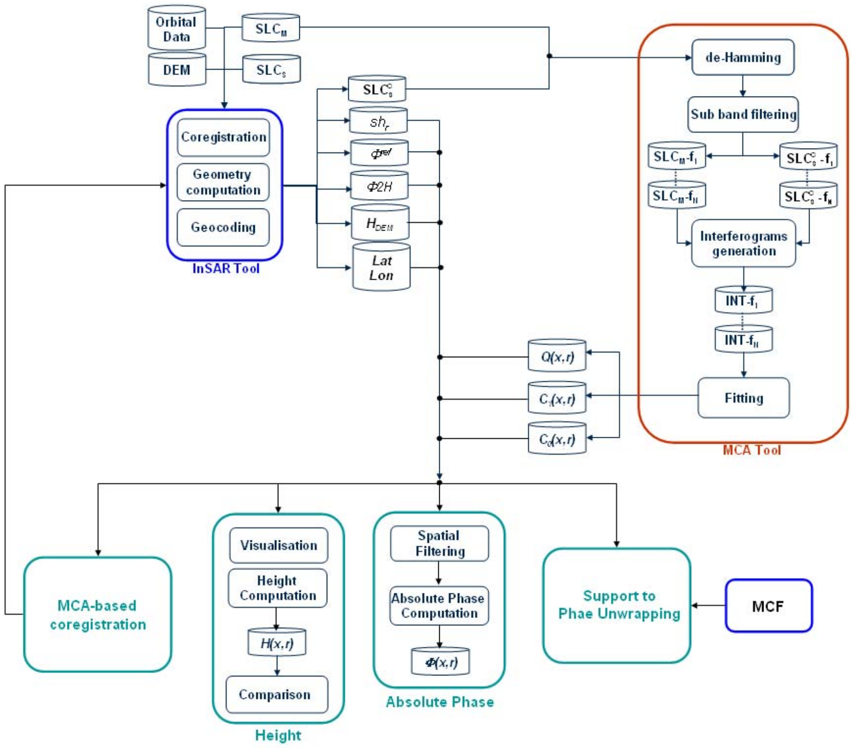

Figure 3. Experiment flow chart. The whole experiment requires different independent tools: InSAR pre-processing (blue), MCA tool (red), the tools for height computation, absolute phase computation, Phase Unwrapping and MCA-based coregistration (all in green).

A validation of the process was performed using the TerraSAR-X spotlight interferometric dataset: the full bandwidth of 300 MHz appears to be sufficient to derive absolute phase measurements on some points on the scene, as it results also from the theoretical parametric analysis. Although the MCA method works on single pixels, an almost continuous unwrapped phase surface can be derived by strongly filtering MCA measurements in the spatial domain. It was shown that this unwrapped phase surface derived through MCA is a valid representation of the interferometric phase unwrapped through conventional methods, thus further validating the approach. In figure 4 the 3D representation of the height profile obtained through MCA is shown together with an aerial photo of the Uluru monolite. It was also demonstrated that best results are obviously obtained using wide sub-band bandwidths and a high sampling rate, which reduces considerably the absolute phase standard deviation. However, retrieval of the absolute unwrapped phase values (theoretically allowed by the MCA approach and related to the complete radiation path from sensor to surface) still remains unreliable, due mainly to orbital parameters inaccuracy, which causes the presence of an offset in the results (related mainly to the reference phase compensation).

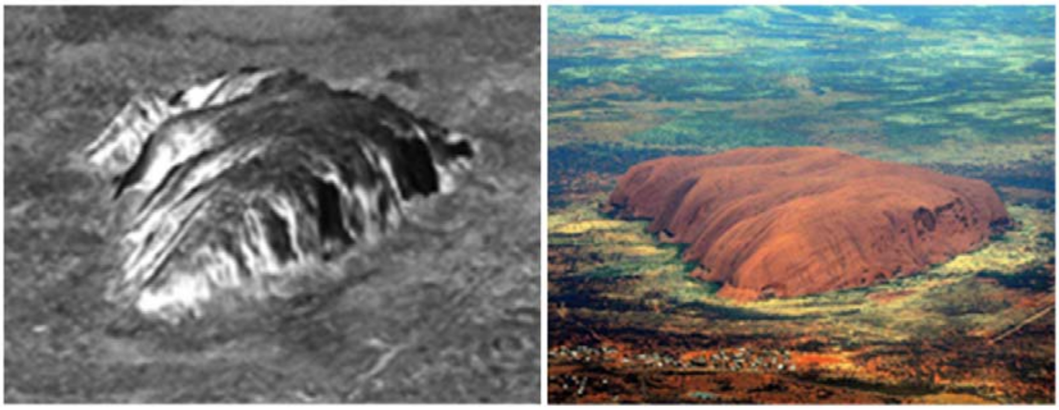

Figure 4. Uluru test site: Projected DSM (left). Aerial picture (right).

Concerning the absolute height retrieval, this may be theoretically possible on single pixels that show an adequate mean square error on the intercepts in the phase vs. frequency linear fit, provided that orbital parameters are known with sufficient accuracy and atmospheric contribution are negligible or compensated. Reaching a metric absolute vertical precision appears nearly impossible with respect to the required precision on the sensor position. Calibration procedures through independent measurements (e.g. reference points) are still required to fully retrieve the absolute heights. Figure 5 shows the maps of height values retrieved through MCA: each pixel is processed independently from the others. Height values are provided only for pixels where $\sigma_\Phi < 0.7$ (left) / 0.6 (right). Further constraints were applied on both σ_Φ values and intercept values to filter out the noise. The height values map on the left shows the presence of an offset if compared to the reference SRTM DEM., due to errors on orbital state vectors. In the present case the calibration procedure was performed by using the external SRTM DEM providing the result on the right of the same figure.

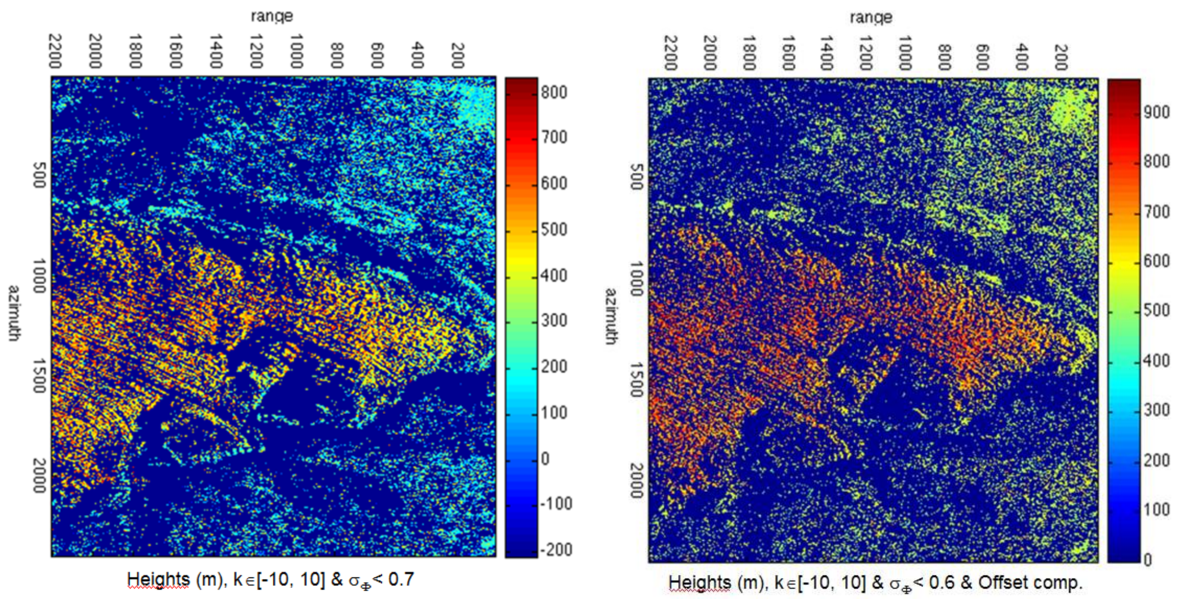

Figure 5. (Left) Heights map through MCA. (Right) Height values after a calibration procedure which compensates orbital errors.

Two different strategies were designed and experimented with the aim of using frequency information to support PU. Interesting results were achieved by using the TerraSAR-X spotlight interferometric dataset, where standard phase unwrapping methods are unable to provide the correct solution due to the steep terrain slopes, which violate the basic assumptions for conventional 2D phase unwrapping. In this case, the use of MCA provided a significant improvement, giving the possibility to estimate the relative corrections to be applied to the disconnected phase regions without the use of external calibration DEMs or GCPs. In figure 6 the corrected unwrapped phase (right) is reported and compared with the model phase obtained by using the SRTM C-Band DEM (left). The profiles of unwrapped phases along a range line are sketched on the bottom of the same figure: it can be appreciated as the phase derived by the minimum cost flow supported by MCA (yellow line) reproduce properly the DEM model while the phase unwrapped by the standard MCA method (pink) lay below the correct values.

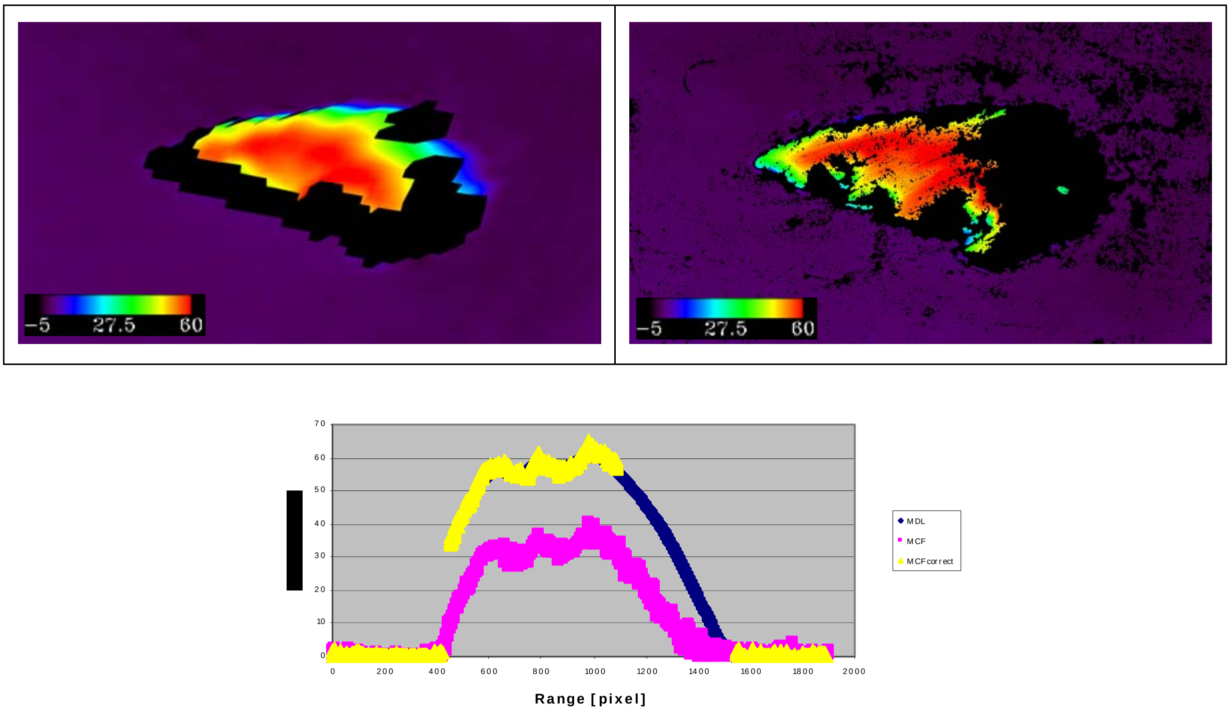

Figure 6. Top: Comparison of interferometric phase model obtained from SRTM C-band 3 arcsec DEM (left) w.r.t. minimum cost flow unwrapped phase after the unwrapping corrections (right). Bottom: Range profiles of interferometric phase on the middle of the analysed area: model (blue), minimum cost flow (pink), minimum cost flow after unwrapping corrections (yellow).

Moreover, a coregistration algorithm based on the split-band concept has been experimented by using both COSMO-SkyMed and TerraSAR-X data and integrated in the MCA processing chain. The proposed coregistration approach using the MCA was able to recover the co-registration errors, with improvements w.r.t. standard methods which depend on the geometrical configuration. The algorithm requires spatial averaging over windows of size of at least 150 m, and results useful mostly in cases when an external DEM, with suitable characteristics, is not available to correct the topography-induced distortions. The algorithm is robust and quite insensitive to the split-band parameters.

Thus, application of the proposed MCA approach appears reliable either as an alternative PU procedure, or for supporting standard PU procedures, provided that the bandwidth is wide enough. In order to also perform absolute path measurements, the impact of atmospheric signals and orbital errors require a further calibration step, possibly with the help of independent measurements (e.g. reference targets).

Some interesting innovative aspects were also investigated.

A model for coherence between sub-views from a single view acquisition was proposed and validated. Inter-band coherence can be considered as an information channel related to local scatterer distributions and scattering processes, this information channel being extracted from a single wide-band SAR acquisition. This figure is thus promising for classifying scene features according to their scattering mechanism.

Moreover, a first experiment was carried out concerning the comparison between pixels behaving temporally as Persistent Scatterers (PS) and pixels showing stable phase linear trend along the frequency (PSfd). Although the bandwidth available for the experiment was quite limited for MCA, the analysis suggested interesting considerations.
Future works will be devoted to:

- investigate the impact of the scattering nature on the frequency behaviour;
- improve the selection of frequency coherent pixels by defining the best quality figures according to the scene;
- introduce the MCA approach within an InSAR multi-temporal analysis scheme by using proper satellite SAR data (B>300MHz).

Concerning the datasets used for the experimentation: the sample airborne AES-1 dataset on Langnau is courtesy of SARMAP, the stripmap TerraSAR-X images on both Langnau and Venice test sites have been provided by DLR under a Scientific Use License for proposal MTH0397, the TerraSAR-X data over AyresRock are freely available by InfoTerra (http://www.infoterra.de/tsx/freedata/start.php) and the COSMO-SkyMed data have been provided by e-Geos.