Multi-mode ENVISAT ASAR Interferometry: Techniques and Preliminary Results

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Abstract

The paper focuses on the interferometric capabilities of the current and future SAR systems, like ENVISAT, RADARSAT-2 etc. We introduce a technique to get interferometric surveys by combining two images, coming from any SAR mode, together with a Digital Elevation Mode. The DEM is exploited during the interferogram generation to provide, at one time, an effective noise removal and the compensation for the topographic-dependent fringes. The final product is a “differential” (topography-compensated) interferogram to be used for monitoring over landslides, upswelling, etc.

An innovative technique is also discussed to estimate local coherence maps, to be used for classification and change detection. Such technique exploits windows whose shapes and sizes adapt locally to the target features, to attain at one time the highest resolution and the best statistical confidence. Finally, applications involving the various ENVISAT ASAR modes are discussed.

1 INTRODUCTION

ENVISAT ASAR sensor provides innovative and enhanced capabilities for interferometric applications like change detection and long term monitoring and classification. The sensor’s full resolution SAR, ScanSAR and alternating-polarization modes can in fact be exploited for generating repeat-pass interferometric surveys. The applications involving SAR and ScanSAR interferometry are well known and assessed in missions like RADARSAT [1] and SRTM [2]. Recently, a technique has been developed to combine interferometry and polarimetry [3], thus disclosing novel applications and potentials.

The different ASAR modes that can be exploited for interferometry are shown in Fig. 1, and their main features are summarized in Tab 1. A list of acronyms adopted in the paper is in Tab. 2.

ASAR IM compares to the traditional STRIP-SAR mode, to provide full resolution interferometry, on one of the seven accessible swaths, covering a range of incidence angles from 15° to 45°, and with either HH or VV polarization.
ASAR WSM is a ScanSAR mode, that accesses simultaneously the 400 km wide swath, and it is suited to be combined interferometrically with the full resolution IM for large scale coverage and fast revisit time.

ASAR AP mode images the same IM swaths, but switching two different polarizations: an AP survey can be either combined either with other AP mode survey, or with an IM mode one. Two interferograms are then generated with different polarizations, and these can be combined to provide a third, differential one. Its phase would be free from topography or meteorological artefacts and would depend only on the target polarimetric signature, for applications in agricultural and forests, change detection & classification [3, 4, 5].

In the paper we first present a technique that allows the interferometric combinations of any two of these modes, namely: IM/IM, AP/AP, AP/IM, WSM/IM together with a Digital Elevation Mode. Thereafter, we will approach the problem of coherence estimation and interferogram filtering by exploiting local windows that adapts their shapes to the area of uniform scattering, whereas their sizes are the finest one that still provide confident estimates. Finally, some examples are presented that had been achieved by means of ENVISAT acquisitions.

2 MULTI-MODE INTERFEROMETRY

The proposed technique takes advantage of a DEM that is always supposed to be available (at least a low resolution, global one like GTOPO30 or ACE), to perform at one time both the compensation of the topographic dependent fringes and the removal of volume scattering decorrelation.

The way a very coarse resolution image (like a ScanSAR WSM one) can be “optimally” combined with a fine resolution one comes out from Fig. 2. According to the spectral shift principle [6], the reflectivity imaged by one sensor is the same imaged by the other, but for a topographic dependent frequency shift. It is then possible, in principle, to combine many pixels in the fine resolution image with the proper “spectral shift” (computed basing on the DEM), and adding all their contributions to estimate that of the “large pixel” in the WSM image [8].

The simplest implementation of this idea will involve first the generation a synthetic interferogram, by exploiting the knowledge of the orbits and the DEM and then the compensation for these phase fringes to the IM image. The resulting image can then be multiplied with the WSM one to generate a virtual “Zero-baseline” (differential) interferogram, thus compensating for topography and, at the same time, removing the geometric decorrelation. This approach is quite different from the conventional DInSAR techniques that exploit the DEM only for removing the topographic dependent fringes with no effect on the geometric decorrelation.

This idea, just discussed for an IM / WSM combination [6], can be easily extended to any combination of SAR acquisitions, where resolution and Doppler Centroid can differ [8, 9, 10]. The implementation, summarized in the block diagram of Fig. 3, is straightforward. The model of the two SAR acquisitions, on the left of the figure, assumes that the same source reflectivity, modulated by a phase term that depends on the topography (the fringes), passes through two different filters, each representing the SAR end-to-end (acquisition + focusing) transfer function.

The two transfer functions can differ in the range and azimuth bandwidth (e.g. different resolutions), and also in the Doppler Centroid. Furthermore, on ScanSAR acquisitions like WSM and AP, the Doppler Centroid sweeps with azimuth. The block diagram in Fig. 3 shows in the right part the simplified sub-optimal implementation that achieves roughly the same quality as the MMSE interferometric combination discussed in [10]. Both master/slave images are first whitened (up to the available bandwidth) in range and azimuth, then compensated for the synthetic fringe pattern (derived from the
DEM) and, finally, filtered with the end-to-end transfer function of the other image. Such processing allows the combination of any SAR mode, however notice that an azimuth-variant filtering is required if at least one image is acquired in ScanSAR mode. In that case, it is necessary to process all the bursts independently, and mosaicking after generating the interferogram. As a welcome advantage of the presented approach one could note that the synthetic fringes provide a local map of the coregistration coefficients, once that they are converted in distance by scaling times $\lambda/4\pi$.

An example of the results achieved on a real ENVISAT data-set, is shown in Fig. 4. The interferogram has been multi-look averaged and geocoded, by exploiting a USGS SRTM DEM (sampled at 30 x 30 m), freely available on the web. Notice that geocoding is quite simple to be implemented as it trivially reverses the transformations assumed to get the synthetic interferogram shown in Fig 3.

### 3 COHERENCE ESTIMATION

The interferometric coherence [11] represents a measurement of the stability of the backscattered SAR signal over an area of interest. It is widely used either as a “reliability map” of the interferogram (e.g. a pixel-to-pixel measure of SNR), or for changes detection and classification [3, 4, 5]. Coherence maps are obtained by iterating the sampled estimator:

$$\hat{\gamma}(k, h) = \frac{\sum_{i,j} s_M(k-i,h-j) \bar{s}_S(k-i,h-j) \exp(i(\omega_k i + \omega_h j))}{\left(\sum_{i,j} |s_M(k-i,h-j)|^2 |s_S(k-i,h-j)|^2\right)^{1/2}}$$

for each pixel (k, h) of the coregistered master and slave images ($s_M$, $s_S$ respectively), after compensating for the estimate of local slopes ($\omega_k$, $\omega_h$).

The estimator (1) is strongly influenced by non-stationarities of amplitudes (see reference[12]): it is enough to have one dominant sample in the summations in (1) to get $\hat{\gamma} = 1$, disregarding the actual scene correlation. Besides this biasing, the estimator variance is likewise worsened by the reduction of the freedom degrees. The technique here discussed follows the approach proposed in [13], where the estimation window is adapted over areas of homogeneous backscatter, identified by a refined Lee speckle filtering [14]. We furthermore adapt the window size according to the statistic of the measured coherence [12]. The goal is to get high spatial resolution (fine details) in areas of high coherence and coarse resolution over decorrelated targets. The local slopes, ($\omega_k$, $\omega_h$) involved in (1), are estimated by iterating a fast 2D-FFT over overlapped windows in the interferogram. Such windows can be rather large as the residual topography (after DEM removal) is assumed smooth.

#### 3.1 SPACE ADAPTIVE ESTIMATE

The coherence estimate is detailed in the scheme of Fig. 5. The interferogram, obtained by combining the MMSE filtered master and slave images, is first coarsely azimuth multi-look averaged. This is done either by averaging lines in full resolution interferometry or averaging interferograms coming from different bursts in ScanSAR and AP interferometry. This first average reduces smooth amplitude fluctuations due to speckle, enhancing SNR.

The coherence estimator then adopted is a slightly modified version of (1):
\[
\gamma(k, h) = \sum_{i,j} s_{ML}(k,h)s_{SL}(k,h) \exp(j(\omega_k i + \omega_h j))
\]

where \(I(\cdot)\) represents the multi-look averaged interferogram, and \(s_{ML}, s_{SL}\) two multi-look averaged amplitudes derived from the master and slave image respectively. As such amplitudes are requested with the highest ENL (Equivalent Number of Looks), to improve detection of backscattering, they are directly derived from the master and slave image with no MMSE filtering at all.

The purpose of this algorithm is to identify a subset of pixels, in the summations in (2), all connected to a seed one (the window centre in our case) and with the same characteristic (same colour, in the normal case, stationary in our case). Starting from the seed position, the algorithm first identifies all the connected pixels along the increasing and decreasing column direction. For all the pixels in this span the connectivity test is then repeated for row above and below. All the connected pixels identified at this step are considered as new seed positions and the algorithm is iterated recursively.

Since the stationary pixels identification step possibly discards some of the pixels contained in the starting window that are considered too different from the central one, in areas of high spatial variability of the SAR amplitude it is possible that only few pixels are considered as stationary. So doing one would risk to get poor and biased estimates in the area of low coherence and high spatial variability of the amplitudes. To overcome this problem, a first rough estimate of the coherence is performed by using a constant relatively small window. If the first estimate of the coherence is above a threshold, a small number is also accepted for the pixels identified as stationary; if the first estimate of the coherence is below this threshold and too few points are identified as stationary, the area scan is repeated by using a larger value for the filter parameter that expresses the speckle’s strength: \(\sigma_v = \text{VAR}(|u|^2)/E(|u|^2)\) in [14]. This process is iterated until a minimum number of pixels are reached for this class of coherence.

An example of the results achievable is shown in Figs. 6, 7, 8. Fig. 6 shows how the amplitude fluctuations due to speckle have been smoothed out by Lee filter. Fig. 7 shows the final coherence map, notice the capability to render fine details while keeping good statistical confidence, and, at the same time, to adapt to the irregular shapes of the agricultural fields. Finally, the interferogram phase before and after space adaptive filtering is shown in Fig. 8. Notice that most of the noise has been removed and confined in the areas of low coherence, these areas should then be masked out.

### 4 APPLICATIONS AND EXAMPLES

The multi-mode interferometric combination, when applied to the different ENVISAT modes, is suited for the different applications, depending on the mode itself.

#### 4.1 IM / IM interferometry

The combination of two Image Mode acquisitions, taken from the same orbit and a repeat interval multiple of 35 days, is suited for all the full resolution differential interferometric applications like change detection, land cover characterization,
natural hazards and even DEM generation. An example of a repeat pass ENVISAT IM/IM interferogram has been already provided in Fig. 4 (area of Las Vegas). It is worthy to note that the coherence, in this desert areas, gets close to 0.95, that corresponds to a SNR of about 10 dB, and this is consistent with the figure expected from the system (\( \sigma_0 = -20 \) dB in IS4, mean \( \sigma_0 = -10 \) dB).

### 4.2 Alternating Polarization

The Alternating Polarization mode of ASAR (see Fig. 1) is capable to provide multi-polarimetric acquisition by means of ScanSAR acquisitions, where switching is made on polarizations instead than sub-swaths.

The purpose of AP interferometry is to estimate the Polarimetric Phase Difference (PPD) and the polarimetric correlation [15]. This information is of great help in the processes of identification and classification of different types of scattering mechanisms areas, and where the penetration depth is different at different polarizations.

The ASAR sensor is capable of simultaneously acquire two different ScanSAR images on the same swath: HH/VV, or HH/HV, or VV/VH. The two AP images have different spectral contributes and could not be combined together, but rather with another AP mode or an IM mode acquisition (either in HH or in VV mode), of the same area. The IM data is split in two parts, each of them coherent with either the HH or the VV AP polarization, through an azimuth space varying filtering [15]. Two interferograms are formed, each of them with a different polarization of the AP set, for example one IM_HH+AP_HH and the other IM_HH+AP_VV. The achievement of these interferograms requires that the IM image is first space-variant filtered to mimic each of the two AP images, a particular case of the scheme in Fig. 3. Obviously, both interferograms will be affected by topographic fringes plus atmospheric and temporal changes. However, it is possible to compute a further interferogram differentiating the two just calculated. In this interferogram, the topographic and atmospheric contribution will be cancelled, like for a simultaneous acquisition, provided that there is enough temporal correlation. An example of such interferogram is provided in Fig. 9.

### 4.3 - WSM / IM Interferometry

The large swath ScanSAR WSM acquisition can be usefully combined with the full-resolution SAR one, for different applications in the field of monitoring, particular over large scale. An example of a combined WSM/IM interferogram is in Fig. 10. The interferogram refers to the area of Las Vegas: an USGS 1-Degree DEM was used for interferogram generation. The quality of the DEM and the accuracy of preliminary orbits were enough to allow fringe compensation also in the sloped terrains, as the detail in Fig. 10 shows. The same figure remark that, if a simple model of ellipsoidal earth is assumed in place of the DEM, no coherence is achieved in presence of slopes, due to the volume decorrelation and the small WSM bandwidth, 7 MHz\(^1\).

The target application for the WSM/IM combination should be large scale monitoring. We can think of two different systems. The first system, could exploit the large swath capabilities of ScanSAR to provide alerts over hazardous areas, and unsolicited events. The use of WSM would reduce the revisit time to a few days due to the very large ScanSAR swath. Such system would require that, for any new WSM acquisition, there has been already acquired an IM over the same area and with a suitable baseline. A different application would be provided by reversing the order of acquisitions. A first set of WSM images could be acquired, say over the area of interest, in a short time.

\(^1\) Currently the WSM bandwidth in SS1 has been increased up to 15 MHz, and this would result in a better interferometric quality.
Thereafter, every new full resolution IM image could be combined with a proper one in the database to get a (differential) interferogram. Such a system would be suitable to monitor large-scale changes like surface deformation, meteorological effect, earth tides, according to user demand.

ACKNOWLEDGMENTS
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CONCLUSIONS
A technique was shown to combine interferometrically the different ASAR acquisition modes: IM, WSM, and AP. This technique takes advantage of a DEM to compute a synthetic interferogram, given the orbits of the two acquisitions. This synthetic interferogram is exploited for image co-registering, for removing volume decorrelation and for providing a final, differential interferogram. Thereafter, the transformations from DEM to SAR reference can be reversed for geocoding.
A prototype software code has been developed under ESA contract and tested with all the foreseen multi-mode combinations. Preliminary results of ENVISAT interferograms, achieved during the commissioning phase demonstrated both the feasibility of such combinations and the good quality of ENVISAT repeat pass interferometry.
REFERENCES

FIGURES AND TABLES CAPTIONS

Figure 1: ENVISAT ASAR “interferometric” modes.

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Table 2: Acronyms adopted in the paper.

Figure 2: Zero-baseline steering.

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Figure 4 - Full resolution, 100x100 km ENVISAT interferogram of Snow Canyon State Park (Las Vegas). Above: geocoded phase, left, and amplitude, right. Below: coherence map, left, and histogram, right. Baseline: 120 m. Swath: IS4 (30°), acquisition dates 7/11/02 and 16/01/03. The interferogram has been obtained by exploiting precise orbits (DORIS) and a USGS SRTM DEM, with no further corrections. The residual phase, less than one cycle (black to white), has some contributions related to topography (due to a small misalignment of DEM and SAR images), plus a marked atmospheric phase screen, but no significant motion.

Figure 5 – Schematic block diagram of the optimal interferogram generation and adaptive coherence estimate.

Figure 6 – Left. Full resolution image: amplitude. Right the same image after refined Lee speckle filtering. Areas of homogenous targets have been identified and then exploited by the space adaptive coherence estimate.

Figure 7 – Coherence maps (abs value), estimated by the proposed adaptive technique. Notice the capability of the estimator to fit irregular shapes.

Figure 8 – Interferogram phase before (left) and after (right) adaptive multi-look filtering. Notice that the topographic dependent fringes have been already compensated in the processing (by exploiting a DEM).

Figure 9 – Differential interferogram obtained by combining two interferograms: one AP-VV/IM-HH and one AP-HH/IM-HH, area of Basel (Swiss). Acquisition dates: 16/09/02, AP, and 21/10/02, IM, normal baseline 45 m. The Polarimetric Phase Difference, on the left, depends on the distance between the HH and VV scattering centres of each target. It is not influenced by topography or atmosphere; however it is affected by the decorrelation in the 35 days revisit time. Note the highly correlated contributions coming from the village of Basel.
Figure 10 – Combined IM / WSM interferogram in the area of Las Vegas. Normal baseline 120 m, temporal interval 35 days, swath IS2/SS1. (a): full frame, phase, and (b): amplitude. (c): phase of the detail in the squared box, achieved by exploiting the DEM. (d): same as (c) but compensating only for ellipsoid earth. Notice that, in this last case, the deorrelation in the highest slopes.
**Figure 1**: ENVISAT ASAR “interferometric” modes

<table>
<thead>
<tr>
<th>Mode</th>
<th>Swath/ Inc. angle</th>
<th>Coverage km</th>
<th>Geometric Resolution</th>
<th>POL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM</td>
<td>14°–45°</td>
<td>50-100</td>
<td>30 m</td>
<td>VV or HH</td>
</tr>
<tr>
<td>AP</td>
<td>14°–45°</td>
<td>50-100</td>
<td>30 m</td>
<td>HH/VV, HH/HV, VV/VH</td>
</tr>
<tr>
<td>WSM</td>
<td>16°–44°</td>
<td>400</td>
<td>150 m</td>
<td>VV or HH, VH or HV</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ACE</td>
<td>Altimeter Corrected Elevation</td>
</tr>
<tr>
<td>AP</td>
<td>Alternating Polarization</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DInSAR</td>
<td>Differential Interferometric SAR</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>GDEM</td>
<td>Global DEM</td>
</tr>
<tr>
<td>GTOPO30</td>
<td>Global Topographic 30-arcsec DEM</td>
</tr>
<tr>
<td>IM</td>
<td>Image Mode</td>
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<tr>
<td>MMSE</td>
<td>Minimum Mean Square Error</td>
</tr>
<tr>
<td>PPD</td>
<td>Polarimetric Phase Difference</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture RADAR</td>
</tr>
<tr>
<td>ScanSAR</td>
<td>Scanning SAR</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>WSM</td>
<td>Wide Swath Mode</td>
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