ABSTRACT

The Multi-Chromatic Analysis, as introduced in [1], consists in performing a spectral decomposition of each image of an interferometric pair. Spectral decomposition is performed extracting sub-bands in range frequency domain, each extracted sub-band leading to a range sub-look of the observed scene, here named a chromatic view, centered on its own carrier frequency but at lower range resolution. From a single interferometric pair, one can then generate several interferometric pairs exploring the frequency band centered on the carrier frequency of the initial acquisitions. The interferometric phase of spectrally-stable scatterers evolves linearly with the sub-band central frequency, the slope being proportional to the absolute optical path difference. Unlike the standard “monochromatic” InSAR approach, this new multi-chromatic technique allows performing spatially independent and absolute phase unwrapping (PU). Potential applications for the study of spectrally-stable targets include topographic measurements, atmospheric research or urban monitoring.

The technique appears optimally suited for the new generation of satellite sensors, which operate with large bandwidths to reach metric range resolution. Previous work on the subject has started demonstrating the practical feasibility of the technique by using a set of SAR data collected by the airborne AES-1 radar interferometer, operating at X-band by multi-channel electronics, which provides a total radar bandwidth of 400 MHz.

This work presents first successful applications of the technique using TerraSAR-X Spotlight interferometric dataset acquired on the desert area of Ayers Rock (Australia), which satisfies the processing requirements derived from previous investigations. In particular, it was possible to validate the use of MCA for performing absolute PU as well as for height measurement on a pixel-by-pixel basis. However, height measurements still needs a calibration procedure through independent measurements (e.g. reference points) due to the impact of atmospheric signals as well as orbital errors.

A height surface derived by MCA is presented and compared to the reference SRTM DEM.

1. INTRODUCTION

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 in [1] and further developed [2], led to the so-called Multi-Chromatic Analysis (MCA) of SAR interferometric data. MCA uses interferometric pairs of SAR images processed at spectral range sub-bands and explores the phase trend of each pixel as a function of the different central carrier frequencies. The phase of spectrally-stable scatterers evolves linearly with the sub-band central wavelength, the slope being proportional to the absolute optical path difference. This new multi-chromatic technique allows performing spatially independent and absolute phase measurements, if the attention is focused on single targets exhibiting stable phase behavior across the frequency domain, without requirement of spatial phase unwrapping (PU), which is needed in the standard monochromatic processing. The same approach allows also precise coregistration between the master and slave images [3]. Moreover, MCA can be applied to single wide-band SAR image to investigate the inter-band coherence [4]. This figure is related to local scatterer distributions and scattering processes, thus being a promising tool for classifying scene features. Also delta-K interferometry [5] explores the spectral dimension but, differently from MCA, it uses just a couple of sub-bands views.

Previous work on MCA has started demonstrating the practical feasibility of the technique by using simulations ([2], [6]) as well as a set of SAR data collected by the airborne AES-1 radar interferometer, operating at X-band by multi-channel electronics, which provides a total radar bandwidth of 400 MHz ([7],[8]).

In particular, through a simplified model, we obtained a first evaluation of the impact of the MCA processing parameters on the phase estimation performances. Results show that the estimation is improved by using wider bandwidths for the sub-look images, and by increasing the number of sub-looks. Moreover, a total available bandwidth of about 300 MHz seems to be required to provide reliable results. Thus, the technique appears optimally suited for the new generation of satellite sensors like as TerraSAR-X (TSX), which operates with larger bandwidths than previously available instruments.
In the following section, we briefly review the MCA mathematical formulation as well as some implementation aspects. In section 3 the TerraSAR-X dataset used for the experiment is described. Before concluding, section 4 presents commented results obtained using MCA for generating both the unwrapped phase and absolute height measurements of the observed scene.

2. MULTI CHROMATIC ANALYSIS PRINCIPLES AND IMPLEMENTATION ASPECTS

The Multi-Chromatic Analysis, as introduced in [2], uses interferometric pairs of SAR images processed at range sub-bands and explores the phase trend of each pixel as a function of the different central carrier frequency. The phase of suitable “spectrally-coherent” scatterers evolves linearly with the sub-band central wavelength, the slope being proportional to the absolute optical path difference.

To perform MCA in InSAR configuration, the range sub-look images, i.e. the chromatic views, have to be generated for both master and slave images with the same parameters setting: \( \{ I_{M,i}, I_{S,i} \} \) with \( i = 1, \ldots, N_f \). Then, a set of \( N_f \) interferometric phase fields can be generated by cross-multiplying the master and slave chromatic views relative to the same central frequency \( f_i \). Since only wrapped phase values are measured, the following relation holds:

\[
\Phi_i^w(x, r) = -2\pi \cdot k(x, r) - \frac{4\pi}{c} \cdot \Delta R(x, r) \cdot f_i = C_0(x, r) + C_1(x, r) \cdot f_i;
\]

(1)

where \( \Delta R = R_M(x, r) - R_S(x, r) \), \( R \) being the optical path between the sensor and the target on the ground, \((x, r)\) being the azimuth–range pixel coordinates and \( k(x,r) \) the integer number of wavelength between the sensor and the target.

According to (1), the wrapped interferometric phase will show a linear trend with central carrier frequency, the linear term \( C_1(x,y) \) being proportional to the absolute optical path difference \( \Delta R \):

\[
\Delta R(x, r) = -\frac{c}{4\pi} \cdot C_1(x, r).
\]

(2)

The coefficient \( C_0(x, r) \), is proportional to the \( k \) integer number of \( 2\pi \) that has to be added to the wrapped interferometric phase of the pixel \((x, r)\) in order to obtain its absolute unwrapped phase value. Phase unwrapping may thus be performed on a point-by-point basis without requiring spatial phase gradient estimations. This solves the main problem of conventional spatial phase unwrapping algorithms at the cost of a range resolution loss that depends on the width of the sub-bands \( B_p \).

Once the set of interferometric phase fields has been generated, the basic MCA processing step is a point-wise estimation of \( C_0 \) and \( C_1 \) through a linear regression method. Like in standard interferometric phase analysis in the spatial domain, the phase of a pixel can be wrapped along the frequencies, too. Hence, before performing the linear fit with standard methods, a one-dimensional phase unwrapping step is needed. Thus, in setting the MCA processing parameters, the frequency spacing, \( df \), should be narrow enough to guarantee no aliasing condition for any elevation in the scene investigated.

An a posteriori estimation of the multi-frequency phase error can be provided by the standard deviation (STD) of the differences between the measured interferometric phases at the different frequencies \( f_i \), and the corresponding values computed by the derived linear model:

\[
\sigma_\phi = \sqrt{\frac{1}{N_f} \sum_{i=1}^{N_f} [\Phi_i(x, r) - C_0(x, r) - C_1(x, r) \cdot f_i]^2}.
\]

(3)

STD (3) evaluated on a pixel-by-pixel basis, can be assumed as a quality index of the measurements: the smaller \( \sigma_\phi \), the better is the achievable accuracy for terrain heights. Hence the last processing step consists in selecting those pixels (targets) whose inter-band phase STD is below a reliability threshold:

\[
PS_{id} = \{(x, r) \mid \sigma_\phi(x, r) \leq \sigma_{th} \}.
\]

(4)

The statistical distribution of the \( k(x, r) \) values can also be exploited, in order to decrease the error of the point-wise estimates. It must be noted from (2) that the absolute path can be derived multiplying the \( C_1 \) by a large scale-factor \( c/4\pi \). Consequently, the method is highly sensitive to noise and, like in classical interferometry, the interferometric coherence must be preserved to grant reliable results.
Therefore, using MCA on highly coherent points allows getting local absolute measurement that can come in support and improve classical phase unwrapping procedures. MCA can also come in support to improve image coregistration, which is less demanding in terms of precision with respect to absolute phase unwrapping.

2.1. Implementation Aspects
MCA processing can start either from raw data or from SLC data. If starting from raw, as it was the case using AES data, chromatic views are generated at the end of the focusing process, performing range sub-looks in the range frequency space before the last Fourier transform bringing the signal back to the image domain. With recent sensors, like TerraSAR-X or COSMO-SkyMed, raw data are not made available to users, implying thus to start working from SLC data.
A global flow chart of the implemented processor starting from SLC data is shown in figure 1. Equivalence between MCA performed starting from Level 0 and Level 1 can be proven. The standard processors for Level 1 data production are considered as linear and phase preserving, thus all information in the frequency space is theoretically preserved, except for a filtering step at the end of the focusing process: the so-called Hamming filter. This step is generally applied to focused SAR data in order to reduce side-lobe ratio of the point scatterers response at the expense of a small loss of resolution. General apodization filtering consists in multiplying the data in the Fourier space by the following function:

\[ H(f, \alpha) = a - (1 - \alpha) \cdot \cos(2\pi(f - f_0)) \]  

(5)

The factor \( \alpha \) is the apodization coefficient. The proper Hamming filter is characterized by an apodization coefficient of 0.54. In the case of TerraSAR-X data, the apodization coefficient used is 0.6 for all acquisition modes. Nevertheless, the term “Hamming filter” is used to indicate this operation.

In order to avoid asymmetry in the spectrum, a de-Hamming filtering step is required along range before the pass-band filtering: an inverse apodization filter, defined as \( 1/H(f, \alpha) \), must be applied in the Fourier space before splitting into sub-bands.

Figure 2 shows an example of de-Hamming processing. The left plot shows the averaged FFT of TerraSAR-X SLC data (blue), the theoretical Hamming filter (green), the theoretical TerraSAR-X apodization filter (red) and the inverse apodization filter (black). The right plot shows the range Fourier transformed TerraSAR-X data, averaged on 1000 lines, after de-Hamming process.

Image coregistration consists in estimating shifts between image pixel centers of corresponding scene features in both the master and the slave image. The coregistration map is then used to transform the slave image toward the master image geometry, transformation being generally approximated through interpolation and re-sampling processes. In order to save considerable processing time, it is of course advisable to perform coregistration only once, on the full-band images, before sub-looks generation, rather than \( N_f \) times after band-splitting. In this configuration, i.e., performing the sub-band filtering after re-sampling induces the loss of a phase term related to the range shift applied to the slave image. This term has thus to be taken into account in order to infer properly the path difference between the two acquisitions. The range shift matrix being available as a side-product of the coregistration step, the needed phase compensation is a trivial and computationally inexpensive task compared to the coregistration process of every sub-looked interferometric pairs. It is worthwhile to point out that the distance related to the coregistration range shift represents a coarse estimation of the path difference between master and slave based on the amplitude cross-correlation, similar to what is done through radargrammetric techniques by using very large parallax values [9]. So what MCA is measuring, following this processing approach, is the coregistration error.

This approach is advantageous also with respect to the constrain on \( df \) needed to avoid aliasing along the frequency domain. Since \( \Delta R \) is decreased by a factor proportional to coregistration shift the minimum value of \( df \) is increased of the same amount, thus slightly relaxing the constraints on the processing parameters.

In Fig. 1 the MCA global flow chart is sketched with all the different tools involved: the InSAR pre-processing (blue), MCA tool (red) and the tools for height computation, absolute phase computation, Phase Unwrapping and MCA-based coregistration (all in green).

3. DATASET DESCRIPTION

The Ayers Rock dataset consists of two images acquired by the TSX satellite over the Uluru monolith (Australia) in spotlight mode. In Fig. 3, a quick look of the SAR image is presented (A) as well as an optical image of the same area extracted from Google-Earth (B). Relevant TSX parameters are shown in the inset table in plot A. The full bandwidth of 300 MHz satisfies the constrain coming from the preliminary analysis of the MCA feasibility and performances [3]. The imaged area is 4.6 × 3.6 km² wide. The selected area is characterized by a plateau and, at the centre of the image, by the world-renowned sandstone formation, called Uluru, that stands about 320 meters high. This rock formation presents strong terrain slopes that cause layover and shadow effects clearly visible in the SAR amplitude image. The land coverage is mainly bare, leading to low temporal decorrelation.

A Digital Elevation Model (DEM) derived from SRTM mission is available on the same area. The DEM has a resolution of 90x90 m² and has been resampled onto the SAR geometry to allow direct comparison wrt the products derived by MCA.
4. RESULTS

In the following we present the application of MCA to perform both phase unwrapping as well as absolute height measurement.

4.1. Phase Unwrapping

The aim of this experiment is to validate the use of MCA as tool for performing phase unwrapping. Thus in this case the goal is to provide an approximated phase surface that represents the absolute phase except for a constant offset. A classical interferometric processing was performed without using the MCA-assisted coregistration procedure in order to point out possible effects of local mis-registration errors.

The co-registered images of the Ayers Rock test site were processed to perform the MCA. Each image was split into 21 sub-bands of 100 MHz each. Sub-band central frequencies gap is thus of about 10 MHz. Very few fringe displacement are visible between adjacent sub-band interferograms, each one being very similar to the one obtained from classical interferometric processing. This confirms that for each point, coregistration is highly accurate. Obviously, only for the fringes on the Uluru monolith is some slight fringe displacement observable. This is due to the fact that for this non flat area, coregistration is locally less accurate. Consequently, the phase component due to coregistration error in the MCA processing is more pronounced.

Phase slope was thus measured for each point and the coregistration-induced phase slope was added to the measured one to derive the complete phase slope. This phase slope is then multiplied by the original carrier frequency to derive the absolute phase shown in Fig. 4 (B). This absolute interferometric phase shows features related to the scene. Nevertheless, as can be seen on the mean square error of computed intercepts, this absolute phase measurement is not sufficiently precise to lead to a smooth phase surface. The mean error is of about 15 radians, i.e. ~2.5 cycles. Only a few points, less than 0.5%, show an absolute interferometric phase measurement that is derived with an accuracy of less than half a cycle.

Consequently, we filtered this absolute interferometric phase measurements using a median filter to derive a smooth continuous phase surface, with phase jumps from one pixel to its neighbor lower than half a cycle. This smoothed absolute phase measurement was then computed modulo $2\pi$ to show the underlying interferogram. The resulting fringe pattern is shown in Fig.4 (C) for comparison with the original one in Fig.4 (A).

Even if the interferogram derived from the smoothed phase is still noisy, the same structure is clearly observable in both interferograms. Moreover, the number of fringes on the Uluru monolith as also their shape appears quite well preserved. To verify this statement, we used the smoothed absolute interferometric phase to flatten the classical interferogram. The result is shown in Fig.4 (D).

Clearly, the flattening is successful. There is less than one residual fringe on the whole flat area, as well as on the monolith top. The only parts where the error appears larger are those showing steep slopes, where smoothing is clearly destructive. Obviously, the areas on which the absolute phase derived through MCA processing is noisy due to important losses of interferometric coherence are not flattened and stay noisy.

It is of prime importance to observe that the top of the monolith and the flat surface are now connected and are part of the same fringe. Consequently, the flattening is fully correct. In itself, this result is a full validation of the MCA process for phase unwrapping. Since the derived unwrapped interferometric phase allows flattening the classical interferogram, it means that this smoothed absolute phase surface is a correct unwrapped version of the classical interferogram within
less than a cycle. Therefore, the smoothed phase surface may be used to derive the integer number of fringes while the classical interferogram gives the residual modulo-2π phase to lead to the absolute phase.

4.2. Absolute height retrieval

The goal of this experiment is to assess the reliability of height measurements through MCA. This experiment was performed on a patch of size 2400 × 2400 pixels which covers part of the flat plateau as well as part of the rock. InSAR pre-processing was performed in order to generate the coregistered SLC images as well as the ancillary data needed to compute height values through $C_1$. All these geometrical parameters vary on a pixel-by-pixel basis according to the sensor coordinates.

In order to compare the heights inferred by MCA w.r.t. independent external measurements, a Digital Elevation Model (DEM) provided by the SRTM mission was back-projected onto SAR geometry. The 3D visualisation is shown in Fig. 5 (B): it can be noted that where steep slopes occur on the terrain, void pixels are present in the SRTM DEM. The heights range from 500 m on the flat plateau up to about 850 m on the top of the rock.

Different sets of MCA parameters ($B_p$ and $N_f$) were exploited to compute $PS_{id}$, $C_1$, $C_0$ and consequently the height values. All the configurations were selected in order to avoid phase aliasing along frequencies. In the following we show results obtained using 31 sub-bands with $B_p$=60 MHz.

Comparison between the SRTM and MCA DEM, computed on pixels having a phase standard deviation $\sigma_\phi < 0.7$, shows a global offset of the MCA DEM of about -300m with respect to the SRTM DEM.

Although the retrieval of the absolute phase values is theoretically possible by the MCA approach can be strongly affected by artifacts due to the atmosphere as well as by the orbital parameters inaccuracy, which causes the presence of an offset in the results (related mainly to the reference phase compensation). A first assumption in performing absolute height measurements is that phase artifacts due to the atmosphere are either negligible or properly estimated and removed. The former assumption holds when real–time (single-pass) interferometry is performed, while the latter requires either proper independent measurements of the parameters used for atmospheric modeling, or a multi-temporal procedure able to filter out the atmospheric contribution by exploring a stack of SAR images.

Errors in orbital state vectors impact on the computation of geometrical parameters, which in turn are involved in the computation of both the reference ellipsoidal phase and the coefficient of phase–to-height conversion [10]. Hence, absolute measurements (both in phase and height) are strongly compromised unless either precise orbital parameters, or measurements on reference points, are available.

Although, we are dealing with repeat pass interferometry which involves possible atmospheric artefacts, the measured offset in the present experiment is probably due to errors on orbital state vectors. Thus a calibration is required to remove this offset.

In the present case the calibration procedure was based on the knowledge provided by the SRTM DEM. Further constraints were applied on both $\sigma_\phi$ values and intercept values to filter out the noise.

In order to generate the height surface of the Uluru monolith, a median spatial filtering on a window size of 21×15 in range and azimuth respectively was applied to filter noise. The result is shown in Fig. 5 (A) where the SAR amplitude is superimposed on the 3D model of the height. For comparison purpose, in Fig. 5 (B) we present also the 3D view of the SRTM DEM resampled on SAR geometry. Both height model are very similar and show the same range of height values. Moreover, the height surface derived by MCA doesn’t show the void values presented in the SRTM DEM.

5. CONCLUSIONS

The MCA is an innovative interferometric technique which looks at frequency-stable targets and is potentially able to provide absolute phase unwrapping on highly coherent points to support standard phase unwrapping as well as coregistration algorithms and to perform topographic measurement. Previous investigations showed that MCA requires a bandwidth of the order of 300MHz to lead to reliable results. Recently launched sensors now offer such requirement. Previous work on the subject has started demonstrating the practical feasibility of the technique by using a set of SAR data collected by airborne radar interferometer, operating at X-band with a bandwidth of 400 MHz.

In the present work we presented the first successful application of the MCA to spaceborne SAR data for both phase unwrapping and height retrieval.

A full validation of the MCA application to satellite data was performed using the experimental spotlight dataset on the desert area of the Uluru Monolith (Australia): the full bandwidth of 300 MHz appears to be sufficient to derive absolute phase measurement on some points on the scene, as it results also from previous theoretical investigations. A valid unwrapped phase surface can be derived by strongly filtering MCA measurements. It was shown that the derived unwrapped phase surface is a valid representation of the unwrapped interferometric phase.
Figure 4. (A) Original interferogram derived from classical interferometry. (B) Absolute interferometric phase derived from MCA process. (C) Interferogram resulting from smoothed absolute interferometric phase derived from MCA processing. (D) Classical interferogram flattened with the smoothed absolute interferometric phase.

Figure 5. (A): SAR amplitude draped on the height surface derived through MCA on the Uluru monolith. (B): 3D view of the DEM provided by SRTM and resampled on SAR geometry.
Concerning the absolute height retrieval on single pixels, it would be possible on pixels that show an adequate mean square error on the intercepts in the linear phase vs. frequency fit, provided that orbital parameters are known with proper accuracy, and atmospheric contributions are negligible or compensated. Reaching a metric absolute vertical precision appears nearly impossible due to the very high precision required on the sensor position. Calibration procedures through independent measurements (e.g. reference points) are still required to fully determine the absolute heights.

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7. REFERENCES