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MULTIDIMENSIONAL VERY HIGH RESOLUTION SAR INTERFEROMETRY FOR MONITORING ENERGETIC STRUCTURES

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ABSTRACT

This paper presents a novel strategy for Stable Scatterers detection and tracking by repeat-pass SAR interferometry by coupling sub-band / sub-aperture decomposition prior to the GLRT-LQ detector. The proposed method is tested with spaceborne InSAR images provided by the TerraSAR-X satellite.

***Index Terms*—** SAR, interferometry, high resolution

1. INTRODUCTION

The multiplicative model has been employed for SAR data processing as a product between the square root of a scalar positive quantity (texture) and the description of an equivalent homogeneous surface (speckle) [1]. For an m-dimensional repeat-pass SAR interferometry (InSAR) system, the single channel model [2] has been extended as follows. In each azimuth / range location, let $\mathbf{k}$ be the $m \times 1$ complex target vector corresponding to the same area on the ground. Recent studies [3] show that the higher scene heterogeneity induced by the high-resolution spaceborne SAR systems (TerraSAR-X, TanDEM-X, COSMO-SkyMed, SAR-Lupe...) leads to non-Gaussian interferometric clutter modeling.

In the case of conventional InSAR system two channels are involved and $m = 2$. Denoting by $c = \rho \exp(j\phi)$ the complex correlation coefficient, the target relative displacement d_{12} between the two acquisitions can be retrieved from the exact knowledge of SAR antenna phase center positions, terrain height, acquisition geometry, and an estimate of the differential interferometric phase ϕ_{12} . ρ_{12} is called interferometric coherence and it describes the phase stability within the estimation neighborhood. The phase information ϕ_{12} allows phase differences (interferograms) to be computed in order to measure topography or target displacements between repeated pass acquisitions.

In the general case, the m-dimensional interferometric target vector will contain information about the $m \times m$ relative displacements between each combination of 2 passes. The main parameter to estimate is the speckle covariance matrix, from which normalized correlation coefficients can be derived. Recently, a novel parameter estimation technique has been proposed in this framework [4].

2. STABLE SCATTERERS DETECTION

This section focuses on the analysis of a subset of scatterers within the scene, the so-called Stable Scatterers (SS), characterized by a deterministic point-like scattering behavior. The advantage of SS is that it is widely unaffected by multiple scattering effects and geometrical distortions allowing, as far as possible, a direct interpretation in terms of its phase center displacement. A similar approach has been proposed by the so-called Permanent Scatterers (PS) in SAR interferometry [5], where the identification of PS is based on its temporal stability (coherence over time) and relies on the availability of large time series of SAR image acquisitions. The SS differs from the PS in the sense that there is no need of temporal stability involved in its detection. The usual way to detect SS is to use Time-Frequency Distributions (Short Time Fourier Transform, Wavelet, etc) to form different sub-apertures (sublooks) or sub-bands of the same scene and to exploit their mutual correlations or coherence.

2.1. Sub-band / sub-apertures decomposition

When a target is illuminated by a broad-band signal and/or for a large angular extent, it is realistic to consider that the amplitude spatial repartition $I(\vec{r})$ of the scatterers depends on frequency f and on aspect angle θ. This repartition, denoted $I(\vec{r}, \vec{k})$, is depending on the wave vector $\vec{k}$ and it represents the energy distribution of the backscattering coefficient $H(\vec{k})$ in the hyperplane $(\vec{r}, \vec{k})$. Rewriting $I(\vec{r}, \vec{k})$ as $I(x, y, f, \theta)$, one can show that for each frequency f_0 and each angle of radar illumination θ_0, $I(x, y, f_0, \theta_0)$ represents a spatial distribution of the backscattered energy for this frequency [6]. It characterizes an "extended image" relative to the spatial repartition $I(\vec{r})$. Such images can be built using the Short Time Fourier transform (STFT) and are called hyper-images [7]. Since the STFT is an atomic decomposition, the phase of hyper-image is preserved and it can be used for interferometric processing. Moreover, this technique decomposes the

SLC signal into 2-D sub-spectra that can be interpreted as frequency sub-bands and angular sub-sectors (sub-apertures).

Consequently, the SS target with one SAR image can be reformulated in terms of hyper-image concept as a particular target (e.g. corner reflector) exhibiting a "stable" phase signal within all sub-bands / sub-apertures: given the m-dimensional complex target vector formed by m coherent sub-bands / sub-apertures, the SS can be described as the product between the reference signal $\mathbf{p} = [1...1]^T$ (target steering vector) times an unknown scalar complex parameter α (target complex amplitude).

2.2. Binary hypothesis test

In this paper we propose the application of the estimation scheme presented in [8] to Stable Scatterers detection in high resolution SAR images. The SS target detection problem in compound-Gaussian clutter can be formulated as a binary hypothesis test shown in (1). Under the null hypothesis H_0, the observed target vector $\mathbf{k}$ is only the clutter $\mathbf{c}$. Under the alternative hypothesis H_1, the backscattered signal can be decomposed as the sum of the target complex signal with the clutter $\mathbf{c}$. Here, the clutter is modeled as a Spherically Invariant Random Vector (SIRV).

$$\begin{cases} H_0 : \mathbf{k} = \mathbf{c} \\ H_1 : \mathbf{k} = \alpha\mathbf{p} + \mathbf{c} \end{cases} \qquad (1)$$

The optimal detector under the SIRV hypothesis is given by the following relation:

$$\Lambda\left([M]\right) = \frac{p_{\mathbf{k}}(\mathbf{k}/H_1)}{p_{\mathbf{k}}(\mathbf{k}/H_0)} = \frac{h_p\left((\mathbf{k}-\mathbf{p})^H[M]^{-1}(\mathbf{k}-\mathbf{p})\right)}{h_p\left(\mathbf{k}^H[M]^{-1}\mathbf{k}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda.$$

where $h_p\left(\cdot\right)$ is the density generator function. Its expression is given by:

$$h_p\left(x\right) = \int_0^{+\infty} \frac{1}{\tau^p} \exp\left(-\frac{x}{\tau}\right) p_\tau(\tau)\, d\tau.$$

This optimal detector depends on the texture probability density function p_τ.

2.3. GLRT-LQ detector

The Generalized Likelihood Ratio Test - Linear Quadratic (GLRT-LQ) detector can be used to detect a particular target. Let $\mathbf{p}$ be a steering vector and $\mathbf{k}$ the observed signal. The GLRT-LQ between $\mathbf{p}$ and $\mathbf{k}$ is given by [9]:

$$\Lambda\left([M]\right) = \frac{|\mathbf{p}^H[M]^{-1}\mathbf{k}|^2}{\left(\mathbf{p}^H[M]^{-1}\mathbf{p}\right)\left(\mathbf{k}^H[M]^{-1}\mathbf{k}\right)} \underset{H_0}{\overset{H_1}{\gtrless}} \lambda, \qquad (2)$$

where $[M]$ is the covariance matrix of the population under the null hypothesis H_0, *i.e.* the observed signal is only the clutter.

In general, the covariance matrix is unknown. One solution consists in estimating the covariance matrix $[M]$ by $[\hat{M}]_{FP}$, the fixed point covariance matrix estimator [4]. Replacing $[M]$ by $[\hat{M}]_{FP}$ in (2) leads to an adaptive version of the GLRT-LQ detector.The adaptive GLRT-LQ assumes knowledge of the clutter covariance matrix and does not require any "a priori" information about the texture PDF. This detector is also reported to present the Constant False Alarm Rate (CFAR) property with respect to the texture statistical characterization, meaning that the GLRT-LQ probability of false alarm is the same for any texture statistics [10].

If the covariance matrix is estimated by the fixed point estimator, it has been proved, for large N, the relation between the false alarm probability p_{fa} and the detection threshold λ:

$$p_{fa} = (1-\lambda)^{(a-1)}\ {}_2F_1(a, a-1; b-1; \lambda), \qquad (3)$$

with $a = \dfrac{p}{p+1}N - p + 2$ and $b = \dfrac{p}{p+1}N + 2$. N is the number of pixels used to estimate the covariance matrix $[M]$. p is the dimension of the target vector ($p = 3$ for the monostatic case). ${}_2F_1(\cdot, \cdot; \cdot; \cdot)$ is the Gauss hypergeometric function.

It is important to notice that the maximum likelihood estimator of the target amplitude $\widehat{\alpha}_{ML}$ has been also derived as:

$$\widehat{\alpha}_{ML} = \frac{\mathbf{p}^\dagger[M]^{-1}\mathbf{k}}{\mathbf{p}^\dagger[M]^{-1}\mathbf{p}}. \qquad (4)$$

This parameter can be used to obtain energetic information about the target previously detected by the GLRT-LQ.

3. STABLE SCATTERERS TRACKING

The relative displacement between two stable scatterers from one SLC image to another can be obtained by means of differential interferometry. The positions in the SLC images of the two scatterers are determined by employing the procedure described in the previous section. Fig. 1 shows the geometric configuration of the satellites and the SS targets (points P and Q) for two acquisitions. Points SM and SS show the positions of the satellite when acquiring the master and respectively the slave image. For each pixel in the SAR interferogram obtained from the two images, the phase difference $\Delta\phi_{i,j}$ can be written as:

$$\Delta\phi = \phi_{orbital} + \phi_{topo} + \phi_{disp} + \phi_{atm} + \phi_{noise}, \qquad (5)$$

where each term is a partial contribution to the total temporal phase difference.

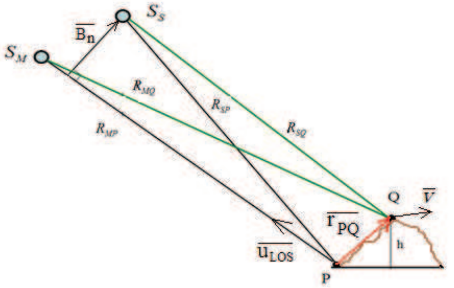

Fig. 1: Interferometric tracking geometry.

In order to compute the displacement in Line Of Sight (LOS) of point Q (the mobile SS target) with respect to the reference point P (the fixed target) an additional spatial phase difference is done (between the temporal phase differences of the pixels containing the two targets). After this double phase difference, by using stable scatterers, and assuming same atmospheric conditions for neighboring points, the terms regarding the noise and the atmospheric effects are cancelled. The remaining phase difference $\Delta(\Delta\phi)$ contains two terms: one regarding the orbital and topographic differences and one provided by the displacement in LOS. The first term is given by the satellite?s orthogonal baseline B_n and the distance between the two targets (the ”ground” baseline r_{PQ}). The relative displacement in LOS can be computed as in [11]:

$$D_{LOS} \simeq \frac{\lambda}{4\pi}\Delta(\Delta\phi) - \frac{\overrightarrow{B_n}\overrightarrow{r_{PQ}}}{R_{MP}}. \tag{6}$$

Although r_{PQ} may be different from an acquisition to another, the relative change is small due to the fact that the maximum measured LOS displacement must be smaller than $\lambda/2$ in order to avoid ambiguities. So the value used for the distance between the targets may be the one measured at the time prior to the master image acquisition.

4. RESULTS AND DISCUSSION

In this section, a real data-set acquired by the TanDEM-X satellite at X-band is analyzed: 2 spotlight (ascending, single polarization, 150 MHz bandwidth, 49^0 incidence) images have been acquired over the "Puylaurent dam" test site on the 20th and on the 31st of July 2011. The best ground projected pixel spacing is respectively 1.1 m in azimuth and 1.5 m in range. The master data corresponds to the first acquisition that was realized in 20.07.2011 and the second data corresponds to the second acquisition that was realized after 11 days, in 31.07.2011.

(a)

(b)

(c)

Fig. 2: The Puylaurent dam, France, TerraSAR-X data, 2011. (a) detected SS image superposed over the target amplitude $\widehat{\alpha}$ from Eq. 4.texture estimated using $\widehat{\tau}$, (b) coherence map and (c) phase image.

Fig. 2 shows the parameter estimation results: (a) amplitude, (b) coherence map, (c) interferogram. The detection result obtained is illustrated by the red red points on Fig. 2-(a).

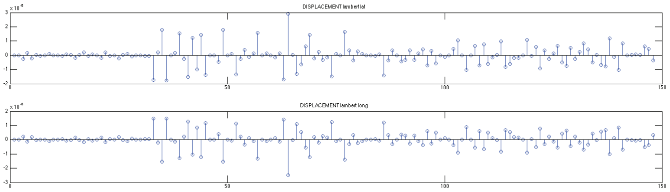

Fig. 3: The Puylaurent dam, France, TerraSAR-X data, 2011: measured latitude (top) and longitude (bottom) displacement in Lambert II cartographic projection.

Finally, Fig. 3 illustrates the projected planar displacement in Lambert II cartographic coordinates. For this, the reference point has been manually selected on the dam border.

5. CONCLUSIONS

A novel strategy for Stable Scatterers detection was introduced by coupling sub-band / sub-aperture decomposition prior to the GLRT-LQ detector. The tracking of slowly moving SS targets was preformed by repeat-pass SAR interferometry. A case study with TerraSAR-X data has been presented also. In the future, this technique will be confronted with the in situ measurements for the Puylaurent dam provided by the EDF company.

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