URBAN 3D RECONSTRUCTION USING COSMO-SKYMED HIGH-RESOLUTION DATA

Fabio Baselice[1][2], Alessandra Budillon[1], Giampaolo Ferraioli[1], Gilda Schirinzi[1][2] and Vito Pascazio[1]

[1] *Università degli Studi di Napoli "Parthenope",*
Dipartimento per le Tecnologie, 80143, Naples, Italy
Email:{fabio.baselice, alessandra.budillon, giampaolo.ferraioli, gilda.schirinzi, vito.pascazio}@uniparthenope.it
[2] *Consorzio Nazionale Interuniversitario per le Telecomunicazioni (CNIT),*
Unità di Ricerca Napoli Parthenope, 80143, Naples, Italy

ABSTRACT

In this paper two techniques developed to recover layover solution in SAR images are presented. SAR Statistical Tomography and Compressive Sensing techniques are described and analysed in order to provide a set of instruments for 3D SAR imaging able to tackle different scattering mechanisms in layover areas and to recover height reconstruction of an observed scene. The performances of the two techniques are compared on simulated data, together with first experiments on X-band COSMO-SkyMed data are presented.

1. INTRODUCTION

Three dimensional Synthetic Aperture Radar (SAR) imaging of earth surface has received a growing interest in recent years, thanks to the launch of new high-resolution radar sensors such as COSMO-SkyMed (C-S). 3-D SAR image formation provides the scattering scene estimation along azimuth, range and elevation co-ordinates.

COSMO-SkyMed sensor provides SAR image stacks characterized by a much higher resolution than the ones of the previous generation systems (ERS, ENVISAT), opening new applications. In particular, for 3-D reconstruction thanks to the high resolution it is expected to find a larger number of coherent pixels per unit area, resulting in more accurate measurements.

The aim of this paper is to exploit the peculiar characteristics of C-S system together with the recently developed algorithms for the generation of the 3-D models of earth surface. In particular, C-S data are used in the multi-pass interferometric configuration for non urban areas and in multi-pass tomographic configuration for urban areas.

2. MULTI-PASS SAR SYSTEMS

A. Multi-pass Interferometric Systems

To achieve high quality DEM reconstruction without imposing any constraint on the height profile of the ground surface, it is useful to adopt Multi-pass InSAR systems, exploiting the availability of many interferograms referred to the same scene, obtained using different baselines (Figure 1) [1] [2] [3]. By the way, a large number of interferograms are not easy to obtain, since they are often characterized by small temporal and spatial correlation. In order to efficiently combine the different acquisitions, statistical approaches based on Maximum Likelihood or on Maximum a Posteriori Estimation have been developed. The effectiveness of the Multi-pass approach for DEM reconstruction, in particular the capability to improve the precision of already available low resolution DEMs (SRTM case), has been proved with reference to ERS multi-baseline data [4]. We expect that the use of C-S constellation data, providing high coherence data sets, will result in a significant improvement of the DEM reconstructions.

B. Multi-pass Tomographic Systems

The innovation introduced by SAR Tomography is the ability to reconstruct, in the same azimuth/range resolution cell, the scattering profile in a two-dimensional domain, elevation and mean deformation velocity. The analysis of this reconstruction allows both the location in space and the monitoring of movements of ground scatterers. The application of the tomographic technique is proving to be very effective particularly on urban areas, where interferences between buildings and reflective ground (layover) are very common, due to the particular side-looking geometry. The technique has been already applied to medium resolution SAR data (ERS and ENVISAT), and it has demonstrated the validity of the method, allowing an increase in the density of monitored points thanks to the ability to distinguish interfering targets within the same pixel. Two different techniques able to retrieve the height of the different contributions that collapse in a layover cell for 3-D SAR imaging have recently been proposed: Compressive Sensing and SAR Statistical Tomography.

One of the main problems that have to be taken into account for the 3-D SAR reconstruction concerns geometrical distortion. If we consider a ground height profile with three point scatterers (A, B and C) lying in the same range-azimuth resolution cell is considered (see Figure 2), the acquired complex SAR signals related to the three scatterers collapse in the same resolution cell, producing the layover phenomenon. The signal corresponding to the layover region depends both on amplitude (related to the material, roughness, slope and viewing angle) and phase (related to the distance between sensor and object and speckle effects) of each single contribution involved [5].

In this paper we discuss two different techniques to retrieve the height of the different contributions that collapse in a layover cell in order to achieve 3-D SAR imaging: SAR Statistical Tomography (SST) [6] and Compressive Sensing Tomography (CST) [7]. We compare the results obtained on

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simulated data in order to provide some insights on the range of applicability of the two methods.

3. SAR STATISTICAL TOMOGRAPHY

The first approach is based on SAR Statistical Tomography [6], which consists of trying to separate and distinctly estimate each complex contribution which collapses in layover pixels exploiting statistical estimation techniques. In particular, it allows the estimation of the height of multiple scatterers lying in the same range-azimuth resolution cell of the image of the scene. SST is based on the assumption of a zero mean Gaussian distribution for the complex contributions corrupted by additive white complex Gaussian noise.

It can be shown that the complex image acquired along the *m*-th orbit computed in a fixed range azimuth pixel, assuming K scatterers in the same range-azimuth resolution cell, can be modeled as:

$$Z_m = \sum_{k=1}^{K} A_k e^{j\alpha b_m h_k} + Y_m \quad \text{with } m=1,\ldots,M \tag{1}$$

where α is a constant coefficient [1], b_m is the m-th orthogonal baseline, with $b_1=0$, h_k is the height of the k-th scatterer lying in the considered image resolution cell, A_k are highly correlated circularly-symmetric Gaussian zero-mean complex random variables and Y_k are low-correlated circularly-symmetric Gaussian zero mean complex random variables which represent correlated clutter and additive thermal noise

From (1) it can be noted that the vector $\mathbf{Z}=[Z_1,\ldots, Z_M]^T$ is a circularly-symmetric Gaussian zero-mean complex vector with a covariance matrix Σ depending on the unknowns scatterers height values h_k [6]. Hence, the probability density function of $\mathbf{Z}$ is given by:

$$f_{\mathbf{Z}}(z) = \frac{1}{\pi^M |\Sigma|} \exp\left\{- z^{\boldsymbol{H}} \Sigma^{-1} z\right\} \tag{2}$$

where ^{H} stands for Hermitian. The covariance matrix Σ is related to the unknown parameters 2K-dimensional vector $\boldsymbol{\vartheta}=[\sigma_1^2\ \sigma_2^2\ \ldots\ \sigma_K^2\ h_1\ h_2\ \ldots\ h_K]^T$ (reflectivity and height of scatterers), which has to be estimated [6].

Once data have been observed, the estimation of the unknown parameters is performed via a simple Maximum Likelihood (ML) estimation, obtained by maximizing the log-likelihood function

$$L(\vartheta) = -\log\left(\pi^M |\Sigma|\right) - z^{\boldsymbol{T}} \Sigma^{-1} z \tag{3}$$

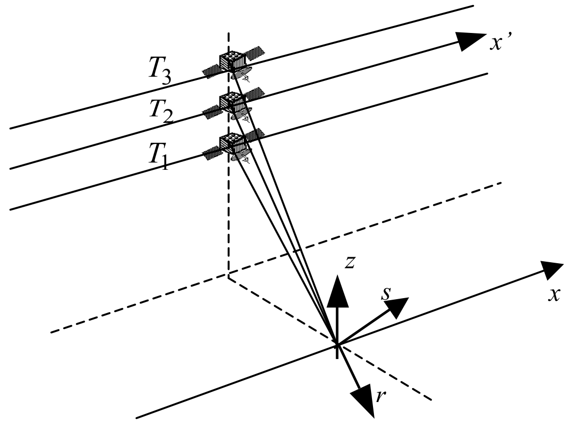


Figure 1. Multi-pass SAR geometry in the case M=3.

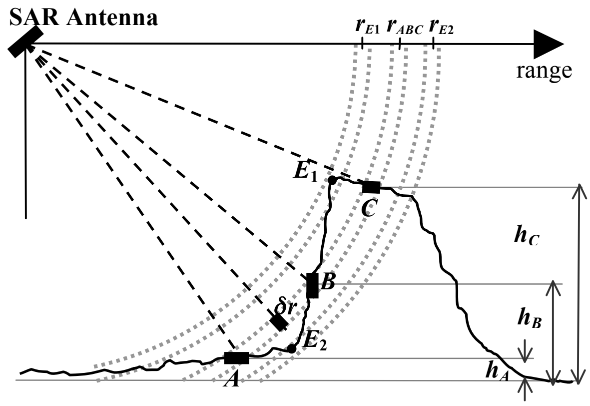


Figure 2. Layover Geometry. The echoes from points A,B and C, respectively at heights h_A, h_B and h_C collapse in the range cell positioned at a distance r_{ABC} from the sensor.

4. COMPRESSIVE SENSING

The second approach considered is a new method allowing 3-D image focusing, using a reduced number of acquisitions and allowing an elevation resolution increased respect to the one achievable with standard tomographic methods, which is limited by the overall orthogonal baseline extent. The method is based on the assumption that a low number of scatterers with different elevations is present in the same range-azimuth resolution cell [7] and exploits Compressive Sampling [8] (CST). CST makes the assumption of dominant, stable and coherent scatterers, treating low-coherent returns as noise. Practically speaking, the CST method has its natural application framework in a urban scenario in presence of high clutter to signal to noise ratio. No statistical assumption is made on the scatterer signal amplitude distribution.

Figure 3. Surroundings of Naples, COSMO-SkyMed amplitude image (mean of the stack)

Introducing a proper discretization of the height values h ,Eq (1) can be written in vector form as follows [7]:

$$z = \mathbf{\Phi \Psi} \boldsymbol{a} + y\,, \qquad (4)$$

where $\mathbf{\Phi}$ is the $M \times N$ measurement matrix containing the phase factors related to the disctretized height values, $\mathbf{\Psi}$ is the sparsity basis matrix (which in our case is equal to the identity matrix of size M), $\mathbf{y}$ is the additive clutter plus thermal noise vector, and $\boldsymbol{a}=[a_1\ a_2\ \dots\ a_N]^T$ is the unknown $N\times 1$ column vector with K nonzero elements in correspondence of the discretized heights values of the scatterers, and representing the scatterers complex reflectivity.
The solution of (4) can be found by solving the following optimization problem:

$$\hat{\boldsymbol{a}} = \arg\min \|\boldsymbol{a}\|_1 \quad \text{subject to} \quad \|\mathbf{\Phi\Psi}\boldsymbol{a} - z\|_2 \leq \varepsilon \qquad (5)$$

where ε is a small positive number.

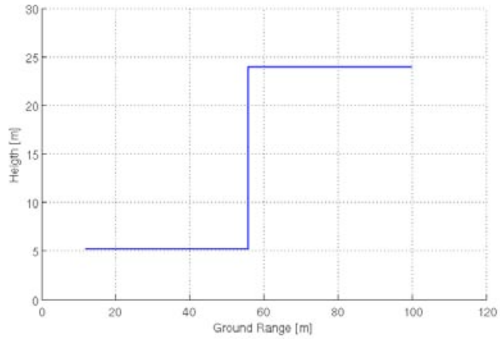
5. RESULTS

A. Simulated data

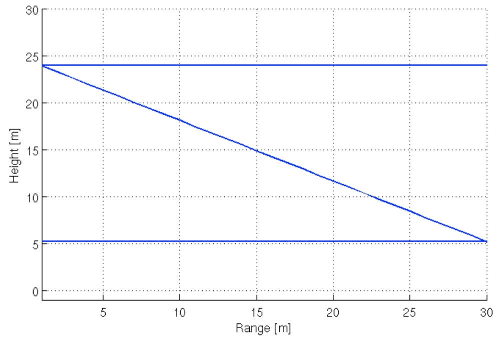
The two previously explained techniques have been compared in a simulated framework for height estimation. The SAR response of a building, characterized by layover has been simulated, using COSMO-SkyMed system parameters, with an overall coherence γ=0.9. We considered an interferometric configuration with 8 baselines b=[-416.874 -393.084 -251.421 -133.201 126.367 235.775 304.739 406.599], taken from a real data set over Naples.
A cut of the simulated noise free profile in both ground and SAR geometry is shown in Figure 4. Figures 5 and 6 show the results of the two considered techniques before and after geocoding, respectively. From the presented pictures, it is clear that both techniques are able to retrieve the different contributions involved in the layover cell, providing an effective reconstruction of the considered profile.

B. Real data

In this section first experiments on real X-band COSMO-SkyMed data are presented.
The data set consists of 18 X-Band SAR images acquired by the COSMO-SkyMed Sensor over the area of Naples. The system parameters are the same as reported in Table 1. Differently from the simulated data, in this case 18 images have been used.
We focused on a particular area close to the city of Nola. The whole area is shown in Figure 3. In this area, we focused on a particular set of buildings (Figure 7). The algorithm has been tested on a single azimuth line (red line in Figure 7)
Height profile reconstructions have been computed with both SVD and CS techniques. Results are reported in figure 8. The SVD nominal height resolution was 20.35 m, while the CS was characterized by 1.85 m of resolution, as it can be noted comparing figures 8(a) and 8(b).

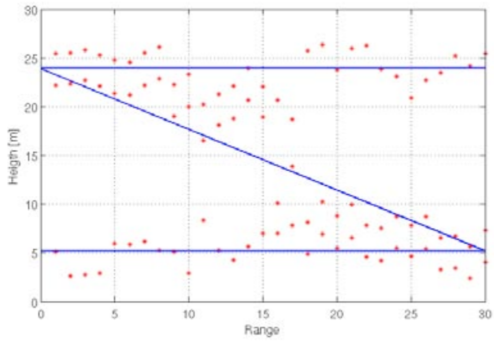


(a)

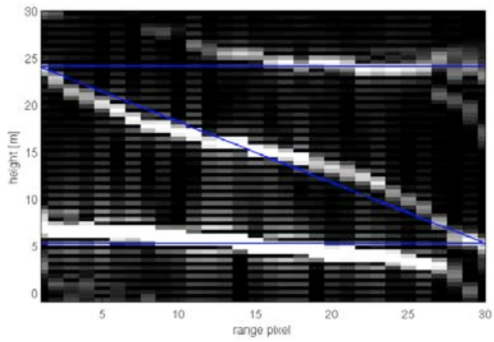


(b)

Figure 4. Noise free reference profile in ground (a) and SAR (b) geometry.

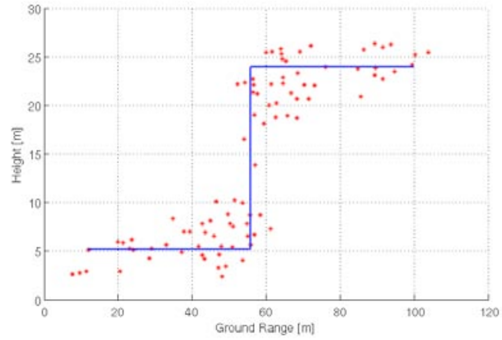


(a)

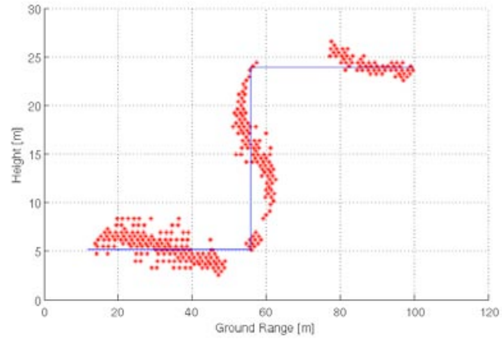


(b)

Figure 5. Reconstructed profile in SAR geometry using SST(a) and CS (b) techniques.



(a)



(b)

Figure 6. Reconstructed and geocoded profile retrieved using SST(a) and CS (b) techniques.

Table 1 COSMO-Skymed System Parameters

Distance sensor-scene	755190
Wavelength	0.031228
Look angle	0.621064

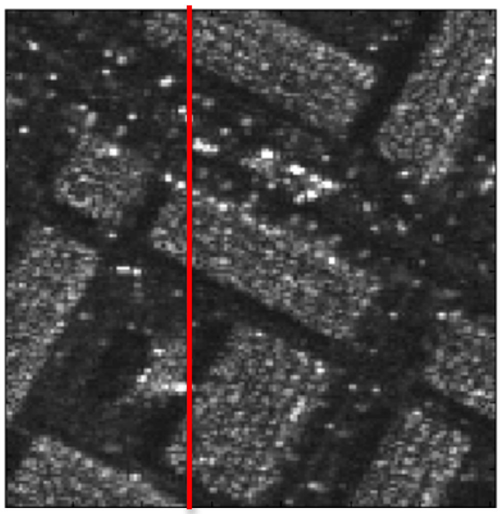
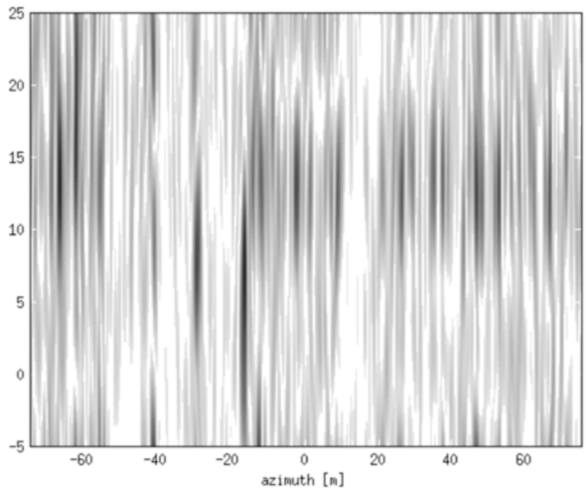
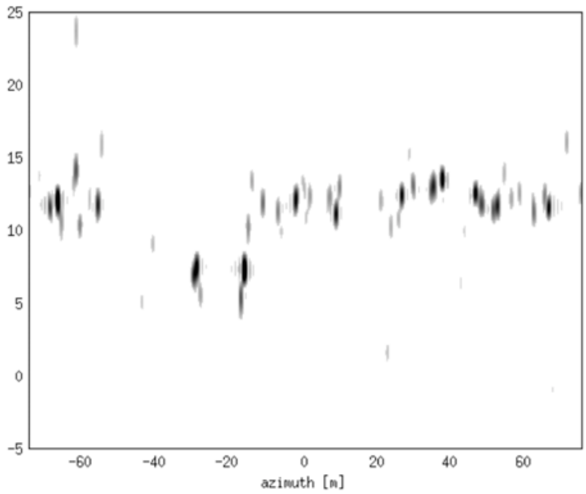


Figure 7. Area of interest: mean amplitude of the stack In red the considered azimuth line.



(a)



(b)

Figure 8. SVD (a) and CS (b) reconstructions of the profile.

6. CONCLUSION

In this paper, a comparison between two techniques able to handle the layover problem, retrieving the 3D reconstruction of an observed scene has been presented. Both techniques have shown their effectiveness in retrieving the height of different scatterers involved in a layover cell.

From a computational point of view, the CS technique requires a shorter time since it is based on an easier optimization problem. The main drawback of the CS with respect to SST is the requirement of high coherence across the scene.

Moreover, in the paper first experiments on multipass COSMO-SkyMed real data have been presented, showing interesting and promising results.

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