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TOWARDS 3D SYNTHETIC APERTURE RADAR ECHOGRAPHY

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ABSTRACT

One of the problems associated with electromagnetic imaging is that the interaction of photons with targets occurs only on part of their surface, namely those exposed to the transmitted energy rays. Imaging of deep localized objects is very hard especially in the presence of short electromgnetic wavelengths. In this paper we propose a new method for through wall imaging, based on photons and sound waves analysis. The technique investigates Doppler analysis in terms of estimating vibrations generated on infrastructures. The proposed method estimates target’s vibration energy in order to perform tomographic imaging of man-made objects, such as buildings. Unlike traditional imaging, this technique allows for through wall imaging. The experimental results are distributed over one case study, where we show the tomographic imaging of a reinforced concrete infrastructure. We consider this preliminary work very promising for future applications performed from the processing of satellite synthetic aperture radar images.

***Index Terms*—** Synthetic aperture radar, micro-motion, echography, phonon, vibrations, Doppler centroid estimation.

1. INTRODUCTION

Synthetic aperture radar (SAR) is a coherent night/day and any weather imaging sensor that allows the synthesis of high resolution electromagnetic imaging. Such systems allow for the production of images of targets of surface areas only, based on the penetration properties of electromagnetic waves, consistent with the considered wavelength. This problem prevents the system from the imaging within distributed targets, due to the low penetration of electromagnetic energy. This energy is completely interdicted in the presence of metallic targets. These limitations, which are distinctive of SAR, suggest the search of an alternative method that in this case allows us to gather information about the internal part of an object. To this end, measuring the vibrations associated with parts of a target would provide important information that can be used to accomplish the above task.

Numerous works have been carried out in the field of sonic imaging, especially in the medical field, through the use of ultrasound. Theoretical studies made in the early 1980’s suggest that ultrasonic imaging using correlation technique can overcome some of the drawbacks of classical pulse echography. In [1] efficient high-resolution techniques are described by transmitting coded signals. High-frequency transducers, up to 35–50MHz, are widely used in ophthalmic echography to image fine eye structures. In [2] the first high-frequency echographic images obtained with the prototype probe are presented. Authors of [3] describe a pulse-echo ultrasound method for measuring nonlinear waveform distortion, and reporting the design, construction, and experimental characterization of the first mechanical scanning probe for ophthalmic echography based on a small piezoelectric ultrasound motor. The work in [4] presents a novel method for line restoration in speckle images. In particular, this task is addressed as a sparse estimation problem using both convex and non-convex optimization techniques based on the Radon transform and sparsity regularization. Lung ultrasound imaging is a fast-evolving field of application for ultrasound technologies. Authors of [5] design an image formation process to work on lung tissue, and ultrasound images generated with four orthogonal bands centered at 3, 4, 5 and 6 MHz can be acquired and displayed in real time.

In the field of vibration estimation by processing SAR images we recall the following work. In [6] authors propose a new procedure to monitor critical infrastructures. The technique is applied to COSMO-SkyMed data, with the aim to monitor the destabilization of the Mosul dam, representing the largest hydraulic facility of Iraq. The procedure is an in-depth modal assessment based on the micromotion estimation, through a Doppler subapertures tracking and a multichromatic analysis. In [7] a complete procedure for damage early-warning detection is designed, by using micro-motion (m-m) estimation of critical sites, based on modal propri-

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eties analysis. Particularly, m-m is processed to extract modal features such as natural frequencies and mode shapes generated by vibrations of large infrastructures. Several study cases are here considered and the “Morandi” Bridge (Polcevera Viaduct) in Genoa (Italy) is analyzed in depth highlighting abnormal vibration modes during the period before the bridge collapsed.

In this paper we test the possibility of performing sonic imaging by processing the single SAR image. The technique involves the estimation of the m-m on particular infrastructures, even large ones, and generated by the intensive mechanical activity present in the cities.

The estimation of m-m is done through multi chromatic analysis, performed in the Doppler direction. Multiple Doppler sub-apertures, SAR images with lower azimuth resolution, are generated in order to estimate the vibrational trend of the pixels of interest. The shifts are calculated through the pixel tracking technique [8, 9], using a coregistrator with an over-sampling factor around 1200. For all experimental results we synthesize a frequency sweep equal to 1 kHz, in order to obtain a sufficient sensitivity useful to perform the tomographic reconstruction.

The experiments are computed by processing data belonging one case study. The first one consists of the sound imaging of an industrial infrastructure made of reinforced concrete. For this case study, single image tomographic imaging was also tested.

2. METHODOLOGY

In this section we describe the analytical formulation of the m-m estimation technique and derive the vibration model of infrastructures belonging to real scenarios [7]. Then, we describe the workflow applied for vibration estimation to subsequently perform its sonic imaging.

In typical SAR scenario, the back-scattered energy from moving targets is distributed over several range-azimuth resolution cells. As a matter of fact, considering the point-like target that is moving with velocity v_t and acceleration a_t whose range-azimuth components are $\{v_r, v_a\}$, and $\{a_r, a_a\}$, respectively, then the slant-range distance can be expressed as function of the complex displacement vector $\mathbf{x}$ [6, 7]:

$$\mathbf{R}(\mathbf{x}) = R_0 - \epsilon_1 \mathbf{x}\left[(1-\epsilon_2)^2 - \xi\right]\frac{\mathbf{x}^2}{2R_0}. \tag{1}$$

where ϵ_1, ϵ_2 and ξ are related to the target range, azimuth velocity and range acceleration respectively.

2.1. Sonic Tomographic model

We consider the vector representation of (1) consisting in the following multi-frequency data input:

$$\mathbf{R}(\mathbf{x}) \propto \mathbf{Y} = [\mathbf{y}(1), \ldots, \mathbf{y}(k)], \in \mathbb{C}^{K\times 1}. \tag{2}$$

The steering matrix $\mathbf{A}(\mathbf{f},\mathbf{z}) \in \mathbb{C}^{K\times F}$ contains the phase information of to the Doppler frequency variation of the sub-aperture strategy $f_D \in \{f_{min}, f_{max}\} \equiv \{0, f_{K-1}\}$, associated to a source located at the elevation position $z \in \{z_{min}, z_{max}\} \equiv \{z_0, z_{F-1}\}$, so that

$$\mathbf{A}(\mathbf{f},\mathbf{z}) = \begin{pmatrix} 1 & e^{2\pi z_0 f_1} & \ldots & e^{2\pi z_0 f_{K-1}} \\ 1 & e^{2\pi z_1 f_1} & \ldots & e^{2\pi z_1 f_{K-1}} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{2\pi z_{F-1} f_1} & \ldots & e^{2\pi z_{F-1} f_{K-1}} \end{pmatrix} \tag{3}$$

The standard sonic tomographic model is given by the following relation:

$$\mathbf{Y} = \mathbf{A}(\mathbf{f},\mathbf{z})\mathbf{h}(\mathbf{z}). \tag{4}$$

where $\mathbf{h}(\mathbf{z}) \in \mathbb{C}^{1\times F}$ is the unknown vertical reflectivity function, so that inverting (4) we finally find the following tomographic solution:

$$\mathbf{h}(\mathbf{z}) = \mathbf{A}(\mathbf{f},\mathbf{z})^{\dagger}\mathbf{Y}. \tag{5}$$

The tomographic resolution is equal to $\delta_T = \frac{v}{2B_D}$, where v is the sound velocity over the reinforced concrete (approx. 2000 km/h), and B_D is the Doppler bandwidth used to synthesize the sub-apertures.

3. EXPERIMENTAL RESULTS

Experimental results are calculated by processing data from the COSMO-SkyMed Second Generation (CSG) SAR satellite constellation. We processed a spotlight image with spatial resolution of about 0.8 m in range and azimuth. The Doppler band synthesized to form the SAR image at maximum resolution in azimuth is about 24 kHz. We generated approximately 1000 Doppler subapertures, each refocused using about half the band in azimuth (thus with half the spatial resolution in azimuth). We generated subapertures by imposing an incremental stepped frequency shift with a bandwidth of about 2 kHz. We estimated the shifts of the distributed target whose single-look complex (SLC) image in magnitude is shown in Fig. 1. It is a flat-roofed concrete building about 4 m high. The estimated shifts of the entire building are shown in Figs. 2, and 3, in magnitude and phase, respectively. Figure 4 represents the calculated vibration energy at approximately 100 Hz, the entrance indicated by the white arrow a, and the central corridor indicated by the white line b are visible. Tomographic slices represented by the yellow lines $1, 2, 3, 4$ were calculated. Figure 5 represents the tomographic image indicated by Figure 4 (line 1), and the interior walls bordering the rooms are clearly visible. Both the ceiling and the floor are clearly depicted. Similar considerations can be made for the results depicted in Figures 6 and 7 (tomographic results of the yellow lines 2, and 3 of Figure 4). Also visible in these figures are the section of the central corridor and a few resonant structures found within the rooms. In contrast, the Transverse Tomography of the rooms is shown in Fig. 8. In this case, the entrance to the building indicated by the white arrow a in Figure 4 is clearly visible.

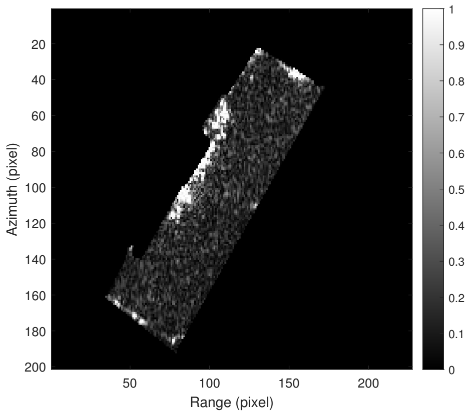

Fig. 1. Single Look Complex image (normalized magnitude).

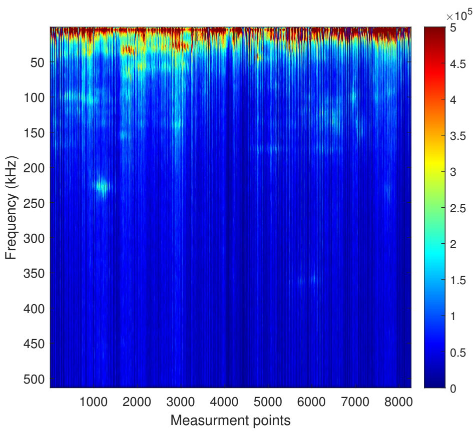

Fig. 2. Sonic raw data ($|\mathbf{R}(\mathbf{x})|$) of the entire building.

4. CONCLUSIONS

In this paper we propose an new approach of imaging the Earth targets. The technique investigates Doppler analysis in terms of estimating vibrations generated on infrastructures. The estimated vibration energy is useful to perform tomographic imaging of man-made objects. Unlike electromagnetic imaging, our technique allows to perform inside object detection. The experimental results are distributed over one case study, where we show the tomographic imaging of a reinforced concrete infrastructure. We consider this preliminary work very promising for future sonic imaging applications performed from the processing of satellite synthetic aperture radar images.

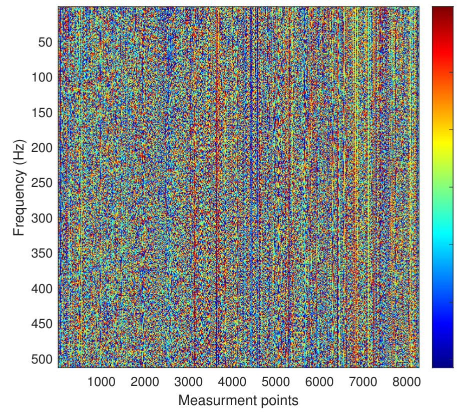

Fig. 3. Sonic raw data ($\angle\mathbf{R}(\mathbf{x})$) of the entire building.

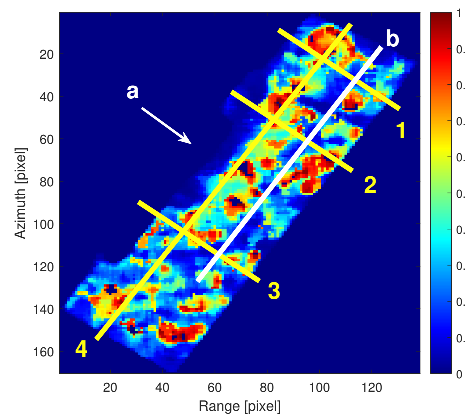

Fig. 4. Range-azimuth sonic image at 100 Hz (magnitude) of the entire building.

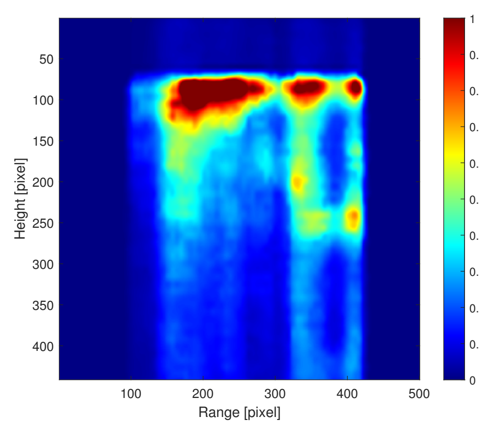

Fig. 5. Magnitude of tomographic slice 1.

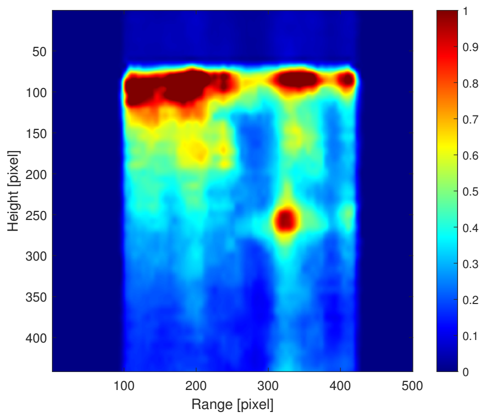

Fig. 6. Magnitude of tomographic slice 2.

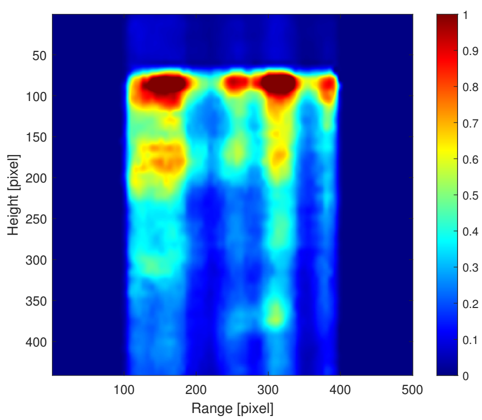

Fig. 7. Magnitude of tomographic slice 3.

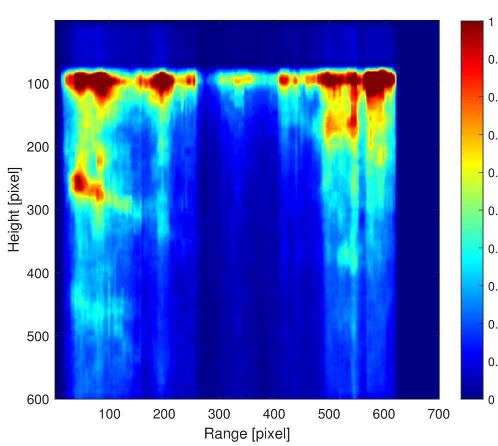

Fig. 8. Magnitude of tomographic slice 4.

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