Ultrawideband Time-Reversal Imaging With Frequency Domain Sampling

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***Abstract*—A new ultrawideband (UWB) time-reversal imaging method based on the unconventional utilization of UWB frequency data is introduced. First, a set of monostatic antennas is used to acquire the scattering data for a given scenario. Then, a corresponding multistatic data matrix is formed by casting the fine and coarse frequency samples of the scattering information into matrix form. The resulting frequency–frequency monostatic matrix is later fed into the adapted DORT (French acronym for decomposition of the time-reversal operator) and MUSIC (Multiple-Signal Classification) algorithms. The performance of the proposed method is investigated numerically by applying it to discrete scatterers embedded in homogeneous and continuously random inhomogeneous media. The effect of frequency bandwidth on image resolution is studied. It is observed that wider frequency bandwidths yield to better focusing resolutions.**

***Index Terms*—Decomposition of the time-reversal operator (DORT), multiple-signal classification (MUSIC), singular-value decomposition (SVD), time-reversal imaging.**

I. Introduction

TIME-reversal (TR) methods have recently attracted attention from different disciplines such as acoustics [1], communications [2], and electromagnetic sensing [3]. It can achieve both temporal and spatial focusing around the original target location(s), owing to the exploitation of wave equation reciprocity in lossless and time-invariant media. Its ability to utilize multipaths in the medium yields to superresolution and statistical stability [1] which are favorable in imaging applications. For the traditional TR-based imaging methods such as DORT [4] and TR-MUSIC [5], the TR operator (TRO) is of fundamental importance. As the TRO eigenvalues and eigenvectors in a given scattering scenario are associated with the scatterers in the probed domain, imaging functionals can be directly constructed from their various configurations. For example, in the DORT method, when applied to well-resolved pointlike scatterers, information on scatterer location and strengths is partially encoded by the TRO signal subspace which is later used to construct the set of backpropagating pulses. DORT has been applied to both time-harmonic and ultrawideband (UWB) electromagnetic waves [6], but its performance deteriorates if the well-resolvedness criterion is not met. The TR-MUSIC method, on the other hand, utilizes the eigenvectors of the TRO noise subspace [7], which is orthogonal to signal subspace and overcomes the difficulty of dealing with non-well-separated targets for DORT. Additionally, TR-MUSIC is valid for detections and imaging of multiple [8] and extended [9] targets.

For both of these methods, TRO is obtained using the so-called *space–space* multistatic data matrices (MDMs). The term *space–space* is coined here as each element of the MDM corresponds to a different transceiver location. A combination of the same space–space MDMs at multiple frequencies is utilized for the UWB extensions of these methods, viz., time-domain DORT (TD-DORT) [6] and UWB-MUSIC [10]. The TD-DORT method needs a preprocessing step to obtain coherent time-domain eigenvectors since the eigenvectors carry frequency-dependent phases. In [11], an alternative method is proposed, which overcomes this problem through the application of singular-value decomposition (SVD) directly to the *space–frequency* MDM (SF-MDM). In this method, by combining MDMs obtained at different frequencies, a new MDM is generated, whose columns and rows correspond to the space and frequency components of received signals, respectively. The resulting UWB imaging functional has been shown to yield statistical stability in random media [11].

The SF-MDM method has some drawbacks in multimonostatic/multifrequency scenarios. For example, for L antenna positions and $N \times P$ frequency samples, one should deal with a diagonal $(L^2, N \times P)$ MDM. Furthermore, due to eigenvector incoherence, a postprocessing stage is needed. An alternative technique which overcomes the aforementioned problems is through the application of the SVD to *frequency–frequency* MDM (FF-MDM) [12], [13], as also practiced here. In an FF-MDM, each matrix element corresponds to a received signal at fine and coarse frequency samples. In this way, the full SF-MDM matrix will decompose into $N \times P$ matrices and the incoherence modification stage will be automatically excluded. Although the SF-MDM method capability for UWB imaging has been proven already, for the special case of monostatic scenario, this method is hard to apply. In contrary, the FF-MDM method is a relatively simple and fast processing technique. In [12] and [13], the FF-MDM of a single antenna in the presence of a ground plane, which is not practical and makes the research limited, is used to detect a target using the DORT method only. In this letter, in addition to the DORT method, we also adapt the TR-MUSIC algorithm by utilizing these unconventional FF-MDM data to obtain new imaging functionals. The data collection is achieved using a set of UWB transceivers at different locations without the need of ground plane. The resulting image is obtained by overlapping

Manuscript received December 11, 2012; revised February 28, 2013, April 19, 2013, and May 14, 2013; accepted May 26, 2013. Date of publication July 18, 2013; date of current version November 25, 2013.

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Digital Object Identifier 10.1109/LGRS.2013.2272033

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