

Aspect Dependent Multipath Ghost Suppression in TWRI under Compressive Sensing Framework

Abdi T. Abdalla, Ali H. Muqaibel and Suhail Al-Dharrab
Electrical Engineering Department, King Fahd University of Petroleum
& Minerals Dhahran, Saudi Arabia
e-mail: {abdit, muqaibel, suhaild}@kfupm.edu.sa

Abstract—In through-the-wall radar imaging, multipath propagation can create ghost targets which can adversely affect the image reconstruction process. The fact that the ghost positions changes with the radar locations which is referred to as aspect dependence has been reported as among the features distinguishing ghost from true target. This paper proposes ghost suppression method which exploit the aspect dependence feature under compressive sensing framework. The existing signal model is modified so that the location of reflecting geometry is no longer a constraint. Also the sensing matrix is greatly reduced making the methods more attractive. Simulation results demonstrate the effectiveness of the proposed methods.

Keywords—Aspect dependence, compressive sensing, multipath ghost, sub-aperture, through-the-wall radar imaging.

1. INTRODUCTION

The main intention of through-the-wall radar imaging (TWRI) is to provide useful information of obscured areas using electromagnetic (EM) waves. Such information is useful in many situations including rescue mission in firefighting, locating or tracking and even classifying the occupants [1]–[4]. This area of research has witnessed a tremendous growth in the last few years. The major challenges in TWRI is multipath stemming from multiple reflections of EM waves from the walls, floors and the ceilings and also multiple reflections within the front wall [5]–[9]. This gives rise to ghost targets which populates the scene and causes confusion with genuine targets and hence increases probability of false alarm [5]. In such scenario, accurate target localization becomes difficult. In the literature, different techniques have been presented to suppress multipath ghosts but their performance and/or practicability are limited.

Ongoing research in TWRI aimed at obtaining highly resolved images which requires wide bandwidth and large aperture. Consequently, large amount of data needs to be collected and processed [5]. To tackle the problem of big data, compressive sensing (CS) was first applied in TWRI by Yoon and Amin [10]. With CS technology only a small fraction of data was used to reconstruct an image of relatively good quality provided that the scene is sparse.

According to Tan *et al.* [11], Li *et al.* [12] and Setlur *et al.* [16] multipath ghosts are aspect dependent (AD): the location of the multipath ghost changes with the change of transceiver location. This property has been successfully used to identify

and suppress multipath ghosts from a group of true targets. To the best of our knowledge, no research has been presented employing AD feature under CS framework to suppress multipath ghost in TWRI.

Tan *et al.* [11] developed ghost suppression technique exploiting the AD characteristic of the ghosts without applying CS. The authors modeled the ghost positions as hidden Markov chain problem. However, the method requires image decomposition into N -sub-aperture images using directional filters and other complex advanced algorithms.

Li *et al.* [12] proposed a ghost suppression technique which also exploits AD feature without CS. The authors formed three images using back projection method; two using sub-apertures and the rest using the whole aperture. Then the three images are multiplied to form the final image. Their method involves searching for appropriate sub-apertures and requires shifting of antenna array in two extreme ends of the room which add inconvenience and complexity.

On the other hand, there are few contributions for ghost suppressions based on CS but not employing AD [5], [13]. Leigsnering *et al.* [5] incorporated front wall reverberation effect which makes their approach more practical. They inverted multipath model assuming complete knowledge of the reflecting geometry. Unfortunately, the knowledge of the geometry not always available. Also, their method requires high dimensional matrices and hence high memory demand and prolonged processing time.

This paper proposes a different multipath ghost suppression technique which incorporates AD feature of the ghosts under CS framework. Inclusion of AD characteristic of the ghost, reduces the size of measurement matrix and also eliminates the constraint of knowledge of the reflecting geometry. We investigate and propose the best way of selecting radar locations to better suppress the ghosts. The effectiveness of the proposed methods is shown using synthesized data simulating the real TWRI scenarios.

The remainder of the paper is organized as follows. Section 2 introduces fundamentals of TWRI. In this section, signal model and front wall reverberation model are presented. Proposed method exploiting AD feature of the ghost is presented in Section 3. Section 4 contains simulation results and conclusions are drawn in Section 5.

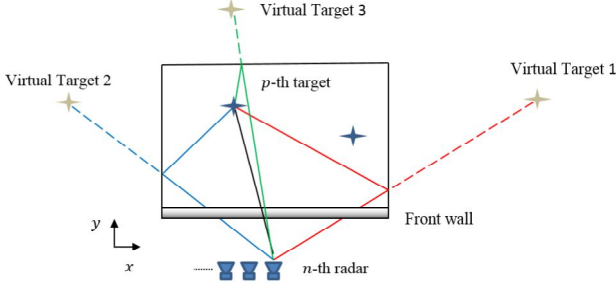


Fig. 1. TWR multipath scenario with first order returns

2. FUNDAMENTALS OF TWRI

A. Signal Model

Consider a scene model in Fig. 1 with N different radar locations. At each location, M monochromatic waves which are equally spaced in frequency are transmitted and received to realize an ultra-wideband (UWB) signal. Similar signal was used by [13]–[15] in their analysis. We divide the scene into N_x by N_y points where N_x and N_y are respectively the number of pixels in crossrange and downrange. The presence and absence of the target on a p^{th} grid point is represented by a target reflectivity, σ_p , with $p = 0, 1, \dots, N_x N_y - 1$. If R returns are considered, the received signal at n^{th} radar position when the m^{th} frequency, f_m , is transmitted is given by [5]:

$$y[m, n] = \sum_{r=0}^{R-1} \sum_{p=0}^{N_x N_y - 1} \sigma_p \exp(-j2\pi f_m t_{pn}^{(r)}) + v(m, n) \quad (1)$$

where $t_{pn}^{(r)}$ represents the round-trip delay between the p^{th} target and the n^{th} receiver due to the r^{th} return, $\sigma_p^{(r)}$ is target reflectivity with respect to the r^{th} return and $v(m, n)$ is Gaussian noise sample. The vector representation of the above equation is:

$$\mathbf{y} = \Phi^{(0)} \mathbf{s}^{(0)} + \Phi^{(1)} \mathbf{s}^{(1)} + \dots + \Phi^{(K-1)} \mathbf{s}^{(K-1)} + \mathbf{v} \quad (2)$$

where $\mathbf{s}^{(r)} \in \mathbb{C}^{N_x N_y \times 1}$, $r = 0, 1, \dots, R - 1$ represents the vectors of reflectivities, $\sigma_p^{(r)}$. The weighting of the returns are included in $\sigma_p^{(r)}$ and $\Phi^{(r)} \in \mathbb{C}^{MN \times N_x N_y}$ represents the dictionary matrix containing phase information of the target due to the r^{th} return with entries defined as [1], [2]:

$$[\Phi^{(r)}]_{ip} = \exp(-j2\pi f_m t_{pn}^{(r)}),$$

$$m = i \bmod M, \quad n = \left\lfloor \frac{i}{M} \right\rfloor, \quad i = 0, 1, \dots, MN - 1 \quad (3)$$

In TWRI applications, only multipath involving single bounce have significant effect. Returns involving multiple bounces will either be very weak due to strong attenuation when interacting with walls or their corresponding ghosts will reside outside the perimeter of interest due to elongated time of arrival [16]. Therefore, they are not considered in this work.

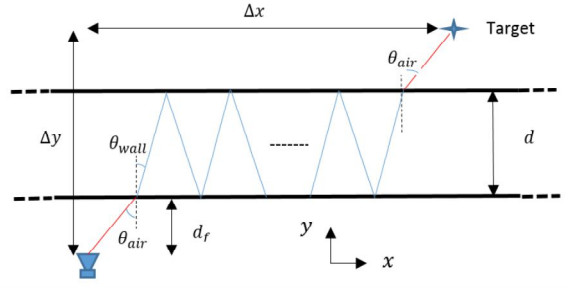


Fig. 2: Wall ringing phenomenon

B. Front Wall Reverberation Model

Besides multipath stemming from multiple reflections of the interior walls, another challenge of TWRI is the presence of the front wall. As the wave propagates through the front wall, it gets reflected from the outer and inner surfaces of the wall causing multiple reflections within the wall. This phenomenon is known as wall ringing or reverberation [5], [17]. Due to this effect as shown in Fig. 2, copies of true targets “ghosts” are created in the reconstructed image spaced in the radial direction from the array with exponentially reducing intensity. From the geometry, the distance between the target and the radar in crossrange direction, Δx , is given by:

$$\Delta x = d_f \tan \theta_{air} + d(1 + 2k) \tan \theta_{wall} + (\Delta y - d - d_f) \tan \theta_{air}$$

$$\Delta x = (\Delta y - d) \tan \theta_{air} + d(1 + 2k) \tan \theta_{wall} \quad (4)$$

where Δy is the distance between the target and the array element in downrange direction, θ_{air} and θ_{wall} are angles in the air and in the wall medium respectively, d_f is the standoff distance and integer k denote the number of wall reverberations. The two angles are related by Snell’s law as:

$$\frac{\sin \theta_{air}}{\sin \theta_{wall}} = \sqrt{\epsilon_r} \quad (5)$$

where ϵ_r represent relative permittivity of the front wall. Equations (4) and (5) form a nonlinear system which is somehow tricky to deal with.

If we assume small incidence angle which is desired in TWRI applications, we have $\sin \theta \approx \tan \theta \approx \theta$ (in radian measure). Using this assumption (4) and (5) can be rewritten as:

$$\Delta x = (\Delta y - d) \theta_{air} + d(1 + 2k) \theta_{wall} \quad (6)$$

$$\theta_{air} = \theta_{wall} \sqrt{\epsilon_r} \quad (7)$$

The system now reduces to a linear system which is much easier to handle. Solving (6) and (7) gives:

$$\theta_{wall} = \frac{\Delta x}{(\Delta y - d) \sqrt{\epsilon_r} + d(1 + 2k)} \quad (8)$$

The one-way extra time delay due to k wall reverberations will be modeled as:

$$\tau(\theta_{wall}, k) = \frac{2kd\sqrt{\epsilon_r}}{c \cos \theta_{wall}} \quad (9)$$

where c is the speed of EM wave in free space. This simplifies the calculation of the time delay involving wall reverberation. For the direct return, $k = 0$ and hence, $\tau(\theta_{wall}, k) = 0$. As the magnitude of the signal gets attenuated when it reflects within the wall, only few reverberations will be noticeable.

3. PROPOSED GHOST SUPPRESSION METHOD

To address the challenges on the existing ghost suppression methods, we propose multipath ghost suppression technique which exploits AD feature of the ghosts under CS framework. The inclusion of AD feature simplifies the problem in terms of complexity and relaxes the requirement of the reflecting geometry.

To reconstruct a ghost-free image, the perfect reverse model is in (2). However, it requires the knowledge of reflecting geometry. This limitation is avoided in our contribution. Factorizing in (2) with respect to $\Phi^{(0)}$, gives:

$$\mathbf{y} = \Phi^{(0)} \left[\mathbf{s}^{(0)} + \Phi^{(0)-1} \Phi^{(1)} \mathbf{s}^{(1)} + \dots + \Phi^{(0)-1} \Phi^{(R-1)} \mathbf{s}^{(R-1)} \right] + \mathbf{v} \quad (10)$$

If we define a residual column vector, $\mathbf{w}$ which contains information from other subimages as:

$$\mathbf{w} = \Phi^{(0)-1} \Phi^{(1)} \mathbf{s}^{(1)} + \dots + \Phi^{(0)-1} \Phi^{(K-1)} \mathbf{s}^{(K-1)} \quad (11)$$

Then (10) can be rewritten as:

$$\mathbf{y} = \Phi^{(0)} (\mathbf{s}^{(0)} + \mathbf{w}) + \mathbf{v} \quad (12)$$

Defining the transformed subimage, $\tilde{\mathbf{s}}^{(0)} = \mathbf{s}^{(0)} + \mathbf{w}$, then (12) becomes:

$$\mathbf{y} = \Phi^{(0)} \tilde{\mathbf{s}}^{(0)} + \mathbf{v} \quad (13)$$

Now only direct path information, $\Phi^{(0)}$ is used to reconstruct the scene. To identify the ghosts in the reconstructed image, we exploit the AD feature.

Then, making independent sets of measurements using under-sampling matrices $\mathbf{D}_1$ and $\mathbf{D}_2$, $\mathbf{D}_i \in \{0,1\}^{J \times MN}$ with $J \ll M$. Down sampling the observation (13), gives:

$$\bar{\mathbf{y}}_1 = \mathbf{D}_1 \Phi^{(0)} \tilde{\mathbf{s}}_1^{(0)} + \mathbf{v}_1 \quad (14)$$

$$\bar{\mathbf{y}}_2 = \mathbf{D}_2 \Phi^{(0)} \tilde{\mathbf{s}}_2^{(0)} + \mathbf{v}_2 \quad (15)$$

The modified subimages, $\tilde{\mathbf{s}}_i^{(0)}$ in (14) and (15) are reconstructed using conventional CS approach by solving optimization problem [18], [19]:

The modified subimage, $\tilde{\mathbf{s}}_i^{(0)}$, can be reconstructed using conventional CS approach.

$$\tilde{\mathbf{s}}_i^{(0)} = \arg \min_{\tilde{\mathbf{s}}_i^{(0)}} \|\tilde{\mathbf{s}}_i^{(0)}\|_1 \quad s.t. \|\bar{\mathbf{y}}_i - \mathbf{A}_i \tilde{\mathbf{s}}_i^{(0)}\|_2 < \varepsilon \quad (16)$$

with $\mathbf{A}_i = \mathbf{D}_i \Phi^{(0)}$. The choice of ε is a function of noise power and is given by [20]:

$$\varepsilon = \sigma \sqrt{2 \log(N_x \times N_y)} \quad (17)$$

where σ is the noise standard deviation.

If the measurements (14) and (15) are taken with respect to different radar locations, then the resulting ghosts in the two subimages will be positioned differently. However, the true targets maintain the same location in both images. This property enables us to identify the genuine targets from a group of ghosts. The overall image is obtained using multiplicative fusion of the two subimages as:

$$\mathbf{s}(x, y) = \tilde{\mathbf{s}}_1^{(0)}(x, y) \odot \tilde{\mathbf{s}}_2^{(0)}(x, y) \quad (18)$$

4. RESULTS

For comparative simulation purpose, we adopt similar simulation parameters and setup as in [13]. The left and right sidewalls of the room are respectively at crossranges of $-1.8m$ and $4m$, while the back wall resides at $6.37m$ downrange. There is a protruding corner on the right at $3.4m$ crossrange and $4.57m$ downrange. A uniform linear monostatic array composed of 77-elements spaced out by $1.9cm$ is used to capture the image. The center of the array is taken to be the origin of the system. The front wall parallel to the array is at $2.44m$ downrange with thickness $d = 20cm$ and relative permittivity, $\epsilon_r = 7.67$. A series of 201 monochromatic waves to realize a UWB signal occupying a spectrum between 1 and 3GHz is employed for scene interrogation which allows a range resolution of $7.5cm$ with maximum unambiguous range of $15m$.

We assume that the front wall reflection has been properly mitigated using one of the approaches in [21]–[23], only wall reverberation effect has been considered. Five multipath returns were considered in this work, where one partial path is always the direct path and the second partial path corresponds to: direct, back wall multipath, left side, multipath with respect to the protruding corner on the right wall and the wall reverberation multipath with $k = 1$. We assume all side walls are perfect reflectors. When they are not perfect reflectors, then ghost targets will have less power and hence, becomes relatively easy to be suppressed. When the side walls are not perfect reflectors, then ghost targets will have less power and hence, becomes relatively easy to be suppressed.

During simulation, a target located at $(0.31, 3.6)m$ is considered. White noise of 0dB SNR is added to the simulated measurements. One-fourth of the radar positions were selected and only one-fourth of the frequency bins were transmitted at every radar position. CS image reconstructions were performed using CVX toolbox in MATLAB to reconstruct subimages.

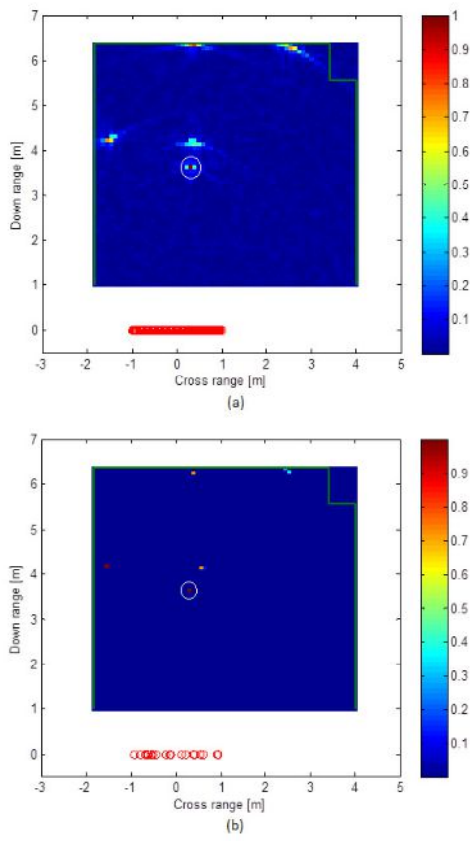


Fig. 3: Image reconstruction using (a) DSBF (b) conventional CS

The CS images are compared with delay and sum beamforming (DSBF) image utilizing full available measurement as shown in Fig. 3.

The given aperture is divided into two parts and we simulated two different scenarios: taking measurements randomly from both sub-apertures (fully random); taking random measurements in the first sub-aperture and take corresponding mirror locations on the second sub-aperture (mirror).

A. Experiment 1: Fully Random Measurements over 2-Sub-apertures

In this experiment, the two under-sampled measurements $\bar{y}_1$ and $\bar{y}_2$ as in (15) and (16) were randomly collected from the left and the right half of the given aperture respectively. Their

corresponding images are depicted in Fig 4(a) and (b). In Fig 4(a) and (b) the ghosts exhibit significant position mismatches and the final image is obtained using multiplicative fusion (19). In spite of having remnant in the final image, the target can be easily detected as the remnant power is deemed significantly. In the final image as shown in Fig. 4(c), multipath ghosts have been highly suppressed and almost have no significant effect on the target detection.

B. Experiment 2: 2-Partial Random Measurements over 2-Sub-apertures

In this experiment, only one sub-aperture measurements are randomly collected from one half of the available radar locations, $\bar{y}_1$. The second set of radar locations is simply the mirror image of the first set about the center of the aperture. The resulting images are depicted in Fig 5(a) and (b) with all ghosts clearly visible in the scene. However, the corresponding ghosts therein are located at different pixels which makes easy to distinguish them from the true target. This configuration on average maximizes the effect because the aspect difference is always guaranteed. In the final image as shown in Fig. 5(c), the given target is clearly detectable and no need for further processing of the image. This approach demonstrates superior performance with increased probability of correct detection. However, since the selection of the radar positions were partially random, it adds extra processing but rewarding excellent results.

To analyze the quantitative performance of the proposed reconstruction methods we defined two performance metrics: the target signal to clutter ratio (TSCR) and the target relative clutter peak (TRCP). The TSCR is defined as the ratio between the maximum target amplitude and the average amplitude in the clutter region. The clutter region in this paper refers to area of the room, excluding only the known target pixels. While, the TRCP equals the maximum target amplitude divided by the maximum clutter amplitude. Fig. 6 shows the variation of TSCR and TRCP with the fraction of measurements. The technique involving partial random data collection shows better performance compared to the full random version. Though, the performances of the two converges to the same value as the fraction of measurement increases. This is because as more radar locations are considered, the cross correlation of position vectors increases and hence the ghosts shifting become less pronounced.

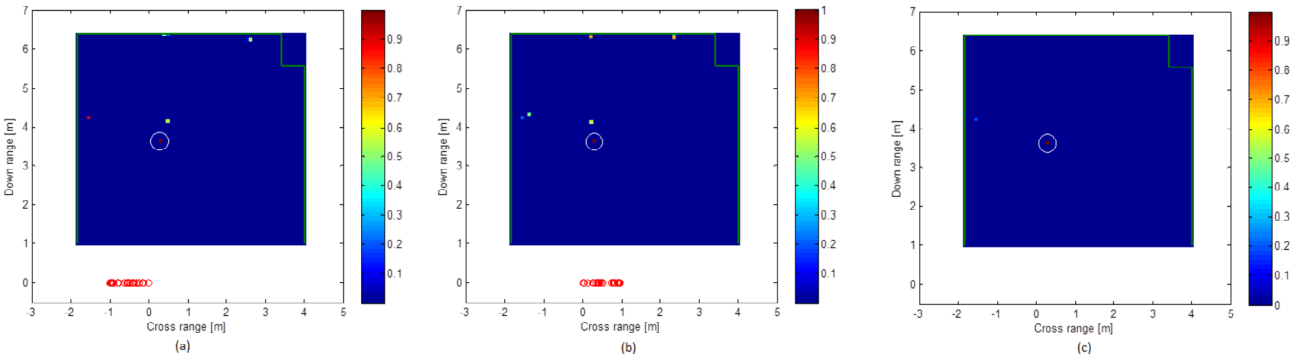


Fig.4: Simulation results for fully random measurements (a) sub-aperture-1 (b) sub-aperture-2 (c) final image

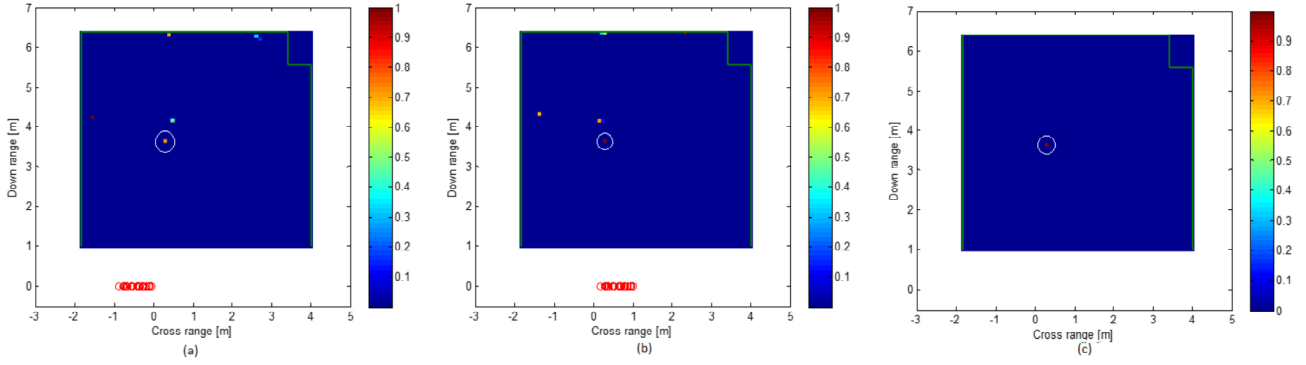


Fig.5: Simulation results for mirrored measurements (a) sub-aperture-1 (b) sub-aperture-2 (c) final image

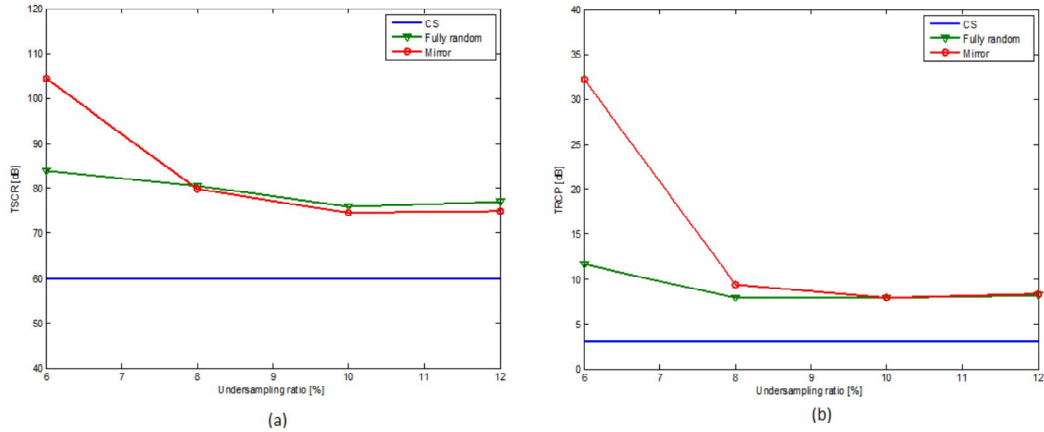


Fig.6: Performance metrics with fraction of measurements (a) TSCR (b) TRCP

The TRCP performance metric depicted in Fig. 6(b) is more crucial and should receive more attention as it tells how easy the target can be distinguished from the surrounding clutters. This has direct consequences on the target detection than the TSCR. When the TRCP is relatively small, the probability of correct detection will be highly reduced and the rate of false alarms will increase

5. CONCLUSION

This paper proposed efficient multipath ghost suppression technique in TWRI exploiting the AD feature of the multipath ghosts under CS framework without the knowledge of the reflecting geometry. The existing sensing matrix and front wall reverberation model were simplified leading to a more attractive system with less memory demand and reduced execution time respectively. Two radar selection modalities were investigated and both show sufficient TSCR and TRCP to correctly detect the true targets. However, the one involving partial random selection exhibits better performance. Though simulation results involved one target, the method works for multiple targets scenarios as long as the scene remain sparse.

As the extension of this work, the case of extended targets is underway.

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