Time-Reversal Processing and Autofocus of Targets Behind Complex Wall

Paul. C. Chang*, Robert J. Burkholder, and John L. Volakis
The Ohio State University Dept. of Electrical and Computer Engineering
ElectroScience Lab, 1320 Kinnear Road, Columbus, OH 43212
E-mail: chang.494@osu.edu, rjb@esl.eng.ohio-state.edu, volakis@ece.osu.edu

Introduction

Through-the-wall radar imaging (TWRI) beyond a single wall is a growing area of study [1]. Some previous work was done to mitigate wall effects under little or no knowledge of the wall [2]-[4]. However, past TWRI work has primarily been focused on imaging behind uniform dielectric walls. In this paper, we seek to leverage such effort for complex cinderblock walls commonly used in modern building construction. For walls formed by periodic blocks, much worse frequency-dependent distortion is expected as electromagnetic propagation through wall structures gives rise to Floquet modes. The work in [5] began dealing with this problem for far-field radar scan. In this paper, we focus on integrating electromagnetic propagation models (of the complex wall) with near zone imaging techniques to improve focusing of interior targets.

Electromagnetic Propagation Through Periodic Wall

Floquet wave analysis [6] of the periodic structure is a suitable choice for numerical analysis of typical building walls. As illustrated in Figure 1, plane wave transmission through a periodic structure gives rise to a discrete set of plane waves propagating at $\theta_m$. The discrete angular spectrum of these waves is

$$\sin \theta_m = \sin \theta_o + \frac{2\pi m}{kd} \quad m=0, \pm 1, \pm 2, \pm 3 \quad k = \frac{2\pi f}{c}$$

(1)

where $d$ is the unit length along the $x$ direction, $k$ is the wave number, and $\theta_o$ is the incident angle. For $m=0$, this corresponds to direct specular reflection and transmission. Alternatively for $m \neq 0$, the wave propagates at an outgoing angle $\theta_m$ if $| \sin \theta_m | \leq 1$, but are otherwise evanescent. Figure 1 gives plots of the reflection and transmission characteristics through some specified cinderblock walls at normal and $45^\circ$ TE incidences. From (1), it is clear that the reflected and penetrated plane waves will depend on the frequency and incidence angle. As shown in Figure 1, the first Floquet mode is not excited until around 2 GHz for normal incidences. However, when the incidence is at $45^\circ$, the first Floquet mode is excited much earlier and at around 1.2 GHz. For imaging, it will be shown that these modes introduce undesired multipath that becomes much worse at higher
frequencies. The issue is even more exacerbated for near zone illumination. In this case, angular spectral decomposition shows that highly oblique plane waves are also excited causing more multipaths.

Near Zone Radar Imaging and Wall Mitigation via Time-Reversal Match Filter Deconvolution

Here a higher frequency band of 2.7 to 3 GHz is chosen intentionally to illustrate undesired propagation effect due to Floquet modes. It should be noted that at lower frequency, the images are less susceptible to propagation effects but have poorer cross-range resolution. On the other hand, high frequency leads to better cross-range resolution at the expense of deteriorated focusing. Such frequency tradeoff needs to be carefully considered in the design of through-wall radar imaging system. To demonstrate the difficulties when imaging in presence of periodic walls, we consider a pair of point targets under the following situations (A) in absence of a wall (B) in presence of a homogeneous wall (C) in presence of a periodic wall. The measurement scan setting by a linear array is depicted in Figure 2a. As seen, the image focus is excellent in absence of the wall (see Figure 2b) and even when the wall is homogeneous (see Figure 2c). Homogeneous wall usually introduces delay resulting in minor target smearing and shifting. However, the presence of a periodic wall structure leads to a highly distorted image with artifacts as shown in Figure 2d. To correct the image in Figure 2d for a typical realistic situation, we consider time-reversal techniques for refocusing.
Figure 2: Near zone radar imaging through complex periodic wall and its wall mitigation (2.7 to 3 GHz) (a) scan setup (b) imaging in free space (c) imaging via slab wall (d) imaging via cinderblock wall (e) time-reversal image deconvolution of cinderblock wall

Time-reversal radar imaging takes advantage of time-reversal wave propagation concepts to improve resolution of targets situated in a complex environment [7]. In many cases, it can be particularly attractive because multipath in such environment may be used to increase the effective aperture without additional spatial samplings. A priori model of the propagation environment is required for these methods. Here a match filter version of the time-reversal imaging is
employed. Since time-reversal operation corresponds to phase conjugate in frequency domain, the near zone imaging function may thus be defined as

\[ I(x, y) = \left| \int \int E^s(w, r') [P_{\text{trans}}(x, y)]^* \right|^2 dw dr' \]  

(2)

Here \( E^s \) is the scattered phase history over the frequency band of interest (\( w \)) and T-R pulses (\( r' \)), and \( P_{\text{trans}} \) is the \textit{a priori} propagation model. As seen from Figure 2e, the time-reversal method has completely recovered the point target image. Indeed, sidelobes become less predictable and do not appear in the form of a sinc function. This is because the Fourier nature of a band-limited signal is no longer relevant. They are instead conformal to the transform of the \textit{a priori} wall propagation model. In addition, the target mainlobes in Figure 2(e) have better cross-range resolution as the Floquet multipath serves to increase effective synthetic aperture.

Conclusions and Future Work

A novel near-field time-reversal match filter deconvolution procedure was proposed to improve imaging behind complex periodic walls. Promising results with improved target resolution were shown. Future work will leverage such technique to tolerate errors in wall parameters leading to an autofocus approach.

References