Electromagnetic Time Reversal Technique – A New Way of Exploiting Multipath for Various Kinds of Radar

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Abstract:

The Electromagnetic Time Reversal (TR) technique is based on the time invariance property of electromagnetic waves. For every forward electromagnetic wave, there exist a back propagating wave which follows the same path. If the medium has less loss and is inhomogeneous, then TR provides better crossrange resolution. The purpose of this paper is to showcase the improved properties of TR and its applications in radar particularly in UWB(Ultra Wide Band) high resolution radars such as GPR(Ground Penetrating Radar), TWIR(Through Wall Imaging Radar),and medical radar.

I. INTRODUCTION

Time reversal is a techniques that is widely being used in acoustics, optics and ultrasonic to improve the imaging quality. First experiments in TR was done by Fink and his colleagues[1],[2]using acoustic waves. Different research groups lead by Y.Jiang, J.M.F. Moura and team of Carnegie Mellon University[3-7] and Fernando L. Teixeira and his collaborators [8],[9] of Ohio State University have extended TR concept to electromagnetics. In time reversal, the source emits the signals to probe the media and the reflected wave is recorded by an array of sensor and reversed in time(complex conjugate in frequency) and retransmitted back in loss-less media, focusing of the energy takes place exactly at the source location. Simultaneous compression in space and time takes place without the use of matched filter. If the medium of investigation is more inhomogeneous, the focussing and SNR improvement is better than homogeneous case. In TR focussing not only takes place at the source, but also at the passive scatters. In homogeneous media TR does not provide any extra benefit and the resolution limit is Raleigh limit. There are two regime of time reversal i.e. narrow band and Ultra Wide Band. In narrow band TR the phase conjugation in frequency domain is equivalent to get the effect of TR. UWB TR is statistically stable and its self averaging effect in random media improves the imaging quality. Research communities are investigating the application of TR in UWB systems. Further, the context of TR naturally fits into the realm of emerging Multistatic/MIMO(Multiple Input Multiple Output) radar[8]. As those use multiple transmitters and receivers, Tx waveform diversity, RCS diversity and geometric diversity to improve the detection, tracking, imaging, multipath fading mitigation, jammer and interference suppression. Time reversal(TR) can be treated as one way of designing the waveform for MIMO radar to match the probing medium and phase distortion compensation to focus the image. If the radar operating environment is rich in multipaths and an adaptive MIMO with time reversal would the one which can exploit multipaths in a better way. The developmentof TR signal processing is accelerated by development of improved electromagnetic modelling using various computational methods. Complex electromagnetic environment representing the actual radar operations of reflection, refraction, diffraction and

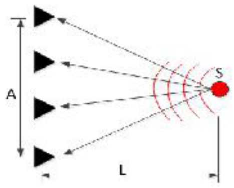

Figure.1 Scattering homogenec medium

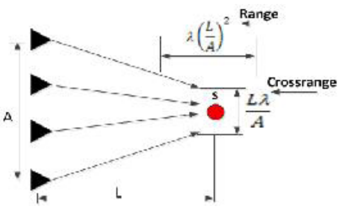

Figure.2 TR homogeneous medium

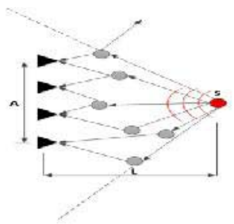

Figure.3 Scattering inhomogeneous medium

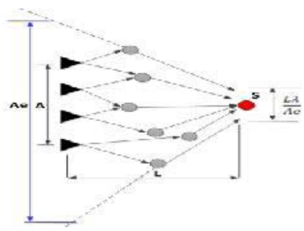

Figure.4 TR inhomogeneous medium

scattering can easily be modelled with these tools. Using methods of FDTD, FEM, MoM, and Integral equations to set up complex scenario and using MATLAB for further image and signal processing is a new approach to solve radar problems.This type of physics based signal processing is becoming popular due to the increased speed of computation and inclusion of close to actual phenomenology in electromagnetic solver. The concept of UWB radars based on the TR can easily demonstrated using Arbitrary Waveform Generator(AWG), High Speed Digital Oscilloscope, Vector Network Analyser to validate the concepts and algorithms. In [10] a S-band UWB prototype radar is developed and the TR and TR DORT for selective focussing is verified. Japanese group[11],[12] have developed single antenna based TR UWB radar to track moving target.

In this paper, we have focused on the application of TR to improve the existing radar performance and for emerging new kind of radars such as GPR, TWIR, Foliage Penetration Radar and medical radar etc.. This paper highlights the potential use of TR particularly for radar.

The paper is divided into five sections covering various radar applications. Possible use of TR in each kind of radar.

i. Sub surface sensing(Ground Penetrating Radar)
ii. Through Wall Imaging Radar(TWIR)
iii. Medical Radar
iv. Foliage Penetration Radar
v. GMTI/SAR

Multistatic/MIMO or conventional monostatic configuration can be adopted depending upon the application for the radar being designed.

II. SUBSURFACE SENSING

Ground Penetrating Radar[13] has become one of the prime sensor is application in mine detection, geological survey, civil engineering, ice depth detection etc.. The cross range resolution is poor due the finite size of the UWB antenna. The complex dispersive propagation medium with unwanted clutter such as tree root, animal holes and stones demand better cross-range resolution for target imaging, detection and classification. The radial range resolution can be controlled by the bandwidth(1/Pulse width) in the case of impulse as well as in FM/stepped frequency radar. But the cross range resolution is direct function of antenna beamwidth. Mostly in vehicle mounted GPR, SAR like processing such as w-k algorithm, Kirchoff's migration and time domain, frequency domain migration algorithms are used to get improved cross range resolution. But most of the algorithms assumes the homogeneous medium and uniform velocity of propagation through out the medium. Some of the techniques such as MPM(Mid Point Method) is used to estimate the velocity of the waves online in a layered media.But they are computationally inefficient. The focussing capability of GPR depends on the assumption how close the estimated velocity is to the true velocity.

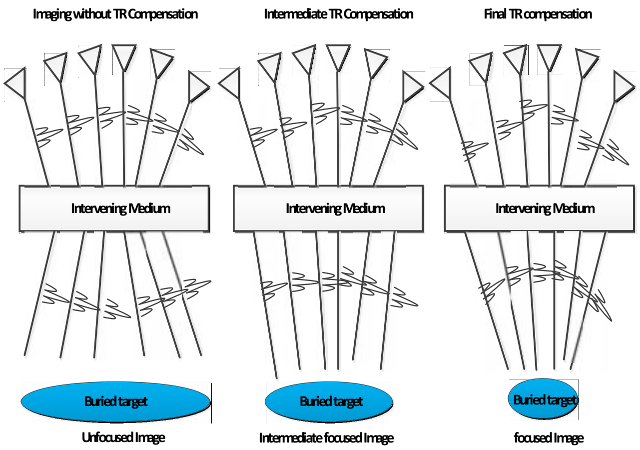

Figure 5 GPR imaging Using Time Reversal[14]

In case of TR for GPR array, it is not required to know about the soil characteristics and array geometry as the forward distortion is corrected by TR. Using more sophisticated TR techniques such as decomposition of Time Reversal Operator(DORT)and TR-MUSIC [8],[9] focussing of a selected scatters can be achieved which possibly enhance the classification capability of GPR.The basic TR application[14] for GPR is given in Figure 5. It explains how iteratively buried target in inhomogeneous intervening medium using TR compensation techniques.

III. THROUGH WALL IMAGING RADAR

Through Wall Imaging Radar(TWIR)[15] is an emerging sensor used for hostage risqué operation, to detect life under debris of earthquake, sensor for robots and many such applications.TWIR uses UWB(Ultra Wideband) waveform pulsed or FMCW/SFCW waveform like GPR. In TWIR EM waves travel in free space after penetrate the wall. The main problem is the unknown wall characteristics of the wall, multipaths due scattering from tables, chairs, roofs, floor etc. resulting in blurred image and positional error of targets. Various TWIR products with co-array, synthetic aperture radar(SAR) type probing techniques with hand held or tripod mounted configurations are available in the market. The main issue is the poor cross range resolution, improper localisation and ghost targets formation. Unknown wall characteristics, multi-paths results into blurred image, hence improper localisation both in radial range and cross range. Since electromagnetic time reversal exploits the multipaths to increase the resolution. It promises to mitigate so many issues related to TWIR. The main application of TR would be autofocussing with unknown wall characteristics, to improve cross range resolution, selective focussing on target and selective nulling of clutter. TWIR with multi-static configuration can use TR to improve the target signature. Firstly due to tighter focusing, it results into brighter image intensity. Secondly due to large forward

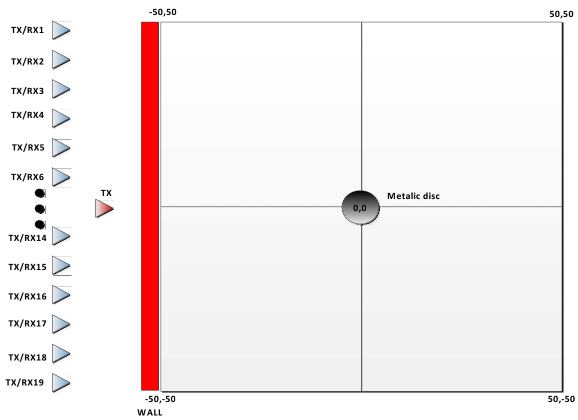

Figure 6 TWIR simulation setup[13]

scatter signal of target[16] which monostatic radar fails to exploit. Differential TR techniques can also be used to detect moving target [17] inside a room.

The simulated TWIR scenario and improvement of imaging in shown in[18]. The simulation set up (Figure 6)has a room of 100cm x 100 cm with disc scatterer at 0,0

(ε_r =46, μ_r = 0.21), wall thickness 9 cm (ε_r =4, μ_r = 0.002) illuminated by source(Tx) and receiving and TR is carried out by nineteen transceivers(TRx). Single scatter is focusing so tight without much artefacts as shown in Figure 7. In the same scenario the conventional backprojection algorithm results in blurred image with many artefacts. This promising result has tempted radar engineer to use TR for TWIR application.

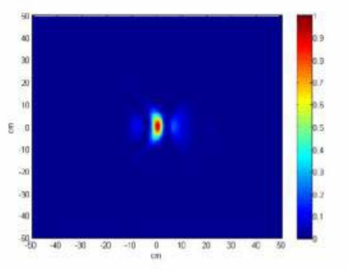

Figure 7 TR focused Image[13]

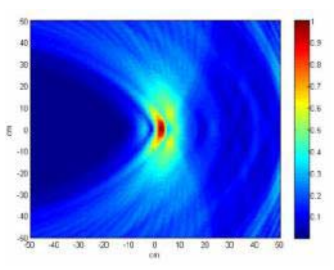

Figure 8 Back projected Image[13]

IV. MEDICAL RADAR

UWB based medical radar[19] are used for localisation of kidney stone, malignant breast cancer tissue, heart beat and remote health monitoring using high resolution imaging, beamforming, radar tomography and Doppler techniques. Due to inhomogeneity in the tissues the image gets blurred using conventional processing. Y. Jina [3] and others have investigated how the TR beamforming concept can be used to localise the breast cancer. They have compared classical beam forming and TR-beamforming and shown that the

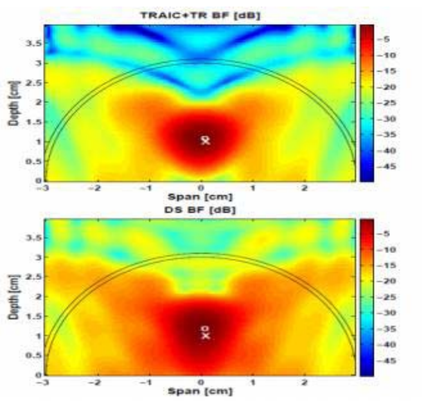

Figure 8 Upper TR Beamforming and lower is conventional[3]

TR-beamformer is superior in terms of focussing and location estimation as shown in Figure 8. Other medical applications such as ultrasonic imaging of skull can also use electromagnetic TR. In [6] the author have shown that TR-MUSIC gives better performance.

V. FOLIAGE PENETRATION RADAR

Foliage penetration radar[20] has been developed using synthetic aperture technique to image, detect and track targets in foliage. There are various Foliage Penetration (FOPEN) radars are available such as FORESTER from USA and CARABUS from Sweden. The challenges faced by the radar engineer are to image and detect target which is obscured by the foliage such as forest. The electromagnetic wave propagation in very complex coupled with heavy attenuation, multipaths, refraction and diffraction of the radar signal. To detect vehicles, human being in the forest the frequency of choice should be such that it should penetrate the foliage and have sufficient reflection from human beings and vehicles. Usually VHF and UHF frequency is used for imaging. But the disadvantages of VHF/UHF is poorer cross range resolution and doppler sensitivity. In current generation FOPEN radar better range resolution is obtained by higher BW and the cross range resolution is obtained by longer

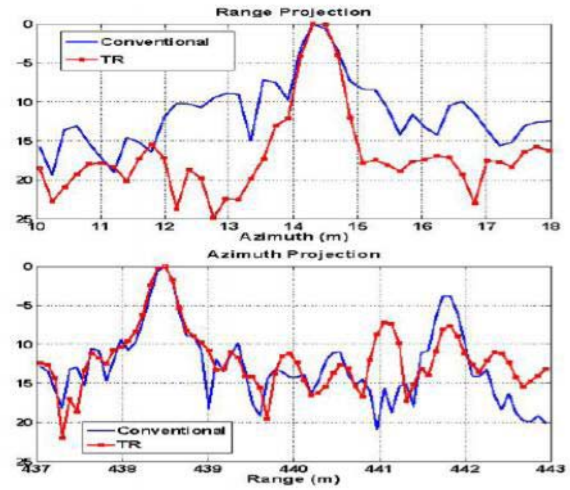

Figure 9 Upper Range Projection(Az. Resolution) and Lower Azimuth Projection(Range Resolution)[6]

integration time(large SAR angle).The range resolution and crossrange resolution [6]

$\Delta r = k_r c/2B\cos\alpha_g$

k_r range broadening factor

c velocity of light

B bandwidth of the signal

α_g Grazing angle

Cross range resolution

$\Delta cr = k_{cr}\lambda_c/4\sin(\theta_I/2)$

k_c Azimuth broadening factor

λ_c Wavelength corresponding to central frequency

θ_I Synthetic aperture angle

TR can improve the azimuth resolution as explained in Figure 9. Paper by Y. Jin and others[4],[6] have attempted to use TR SAR technique and shown improved azimuth resolution and imaging capability. The main characteristic of the UWB TR is statistical stability due to self-averaging property in random media. UWB waveform posses the both penetration capability due to low frequency and finer resolution due to higher frequencies.

VI. SAR/GMTI

General SAR/GMTI radars fitted in airborne platform uses concept of synthetic antenna array to improve the azimuth resolution. This mostly used for remote sensing application. It uses higher frequencies such as X-band or Ku band operation to obtain better cross resolution. Various image construction techniques being used with their variants to improve the imaging quality. Auto focussing algorithms are used to remote the higher order errors due to platform motion. SAR is used for imaging static scene. GMTI is used for detection of moving targets. It uses doppler techniques and in line track interferometry to detect very low minimum discernable velocity(MDV) signal in the order of centimetre per second. Complicated clutter environment results into blurred and ghost images. There are standard techniques used in SAR algorithms such as w-k migration, chirp scale processing, range migration algorithms(RMA), backprojection to improve the SAR image. The TR offers new kind solution along with existing algorithms.

Military application such as cruise missile(sub-sonic)[21]detection and tracking is difficult as these flies at the nap of the earth with a speed around 200 kmph to 400 kmph. The electromagnetic environment is very complex so very a high resolution waveform possible UWB waveform with TR can be used to get better intra clutter visibility.

VII. CONCLUSION

The Time reversal(TR) is promising for exploiting multipath in order to solve the various perennial problems related to radar. Multipath usually treated as nuisance in a conventional radar. Using TR improves the resolution in rich multi path environment. Different kinds of radars such TWIR, GPR, Foliage penetration radar(FOPEN), Medical radar, Airborne SAR/GMTI can use TR to improve the quality of imaging and detection. There are still unsolved issues of TR use in radar such as quantification of the improvement, TR in lossy medium and noise, optimal length of TR array, TR performance at higher order electromagnetic phenomena such as multiple reflections and TR based designs rules in line with conventional radar.

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