Time-Reversal Approach for Buried Point Scatterer Detection using a Low Frequency SAR

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Abstract—Time-reversal technique is more often applied in ultrawideband remote sensing. Its use is limited to the media in which the wave equations invariance condition is satisfied, i.e. a lossless and non-dispersion media. However, the loss (conductive) and dispersive media often occur in nature and are the subject of increasing attention. An example of such media is the soil, and its subsurface layered structure, which is subject of an investigation in a number of applications, for example: archaeological, environmental and civil engineering and security - detection of mines and unexploded ordnance. The motivation of this work is to apply the time-reversal technique of high resolution SAR imaging of subsurface soil. Firstly, on the basis of real soil geological database SPADE/2 the 3D model of soil was created as a cascade connection of thin and planar layers with a height d = 0.5 cm. Secondly, simulation for SAR Stripmap geometry were performed. Time-reversal operation on backscattered echo (from Forward probing) and TR probing were execute consecutively after Forward Probing an individual SAR platform position. Results for the three point scatterer, located at the different depth and at the different position along synthetic aperture, are presented, in detail, for closed point approach along aperture.

Keywords—time-reversal, ground penetrating radar, syntetic aperture radar.

I. INTRODUCTION

Subsurface soil imaging is a consistently growing area of remote sensing. The example applications can be listed as hydrology, survey of buried structures, pollution detection, as well as detection of unexploded ordnances (UXO) and landmines. Ground Penetrating Radar (GPR), mostly operates as ultrawideband (UWB) systems in low frequency range (P, L, VHF/UHF). Nowadays, more often GPR systems use the synthetic aperture technique for high resolution imaging of the subsurface soil structure. Due to the inhomogeneous nature of soil, backscattered signal derived from multi-reflection of the electromagnetic (EM) waveform transmitted through the soil is laden by dispersion and loss effect. This leads to energy dissipation and pulse distortion, and thus strongly affects the results of matched filtering (MF) operation causing their significant degradation. Detailed analysis of the low frequency SAR focusing problems was carried out in [1]. The most important problem is strong defocusing of the backscattered signal in range (depth) dimension, which does not allow one to fully benefits from the SAR processing. This is due to the fact that the soil is inhomogeneous, dispersive and loss medium with an inconstant moisture profile, and which inhomogeneous nature is revealed by layered structure in depth dimension with planar or rough interfaces between consecutive layers. The primary step to fully take advantage of the SAR processing should be the neutralization (or compression) of the defocusing effect in depth dimension. Refocusing approach to defocused signal seems as one of the potential and natural solutions. Time-Reversal (TR) [2-5] technique is used in the wide range of remote sensing application to obtain super-resolution. This technique was firstly developed by M. Fink [2] for acoustic frequency range, later, F. Moura [3] and J. de Rosny [4] have demonstrated its applications in microwaves frequency range. The foundations of TR are based on the assumption of time reversibility (reciprocity) of medium. This means that both the wave $E(t,x)$ and its equivalent time-reversed version $E(t,-t)$ are solution of the same wave equation which describes propagation through material medium. Time-Reversal measurements protocol (presented in [2,3,8,9]) can be defined in the three separate steps performed consecutively and operating on the radar waveform. The first step consists of the transmission of EM waveform into medium and registration backscattering pulse. The second step realizes the time-reversal operation on the EM pulse recorded in first step. This operation is equivalent to mirror operation, i.e. samples placed at the begin of the recorded pulse are transferred to the end of recorded pulse and vice versa. Last step consists is the re-transmission of the time-reversed EM pulse into the same medium and recording the new backscattering pulse.

In the numerical simulation it was assumed that the propagation of EM waveform inside the soil is similar to the propagation of EM waveform in a waveguide. Dielectric constant of each thin soil horizon has been calculated using the pedotransfer function proposed by Peplinski [6], which at the input has soil texture in horizon (percentage of clay, silt, sand and also bulk density) and soil moisture value. Real geological data form the soil database SPADE2 has been used for simulation, as well as for estimation of soil moisture profile, calculated by applying the finite difference method for solving the Richards’ equation in depth dimension. The paper is divided in section as follow. Inhomogeneous 3D soil model is presented in Section II. In this section, only results of modeling are presented, details of the simulation method has
been discussed in [7]. Section III presents the stripmap SAR [9,10] geometry configuration and radar parameters. Section IV presents the result of the SAR imaging with TR measurement protocol verification for three theoretical point scatterers placed in soil at different depth at the closed point approach position (minimum slant range between target location and platform position along synthetic aperture). Focused SAR images are presented in Section V. The paper is summarized in Section VI.

II. 3D LAYERED SOIL MODEL

Modeling of soil dielectric properties is performed by pedotransfer function that allows to calculate dielectric constant based on information about soil texture and moisture profile [6, 7]. In [7] we showed that the valuable source of information about the soil texture, its inhomogeneous and layered nature is geological database. Fig. 1 presents geologic data for selected soil topologic unit (STU), soil texture (left) is represented as five-horizons structure with different texture. The key input parameter for pedotransfer function is moisture profile. One of the method for its calculation is solving the Richards’ equations with appropriate boundary conditions for initial moisture profile and evaporation coefficient. Calculated moisture profile for selected STU is presented on Fig. 1 (right).

III. STRIPMAP SAR CONFIGURATION

For simulation, the stripmap SAR configuration has been assumed using side-looking airborne radar (SLAR) and with altitude $H = 3500$ m and platform velocity $v_p = 100$ m/s. Fig. 3 presents the swath width, footprint dimensions and its location on first, center and last position of SAR platform. As stated before, in soil cube the three point scatterers are placed in different coordinates (see Fig. 3 - red dots, and Table I). Each target lies in different horizon.

<table>
<thead>
<tr>
<th>Scattering Number</th>
<th>Coordinates</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target 1</td>
<td>0.625</td>
<td>127,875</td>
</tr>
<tr>
<td>Target 2</td>
<td>1.250</td>
<td>255,750</td>
</tr>
<tr>
<td>Target 3</td>
<td>1.875</td>
<td>383,625</td>
</tr>
</tbody>
</table>

For AGPR simulation, one P-band radar configuration has been assumed, which parameters are given in Table II. As a radar waveform the LFM chirp $s(t)$ pulse has been used:

$$s(t) = \exp \left( j2\pi (f_0 t + Kt^2/2) \right) \Pi_{T_i}(t).$$

<table>
<thead>
<tr>
<th>Radar Configuration</th>
<th>Band</th>
<th>$f_c$ [GHz]</th>
<th>$B$ [MHz]</th>
<th>$T_i$ [μs]</th>
<th>$\alpha_{in}$ [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radar_1</td>
<td>P</td>
<td>0.430</td>
<td>200</td>
<td>1.5</td>
<td>30</td>
</tr>
</tbody>
</table>

Pulse instantaneous frequency lies in the range 300 MHz to 530 MHz, referring to Fig. 2, it is a frequency range where
imaginary part of the soil dielectric constant varies the most. Pulse Repetition Frequency (PRF) is equal \( PRF = 200 \) Hz. The SAR simulation performed along 1024 positions of platform, which results in a synthetic aperture length \( L_s = 512 \) m. Due to different position along synthetic aperture, for each point scatterer inside soil the closed point approach range \( R_{CPA} \) center of synthetic aperture can be determined. In next section results obtained for this position, i.e. forward probing echo, TR source pulse and TR echo will be shown. The total SAR images coordinates are 512 m for 470 m, in azimuth and range, respectively.

IV. TIME-REVERSAL SAR PROCESSING

As was state before, TR measurements protocol can be defined in the three separate steps performed consecutively and operating on the radar waveform. In case of SAR, these steps are performed consecutively at each position of synthetic aperture.

A. Forward Probing

In case of Airborne GPR, first step is “traditional” SAR probing of soil subsurface by transmitted pulse and recording backscattered echo. Fig. 4 presents envelope of backscattered pulse (top), corresponding spectrum (center) and normalized output of matched filtering (bottom) of signal recorded from three point scatterers. Irregular attenuation shows that the soil acts as a filter for EM waveform and distorts backscattered pulse. Backscattered echo from deeper targets is more distorted due to accumulation of the dispersion effect, effective duration time of echo is shorter, and corresponding output of matched filtered is wilder and is more shifted for its expected position. This time shift value is proportional to pulse distortion.

B. Time-Reversal Operation

Time-Reversal probing assumes the use of FP echoes for re-probing of medium. Fig. 5 presents the time-reversed echoes of forward probing. More distorted and attenuated echoes are strongly amplified. New sources pulse consist of the same information like forward probing echoes but in “mirror” order.

C. Time-Reversal Probing

TR probing is carried out as transmission of TR source pulse, in fact, re-transmission of time-reversed forward probing echoes in “mirror” order. Still, dispersion and loss phenomenon occurs at the same level. Fig. 6 presents envelope of backscattered pulse (top), corresponding spectrum (center) and normalized output of matched filtering (bottom) of signal recorded from three point scatterer. It should be notice that matched filtering after TR probing is performed between TR source and TR echo. The results are similar to forward probing. Due to still present dispersion, the recorded echo is also distorted in time but now in “mirror” order, i.e. the effective pulse duration of TR echoes are longer than TR source pulse.
Additionally, due to adapted energy normalization method during Time-Reversal operation, the envelope of pulses form the three point scatterers has similar amplitude in time and frequency domain. Furthermore, results of corresponding matched filtering are still wider than expected shape, but now are centered on expected location and show a slight symmetric property in shape of envelope.

D. Time-Reversal Refocusing Phenomenon

As presented previously, matched filtering is performed after each probing between source pulse and backscattered echoes. Thus:

- For Forward Probing, matched filtering is performed between a well-known LFM chirp and a backscattered echo recorded in “traditional” SAR scanning.
- For Time-Reversal Probing, matched filtering is performed between a TR source and a backscattered echoes recorded in “additional” SAR scanning.

Signal used in TR probing as a source is time-reversed copy of signal recorded in forward probing. Furthermore, a dispersion and loss phenomenon is unchanging in time of observation. Thus it is possible to perform an additional matched filtering between a well-known LFM chirp (source for “traditional” SAR scanning) and a backscattered echoes recorded in “additional” SAR scanning.

Fig. 7 presents result of normalized “cross” matched filtering obtained for three targets placed at different location. All results of “cross” MF are located on expected position and have a nearly amplitude, the same main lobe width and first side lobe level. Additionally, refocusing phenomenon has occurred independently of target location (especially in depth dimension). Due to adapted energy normalization method, all targets has the same (differs slightly) maximum peak level. This confirms that weaker backscattered echoes form deeper targets or placed in more dispersive horizons should be covered by stronger energy normalization. Especially when time window of recording backscattered echo in forward probing is longer than pulse duration [8,9]. Additionally, dilatation time cannot be ideally reconstructed, because of the constant value of radar sampling frequency, it could be too small for fully sampling distorted echoes.

V. TIME-REVERSAL SAR IMAGING

Results presented in Section IV are obtained for TR-SAR probing at CPA position for each targets. Performing the SAR mission along synthetic aperture and matched filtering for three stage (forward probing, time-reversal probing and cross matched filtering, respectively) the data presented in Fig. 8 has been obtained. Red crosses represents true target position in along-track vs. across-track plane. Fig. 8a presents results of the forward matched filtering between radar pulse and distorted in energy and time duration echoes related to point scatterers. Characteristically for SAR imaging, echoes form theoretical point scatterers are placed along curve that reflect range changing between point location and SAR platform position. Result of MF for point scatterers has similar amplitude, that result from adapted energy normalization which causes the TR echoes has slightly the same amplitude (see Fig. 6a.). Also, additional time shift proportional to distortion effects occurs. Finally, Fig 8c. presents result of cross matched filtering between well-defined radar pulse s(t) constant along synthetic aperture and TR echoes recorded during platform flight. Refocusing phenomenon occurs for three theoretical point scatterers placed at the different depths. The echoes are located similarly along curve that reflect range changing between point location and SAR platform position. Result of MF for point scatterers has similar amplitude, that result from adapted energy normalization which causes the TR echoes has slightly the same amplitude (see Fig. 6a.). In all three case, results presented at Fig. 8 should be identified with SAR range compression operation. When the result of range compression after forward probing and TR probing is deformed by the distortion effects (clear deterioration of resolution in depth dimension), the result of cross matched filtering does not suffer from the effect of distortion and depends only on bandwidth of LFM chirp signal.
A. SAR Azimuth Compression

For SARs, high resolution is achieved by coherent pulse compression in range and azimuth coordinates. Based on results of range compression presented above, only compression in azimuth should be additionally performed. Azimuthal compression factor is given by $K_a = \frac{2 V_p^2 \lambda c}{R_s}$, and is a function of slant range $R_s$ between center of synthetic aperture length and each range resolution cell. Azimuth reference function $a_{ref}(u,r)$, defined in slow time $u$ and slant range $r$, is given by:

$$a_{ref}(u,r) = \exp \left[ -j \left( \frac{2\pi}{\lambda c} V_p^2 (u-u_0)^2 / R_s(r) \right) \right]$$

Using the fast convolution theory for azimuth “off-line” compression, the data presented on Fig. 9 has been obtained. Both SAR images obtained after forward probing (Fig. 9a) and TR probing (Fig. 9b) have unacceptable azimuth resolution which decreases with depth of the targets. Results of azimuth focusing are strongly distorted and targets are unresolved. Contrary, SAR images for cross matched filtering (Fig. 9c) is well focused both in range and azimuth dimension. All targets are clearly resolved with nearly the same amplitude (see Fig. 7). Time delay (shift) in depth dimension results from smaller and irregular velocity of electromagnetic wave propagation through soil layered structure. Deeper targets have a greater displacement compared to the true location than shallow targets. Such not uniform displacement results from inhomogeneous nature of soil layered structure (soil horizons) and is related to inhomogeneous relative dielectric constant of soil, which is dependent on soil texture in layer and moisture.

VI. CONCLUSION

We have simulated Airborne GPR in case of 3D soil dispersive and loss structure. The purpose of this research is to find a method for compensation the defocusing effect that strongly distorts results of range compression and does not allow for high resolution imaging of soil subsurface structure. Despite the presence of the strong attenuation both for forward probing and TR probing the dispersion effect was reversed in time. Adapted energy normalized method has been applied and allowed for correction of the TR echoes to uniform level. Typically for SAR techniques, for each step echoes are located along range curve that reflect distance changing between point location and SAR platform position. Ours results obtained with TR technique indicates that deeper targets location not necessarily mean harder to resolve and correct detection. Additionally high resolution SAR images of soil subsurface layers can afford to perform the next step which is the use of interferometry technique for creation of the Digital Soil Subsurface Model, in contrast to Digital Terrain Model (or Digital Terrain Map).

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