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Ground penetrating radar simulations of non-homogeneous soil with CST Studio Suite

***Abstract**. The paper describes the simulation results for a ground penetrating radar with CST Studio Suite. Non homogeneous soil composed of four different materials has been investigated by pulse GPR. The aim of the experiment is to obtain fully focused image of the tested soil structure. The raw GPR data collected with CST Studio Suite has been processed using Matlab. Simulation results presented in the paper show good possibility of focused SAR method for underground targets imaging.*

Streszczenie.** Artykuł przedstawia wyniki symulacji radaru do sondowań podpowierzchniowych z wykorzystaniem oprogramowania CST Studio Suite. GPR (ang. Ground Penetrating Radar) bada niejednorodną ziemię złożoną z czterech materiałów. Celem eksperymentu jest otrzymanie w pełni zogniskowanego obrazu badanej struktury ziemi. Surowe dane pomiarowe wygenerowane w programie CST Studio Suite przetworzono w środowisku Matlab. Przedstawione w artykule wyniki symulacji potwierdzają duże możliwości zobrazowania ukrytych w ziemi obiektów przy wykorzystaniu algorytmu SAR (ang. Synthetic Aperture Radar) zogniskowany. (**Symulacje niejednorodnej ziemi radarem do sondowań podpowierzchniowych z wykorzystaniem CST Studio Suite)

Keywords: CST, GPR, SAR.
Słowa kluczowe: CST, GPR, SAR.

Introduction

CST Studio Suite is the powerful simulation platform for electromagnetic field problems. The transient solver gives appropriate results of non-homogeneous soil imaging. In order to obtain raw GPR data, wideband horn antenna, transmitting and receiving signal, has been applied. Decisive parameter during selection of appropriate antenna is S_{11}. S_{11} refers to the ratio of signal that reflects from the port for a signal incident on that port. The main aim of ground penetrating radar is to obtain good resolution of underground targets. Before one can perform real data measurement it is recommended to simulate radar scene with professional electromagnetic simulator. In that way many measurement problems can be avoided, what is more, the best radar parameters (such as type of antenna, type and bandwidth of transmitted signal) can be selected.

The CST transient solver calculates the development of fields through time at discrete locations and at discrete time samples. Program provides possibility of various propagating signal properties and tested soil structure definition. Moreover CST performs irregular time sampling of simulated data. If radar transmit signal with linear frequency modulation, CST Studio sample rate for that part of the signal with higher frequencies will be much greater than for lower frequencies part. This gives good accuracy of computed date, however collected data need to be resampled before performing pulse compression.

Presented simulation with CST Studio Suite has been prepared by the author in Bumar Elektronika S.A.

Simulated Radar Scene

The simulated soil structure is composed of four materials of different electric permittivity values. The analyzed ground has 2 meters length in GPR movement direction, 0.7 m width and its thickness is 0.6 m. The main component of the model is dry sand which covers loamy soil, bones and forty years old concrete. Selected horn antenna is positioned 10 cm above the ground. GPR antenna has been placed in 145 points, the movement step is 1 cm which gives 1.45 m of simulated raw data. Investigated non-homogeneous soil structure is presented in Fig. 1. Each of the layers of the ground, made of loamy soil, bones and forty years old concrete and located inside dry soil, have shapes of prism. Analyzing the plane intersecting the soil in movement and depth direction, these layers have shapes of triangles.

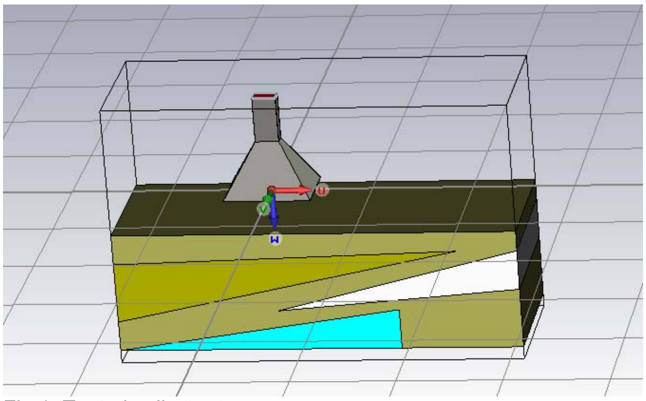

Fig.1. Tested soil structure

Loamy soil has the following coordinates of vertices [cm]: (0,-15), (0,-45), (170,-10). Medium made of bones has coordinates of vertices [cm]: (200,-10), (200,-30), (80,-40). The third layer made of forty years old concrete has coordinates of vertices [cm]: (0,-60), (140,-60), (140,-40). At the border of two medium with different permittivity values electromagnetic wave is reflected [1][3]. GPR performance is based on reflection phenomenon. Unfortunately, image of buried objects generated by ground penetrating radar does not correspond to its geometrical representation. The image collected from single point target has hyperbolical shape [3][4]. The radius of this curve is strongly connected with target depth and electrical parameters of the soil surrounding the object. Increase in depth of an object or decrease in permittivity causes increase in the radius of curve [5]. Direction of propagated wave is dependent on soil properties. What is more, each layer of the ground attenuates electromagnetic wave, which causes the maximum range equal to several meters [1]. Ground is heterogeneous medium, for these reason, the GPR signal processing is much more sophisticated than in other types of radars. The aim of the experiment is to obtain fully focused image of each soil component. Improvement of pulse GPR resolution in depth direction can be obtained using signal with linear frequency modulation LFM [6]. Depth resolution for LFM pulse is inversely related to signal bandwidth. The matched filter output for pulse radar with linear frequency modulation can be approximated as sinc(x) function. LFM has significant sidelobes at the level of about

-13 dB which can mask weak echoes from deeper located objects [5][6]. Commonly know method of LFM sidelobes suppression is based on window function application [5]. This operation can suppress sidelobes to the required level. Time domain weighting are used to suppress Gibbs oscillations caused by the truncation of a Fourier series. However, matched filter amplitude weighting causes mismatches, which reduces signal to noise ratio. As a consequence, maximum radar range is decreased [5]. Presented simulation results has been achieved for LFM signal with bandwidth B = 2 GHz, time duration $\tau = 5ns$, carrier frequency f_C is equal to 2 GHz.

Raw GPR signal processing

Raw GPR data calculated with CST Studio Suite need to be processed in order to obtain radar image. As it has been mentioned, CST performs irregular time sampling. The highest frequencies of LFM signal are sampled with much faster than parts of the echo signal with low frequencies. This results in accurate mapping of the analog signal. Such given signal can not be directly processed by matched filter. Before pulse compression could be done, collected data need to be resampled. It can be done using Matlab interpolation method called interp1. Finally, sampling frequency is equal to 40 GHz. Resampled raw data is presented in Fig. 2 and contains signal reflected from antenna port. The signal has been obtained from CST Studio Suite.

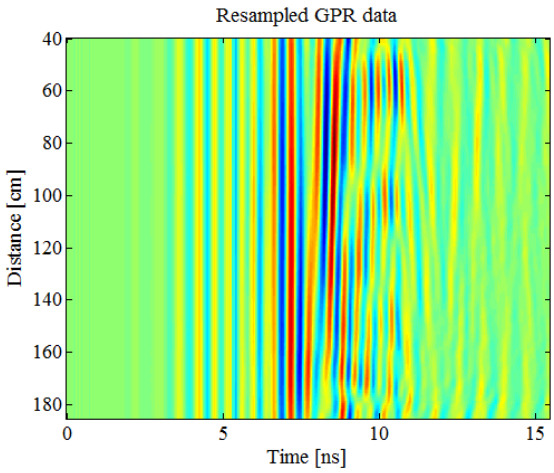

Fig.2. Raw data from CST Studio Suite

Undesired S_{11} signal has been removed using lattice filter based on Burg's algorithm [2] (Fig. 3). For that purpose, S_{11} data without soil has been calculated and used as reference signal x_{ref}. Signal labelled as x_{rec} is signal reflected from soil structure.

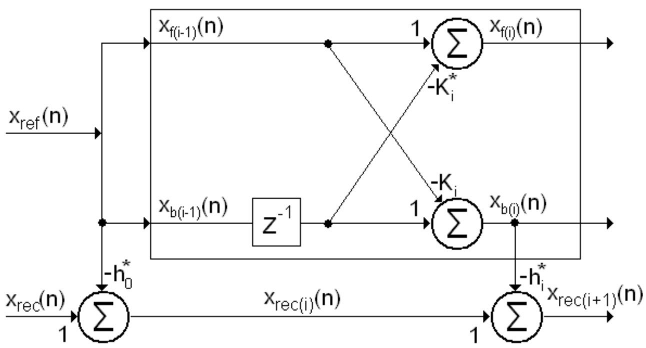

Fig.3. Lattice filter

Lattice filter is described by following equations [2]:

$$h_i = \frac{\sum_{n=0}^{N-1} x_{rec}(i)\, x^{*}_{b(i-1)}(n)}{\sum_{n=0}^{N-1} \left| x_{b(i-1)}(n) \right|^2} \tag{1}$$

$$K_i = \frac{\sum_{n=i+1}^{N} x_{b(i-1)}(n-1)\, x^{*}_{f(i-1)}(n)}{\sum_{n=i+1}^{N} \left(\left| x_{b(i-1)}(n-1) \right|^2 + \left| x^{*}_{f(i-1)}(n) \right|^2 \right)} \tag{2}$$

After removing S_{11}, spectrum of raw data is still located around carrier frequency and need to be demodulated. In order to demodulate the signal, LFM signal is given at the first input of mixer, at the second input coherent heterodyne signal is given. At the mixer output demodulated signal is obtained. The next step of the computation is low-pass filtering. That process removes undesired signal spectrum components. The spectrum of demodulated GPR data after low-pass filtering is visible in Fig. 4.

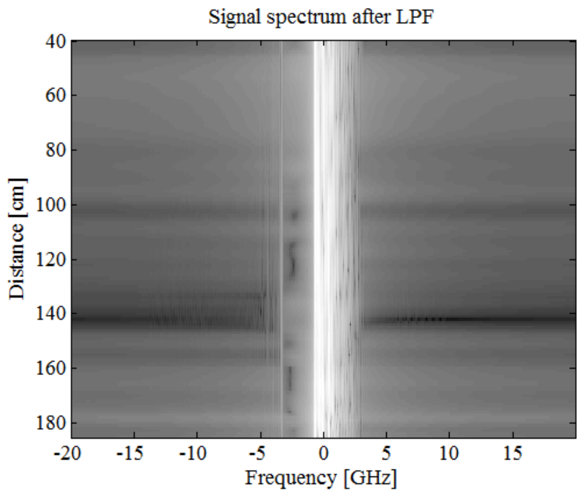

Fig.4. Signal spectrum after LPF

Low-pass signal representation in time domain is presented in Fig. 5. Calculated data does not give enough information about soil structure, the depth of an layer cannot be reliable determined. However, processed in described way echo GPR signal can be subjected to pulse compression [6].

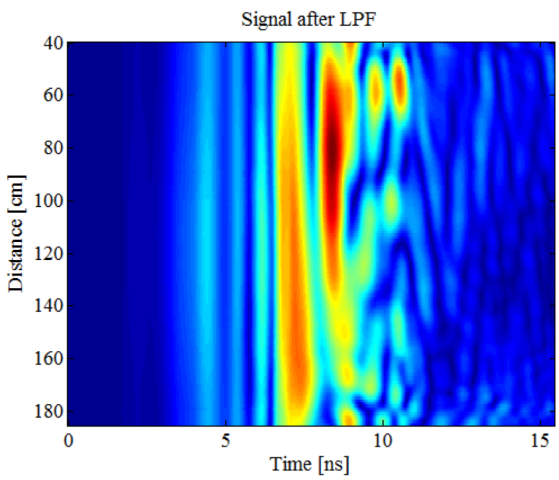

Fig.5. Signal after low-pass filtering

Depth compressed GPR data is visible in Fig. 6. In order to suppress sidelobes level, the matched filter is weighted by Hamming window. Theoretically [6], level of Hamming window sidelobes is -41 dB. Matched filter output of signal with linear frequency modulation is characterized by good depth resolution on condition that time duration and pulse bandwidth product is large enough. It is assumed that time and bandwidth product should be not less then 100, for that value LFM spectrum is square. Analyzing Fig. 6 one can see, that the first reflection from the antenna port (S_{11}), which has been suppressed by lattice filter, is visible in fourth ns. Due to lattice filtration, undesired S_{11} does not mask remaining reflections. The echo signal reflected from the border between air and sand return to the GPR after 7 ns. The strongest amplitude of echo signal is obtained from the border between dry sand and loamy soil and is located from 8th to 9th ns. Echo signal reflected from the rest of soil layers are barely seen. Appearance of buried objects change electromagnetic and mechanical properties of the earth. The shape of received echo signals after range compression does not correspond to geometrical dimensions of located objects. Propagated wave is reflected, refracted and scattered on the border of two mediums. What is more, transmitted electromagnetic waves are strongly attenuated by surrounding soil.

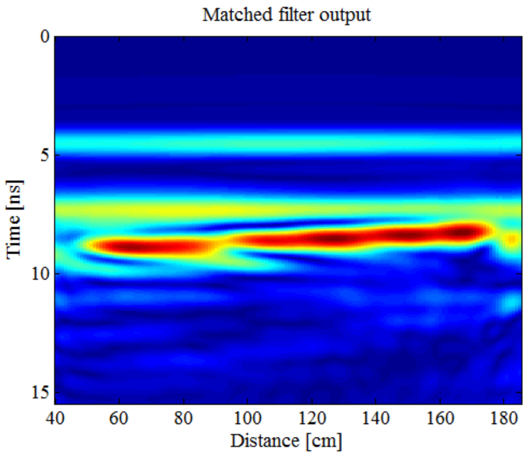

Fig.6. Matched filter output

CST Studio Suite introduces noise associated with carried out computations, it is good seen in reflected signal from second to 4th nanosecond, where there should not be any echo signal. Unfortunately, presented results does not meet requirements, not every layers can be detected from Fig. 6. The general objective of digital signal processing as applied to surface penetrating radar is either to present processed image that can be readily interpreted by operator. For that purpose cross range resolution must be increased. These requirements may be satisfied by performing focused SAR filtering in movement direction [3][7]. Nevertheless, majority of know ground penetrating radar devices use non-coherent Hough Transform in order to increase image resolution in movement direction [1][8]. That technique is based on detection of specific, hyperbolical shapes in depth compressed image. Hough Transform provides good results on condition that analyzed image has good quality and curve shapes are easily distinguished [4]. When obtained image is contaminated by high level noise, non-coherent algorithm will not give expected results [8]. For that reason SAR technique is much effective and allows to achieve optimal cross range resolution.

Focused SAR Filtering

Azimuth resolution improvement is obtained using two-dimensional SAR filtering. The most important parameters of matched filter is its phase and geometrical shape of impulse response. These parameters include information about the depth of an object and permittivity value of tested soil. Two-dimensional convolution of range compressed data *S(n,m)* and SAR matched filter *h(n,m)* can be calculated [3][4]:

$$S_{SAR}(n,m) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} S(k,l) \cdot h(n-k, m-l) \quad (5)$$

Distance *n* in movement direction is changed from 0 to *N*, range cells are changed from 0 to *M*.

SAR matched filters are initially multiplied by hamming window function. This procedure results in sidelobes suppression in movement direction. Two-dimensional filtering is carried out according to following scheme:

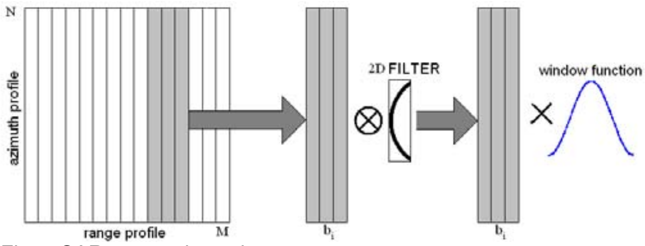

Fig.7. SAR processing scheme

Two dimensional SAR filtering, presented in the article, has been performed in few steps. Depth compressed data initially is divided into blocks [4][5]. For each block, 2D matched filter is prepared. SAR filter properties are strong connected with the depth of an target and permittivity value of surrounding medium. Calculated matched filter is convolved with selected block and the nearest neighbourhood. Filtered three blocks are then multiplied by Hamming window to smooth the final image. After calculating the convolution for all blocks, overlapping blocks are summed. GRP image after applying focused SAR algorithm is presented in Fig. 8.

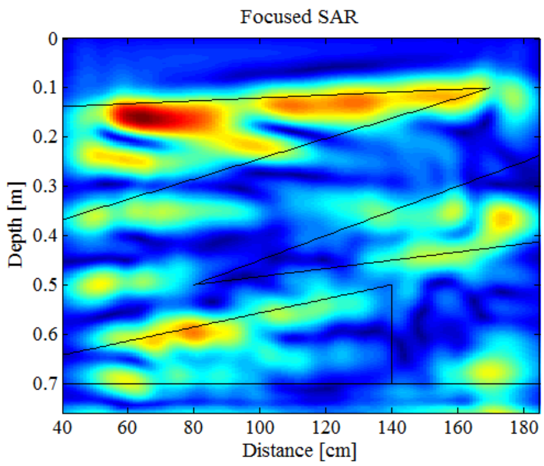

Fig.8. Focused SAR image

During the SAR filtration a constant value of electric permittivity, equal to permittivity of dry soil, has been assumed. What is more, the image has been shifted in such a way that the first reflection from the dry sand is now located at 0 m depth. As a consequence of digital signal processing, reflections from each of layers constituting soil structure has been observed.

Unfortunately, calculated focused GPR image (Fig. 8) does not give enough information about all buried structures. Radar signal is propagated throw each structure with different velocities. For that purpose, using the same permittivity for each layer to calculate GPR range from time delay, each soil structure is shifted in depth direction. What is more, soil structures are not parallel to each other and to the border of soil and air. This is the reason why the echo signal received from a structure has different amplitude for each point of that structure and shape of each structure do not correspond to its physical size. There are points located on structures from which transmitted signal is reflected in the different direction to antenna position. There is no received signal for that points. Another distortion of the final image is caused by multipath direction of echo signal. It can be seen as a places of the image with high amplitude that does not correspond to any structure.

The signal parameters such as bandwidth and time duration does not give the theoretical range resolution. Time and bandwidth product is much less than it should be and is equal to 10. In this case mainlobe of range compressed signal is wider in contrast to theoretical resolution. In order to improve image resolution longer signal or FMCW GPR should be used.

Conclusions

Presented simulation results confirm that CST Studio Suite can be used to simulate different kind of GPR. The program allows to design complicated soil structures and antenna design. Performing proper GPR algorithms one can achieve good resolution of underground targets. However, before digital signal processing can be performed, signal data from CST need to be resampled. Focused SAR algorithm gives good results of explored soil. What is more, presented ground penetrating radar could be used to investigate the soil structure, unless the permittivity coefficients is correctly determined.

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