A Software Tool for GPR Data Simulation and Basic Processing

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Abstract: *In this paper, a software tool developed in Matlab for stepped-frequency GPR (Ground Penetration Radar) is presented. It is intended for data simulation, image formation and basic GPR signal and image processing.*

The designed software can be useful for the researchers to help them analyze the performances of the different algorithms for data acquisition, signal processing and image processing. A part of the results, achieved using this package, is presented in this work.

Keywords: *Ground penetrating radar, image processing, Monte Carlo simulation analysis.*

1. Introduction

Typically, GPR data are basically processed with commercial packages (such as Radan Geophysical Survey Systems Ins. or Haescan Roadscanners), which are aimed more at the commercial users than the researchers. The software source codes of these packages are often not open and they are not always available for the researchers. These facts make commercial packages less useful for research needs. Because of this, a mini-package for realizing the most important basic processing algorithms is developed. There are different algorithms for noise and spice events suppression, direct and air waves removing, attenuation losses correction. The input data can be real or simulated radargram. These data can be the output radargram of new currently investigated processing algorithm as well.

The general algorithm for B-mode image (radargram) simulation and processing includes: calculation of the amplitude and two-way time delay of a

signal reflected from each layer of a multi-layered media; simulation of useful echo signals, clutters, speckle and impulse noise; construction of the synthetic range profile; image formation.

The experimental results obtained enable to conclude that the software tool presented in the paper can be successfully used for analysis and parameter optimization of the basic signal processing algorithms.

2. Software tool blockscheme

The general block-scheme of the developed software tool is presented in Fig. 1. The input data can be real radargram or radargram model (simulated data). These data can be the output radargram of a new currently investigated processing algorithm as well (see Section V). There is the possibility of adding active noise (pulse jamming) environment. The simulation algorithms are described in Section III.
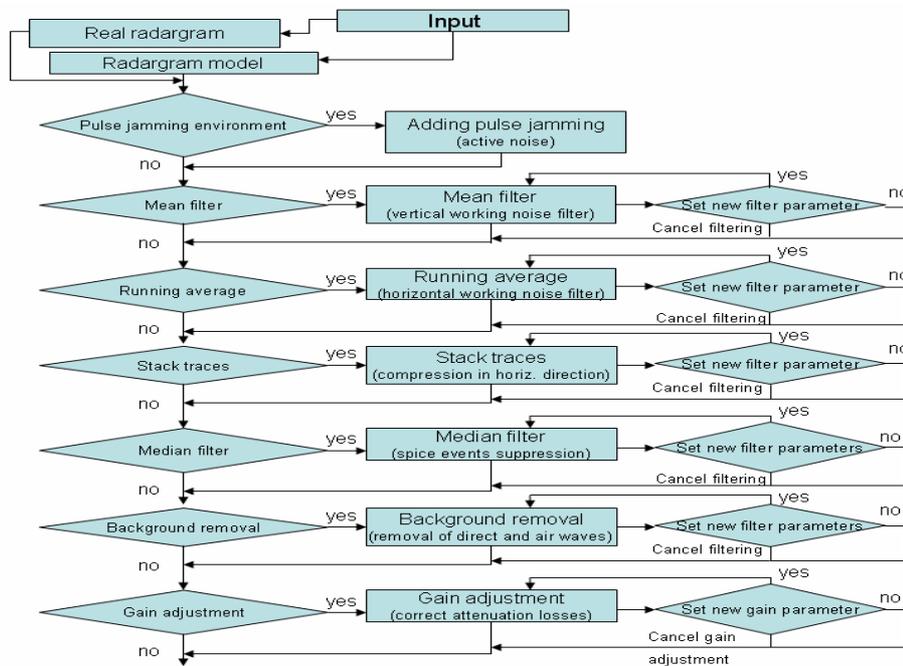
Fig. 1. Software tool blockscheme

The analysis of GPR data is carried out by processing the data using different filtering techniques and gains. Filtering is the use of mathematical processing algorithms to clean noise from the data and/or enhance certain characteristics of the data. Gain is a value by which raw data are multiplied to enhance low-amplitude reflections. Signal amplitude commonly decreases exponentially at increasing travel. This was compensated by designing a custom time gain that increases the signal strength.

The developed software tool allows flexible and iterative processing for realizing the most important basic processing algorithms. These algorithms are:
- mean filter (vertical working low-pass filter);

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- running average (horizontal working low-pass filter);
- stack traces (compression in horizontal direction);
- median filter (pulse jamming and speckle noise reduction);
- background removal (spatial high-pass filter which make visible the shallow objects);
- gain adjustment (corrects the attenuation losses and makes visible the deep objects).

3. Simulation and processing of GPR B-mode images

The general algorithm for simulation and processing of GPR B-mode images (Fig. 2) includes:
- Calculation of the amplitude of a signal reflected from each layer of a multi-layered media.
- Calculation of the two-way time delay of a signal reflected from each layer.
- Simulation of echo signals reflected from the multi-layered media, clutters, impulse noise and speckle noise.
- Construction of the synthetic range profile. It is done for each of N positions of the transmitter-receiver system. At this stage, the matrix of M columns is simulated. Each column of this matrix contains the echo signal simulated for one of M transmissions.

This signal matrix is used for construction of a synthetic range profile by the stepped-frequency approach:
- Basic signal processing (removing clutters and interference, wow, so on).
- Image formation. The GPR B-mode image is formed on the base of N constructed synthetic range profiles. This stage includes also interpolation, logarithmic-compression and visualization.
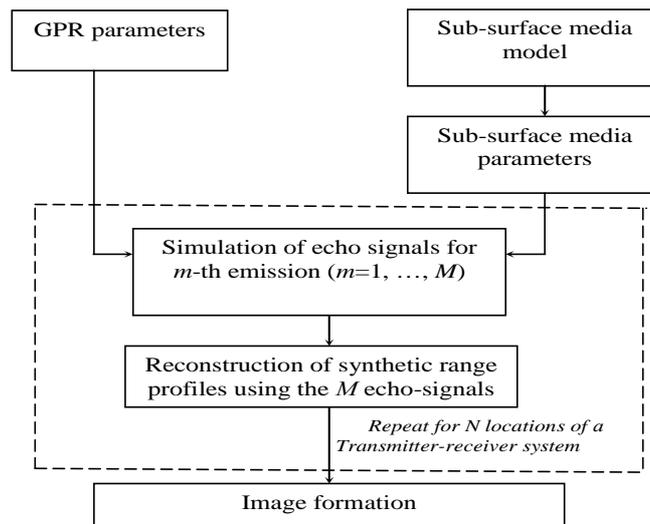
Fig. 2. Blockscheme for simulation of GPR images

A. Simulation of echo-signals

The complicated convolution model is used for simulation of signals reflected from a multi-layered sub-surface media. This model takes into account both, the GPR parameters and the sub-surface media parameters. For the m-th transmission of a pulse, the signal reflected from a multi-layered media with L layers can be mathematically described as:

$$(1) \qquad r(m,t) = \sum_{k=1}^{L} \mu_{m,k} \sqrt{\mathrm{SNR}_k}\, s(m,t)\delta_k(m, t - \tau_k) + N_0(m,t)$$

where:

$s(m,t)$ is the m-th transmitted pulse with an unity envelope;

SNR_k – the signal-to-noise ratio of a signal reflected from the geological interface between layers k and $(k+1)$;

$\mu_{m,k}$ – the multiplicative (speckle) noise (the Rayleigh noise with unity mean);

$\delta_k(m,t)$ – the impulse response of the geological interface between layers k and $k+1$ after transmission of the m-th pulse;

τ_k – the two-way time delay of a signal reflected from the geological interface between layers k and $k+1$;

L – the number of geological layers;

$N_0(m,t)$ – the normalized Gaussian noise with zero mean and unity variation.

B. Algorithms for formation of synthetic range profiles

For construction of a synthetic range profile by the stepped-frequency approach, the time-domain method or the frequency-domain method can be exploited.

The time-domain technique, proposed in [2] for SAR applications, uses a sequence of stepped-frequency narrowband waveforms to produce a high-resolution synthetic range profile. In the time domain, a long wideband chirp is constructed from M narrowband chirps, each of duration T_p, separated in time by a repetition interval T. The central frequencies of narrowband chirps are spaced by step Δf. Since the spectrum of each narrowband chirp is a fraction of a constructed wideband chirp, all transmitted chirps should have the same frequency rate. The total bandwidth of a reconstructed wideband pulse equals $\Delta f = \Delta f M$. The construction of a synthetic range profile is performed by the following processing steps: upsampling, frequency shift, phase correction, time shift, coherent summing, and pulse compression.

The frequency-domain technique, proposed in [3] for SAR applications, constructs a wideband target reflectivity spectrum by combining the spectra of the transmitted narrowband pulses. In the frequency domain, a wideband target's reflectivity spectrum is formed by concatenating together M adjacent sub-portions of the spectrum, each obtained by separate transmission and reception of narrowband pulses of bandwidth Δf. The reconstructed spectrum at baseband is $V'(f) = \sum_{m=0}^{M-1} V_m(f - \delta f_m)$ where $V_m(f)$ is the frequency spectrum at baseband of

the *m*-th narrowband pulse. The frequency shift of each spectrum in the positive direction is determined by δf_m.

The reconstruction of a synthetic range profile is performed by the following processing steps: upsampling, fast Fourier transform, frequency shift, wideband spectrum construction, and pulse compression.

C. GPR image formation

The process of GPR image formation includes the following stages:

- *2-D Interpolation.* Between each two neighboring range profiles are additionally included ID synthetic range profiles in order to improve the final quality of GPR images;

- *Normalization.* The image intensity is normalized;

- *Log-compression.* This operation is performed in order to reduce the dynamic range of the image intensity to 50 dB;

- *Quantization.* The image intensity is quantized in the diapason from 0 to 255.

4. Experimental results

In this section some results achieved using the above presented software tool are shown.

The simulated radargram with four layers (Fig. 3) is masked by pulse jamming. It can be seen that after pulse compression, the pulse jamming looks like the speckle noise. In order to remove this noise, a median filter can be applied over the selectable time/range area for each time step Fig. 4 shows real GSSI SIR [1] radargram contaminated with noise (a) and "cleaned" by mean and running average filtering (b). The image presents five underground fuel storage tanks.
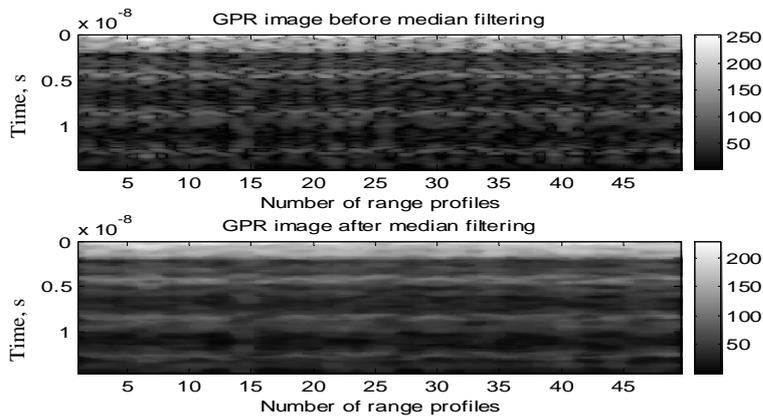
Fig. 3. Median filtering (number of time samples = 3; number of traces =13)

Fig. 5 illustrates the benefits of gain adjustment algorithm. This algorithm makes visible the deep objects. The simulated radargram with three layers is shown. The gain acts on each trace independently. The algorithm parameter forms a jumping window. The time window samples are normalized in the range [0, 1].

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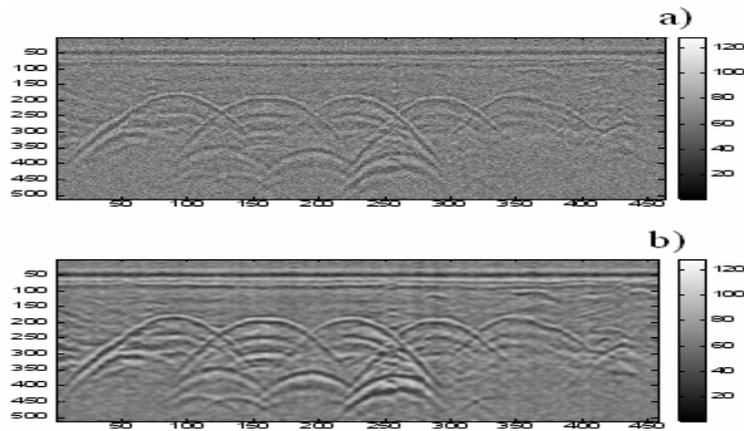
Fig. 4. Noise filtering (number of time samples 7; number of traces 9)

However this process destroys the original information of the signal. So it should be applied only for displaying the GPR radargram.
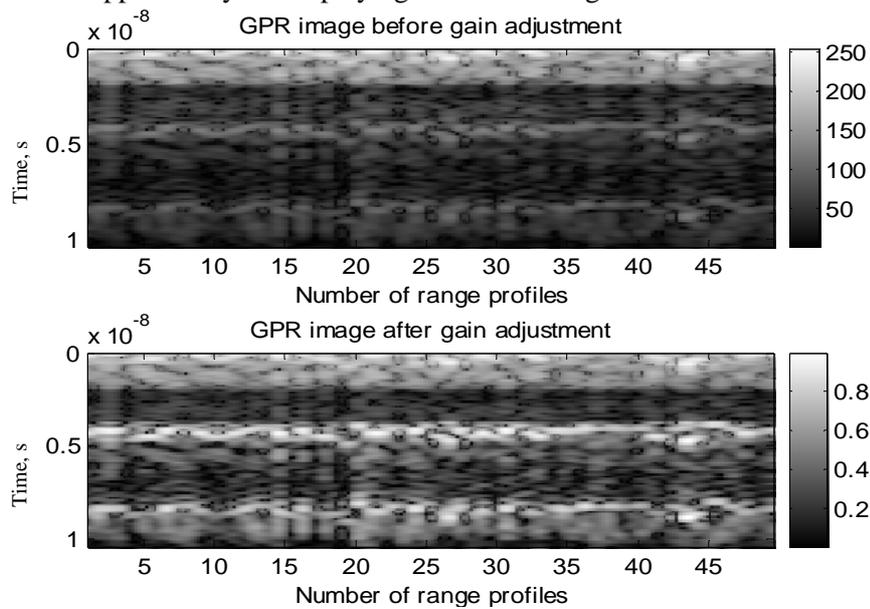
Fig. 5. Gain adjustment corrects the attenuation losses (window length = 30)

5. Investigation of some SSA based algorithms

The developed software tool is used to investigate the performances of novel algorithms for image improvement based on Singular Spectrum Analysis (SSA) algorithm followed by some conventional (see Section II) basic processing algorithms.

The SSA method [4, 5] was developed as a tool for time series analysis. This method is partially suited to short, noisy time series. It operates in the time domain

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and as such is suited to time series containing quasi-periodic signals, rather than strict sinusoids. This is the typical situation for GPR traces. The aim of SSA is to make a decomposition of the original series (GPR traces in the considered case) into the sum of a small number of independent and interpretable components such as: low-frequency trends, narrowband quasi-periodic signals and noise.

SSA operates by examining the system dynamics using only the information that comes from a time series of observations, in this case the voltages of the receiver antenna by applying time-lagging (embedding) method. The single parameter of the embedding is the window length L. The shorter length of the window leads to the smaller frequency resolution of each component. The longer window leads to the higher frequency resolution of each component, but the greater the chance that noise is mistaken for signal.

Fig. 6 illustrates some benefits of the SSA algorithm followed by running averaging and background removal.
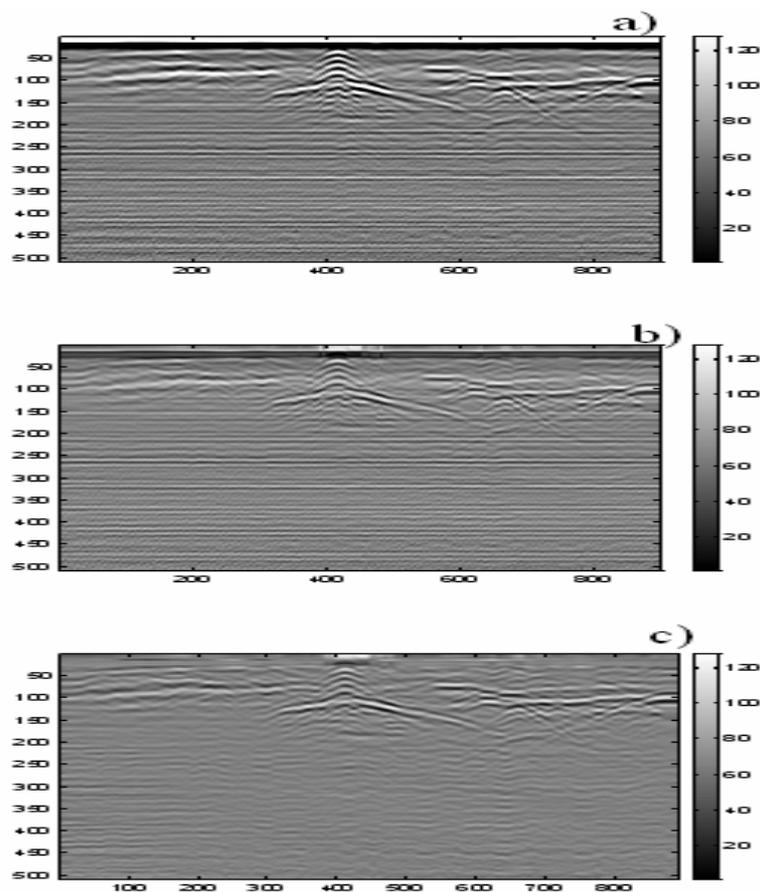
Fig. 6. SSA based algorithm

The first radargram (a) presents sewerage shaft before processing. Fig. 6 (b) shows the same radargram after SSA processing with L=30, using eigenvalues in

range 2-9. This filtering make shaft lid visible. After running average (number of traces = 9) and background removal, the horizontal lines which are produced by antenna ringing and reflections between the antenna and the ground surface, are removed (c). The image improvement is significant.

Conclusions

The designed software toll is intended for researchers in order to help them analyse the effectiveness of the different variants of the algorithms for data acquisition, signal processing and image processing. Some results, achieved using this package are presented in this work.

The experimental results obtained enable to conclude that the software tool presented in the paper can be successfully used for analysis and parameter optimization of the basic signal processing algorithms.

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