Time delay and interface roughness estimation of pavements using modified MUSIC: experimental results

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Context

In civil engineering, ground-penetrating radar (GPR) is widely used for road pavement survey. This work takes account of the influence of interface roughness within the scope of the data processing of radar signals. The observed frequency behaviors of the radar magnitude introduce some shape distortions on the radar wavelet, which is varies with the change of frequency bandwidth. A modified MUSIC with interpolated spatial smoothing is proposed for jointly estimating the time delay and the interface roughness, which can take into account several possible frequency behaviors, more adaptable for ultra-wide-band GPR.

Main Objectives

1. Develop a modified MUSIC with interpolated spatial smoothing for time delay and interface roughness estimation.
2. Evaluate the proposed method in real measurement.

Materials and Methods

Signal Model

Received signal in vector form:

$$\mathbf{r} = \mathbf{\Lambda A s} + \mathbf{n} \tag{1}$$

- $\mathbf{r} = [r(f_1)\ r(f_2)\ \cdots\ r(f_N)]^T$ is the $(N \times 1)$ received signal vector, called observation vector, which may represent the measurements by a step-frequency radar; the superscript T denotes the transpose operation;
- $\mathbf{\Lambda} = \mathrm{diag}\{e(f_1), e(f_2), ..., e(f_N)\}$ is a $(N \times N)$ diagonal matrix, whose diagonal elements are the Fourier transform of the radar pulse $e(t)$;
- $\mathbf{A} = [\mathbf{W}_1\mathbf{a}(t_1)\ \mathbf{W}_2\mathbf{a}(t_2)\ \ldots\ \mathbf{W}_d\mathbf{a}(t_d)]$ is the $(N \times d)$ mode matrix;
- $\mathbf{a}(t_k) = [e^{-2j\pi f_1 t_k}\ e^{-2j\pi f_2 t_k}\ \ldots\ e^{-2j\pi f_N t_k}]^T$ is the mode vector;
- $\mathbf{W}_k = \mathrm{diag}\{w_k(f_1), w_k(f_2), \ldots, w_k(f_N)\}$ is a $(N \times N)$ diagonal matrix, whose diagonal elements represent the frequency behaviour of the backscattered echoes coming from interface roughness;
- $\mathbf{s} = [s_1\ s_2\ \cdots\ s_d]^T$ is the $(d \times 1)$ vector of echoes amplitudes;
- $\mathbf{n} = [n(f_1)\ n(f_2)\ \cdots\ n(f_N)]^T$ is the $(N \times 1)$ complex noise vector in which all the elements $n(f_i)$ are complex white Gaussian noise with zero mean and variance σ^2 and are independent from each other.

According to the signal model and assuming the noise to be independent of the echoes, the covariance matrix $\mathbf{\Gamma}$ of $\mathbf{r}$ after data whitening can be written as

$$\mathbf{\Gamma} = \mathbf{ASA}^H + \sigma^2 \mathbf{\Lambda}^{-1} \mathbf{\Lambda}^{-H} \tag{2}$$

Interpolated spatial smoothing (ISS)

By using the interpolation and denosing procedure, the new covariance matrix can been written as follows:

$$\mathbf{R} \approx \mathbf{BASA}^H \mathbf{B}^H + 0 \times \mathbf{I} \tag{3}$$

where $\mathbf{B}$ is a transformation matrix. Then, spatial smoothing preprocessing technique can be applied:

$$\mathbf{R}_{SSP} = \frac{1}{M} \sum_{k=1}^{M} \mathbf{R}_k \tag{4}$$

where $\mathbf{R}_k$ is the k^{th} sub-band of the covariance matrix $\mathbf{R}$. N frequencies, M overlapping sub-bands of length L are considered.

Time delay estimation

The modified MUSIC allows to estimate the time delay by

$$P(t) = [\min_k \{ \frac{\mathbf{k}^H \widehat{\mathbf{A}}^H(t) \mathbf{U}_L \mathbf{U}_L^H \widehat{\mathbf{A}}(t) \mathbf{k}}{\mathbf{k}^H \widehat{\mathbf{A}}^H(t) \widehat{\mathbf{A}}(t) \mathbf{k}} \}]^{-1} \tag{5}$$

with

$$\widehat{\mathbf{A}} = \mathrm{diag}\{\exp(-2j\pi f_1 t), \exp(-2j\pi f_2 t) \ldots, \exp(-2j\pi f_L t)\}$$

and

$$\mathbf{k} = [\bar{w}(f_1)\bar{w}(f_2)\ \ldots\ \bar{w}(f_L)]^T,$$

$\mathbf{U}_L$ is the $L \times (L-d)$ noise matrix, $\bar{w}(f_i)$ is the frequency behavior after interpolation.

Interface roughness estimation

The interface roughness can be characterized by a particular frequency behavior of the backscattered echoes, which can be calculated from the estimated time delay $(\hat{t})$ as follows:

$$P = [\min_k \{ \frac{\mathbf{k}^H \widehat{\mathbf{A}}^H(\hat{t}) \mathbf{U}_L \mathbf{U}_L^H \widehat{\mathbf{A}}(\hat{t}) \mathbf{k}}{\mathbf{k}^H \widehat{\mathbf{A}}^H(\hat{t}) \widehat{\mathbf{A}}(\hat{t}) \mathbf{k}} \}]^{-1}$$

$\mathbf{k}_{min}$ is the corresponding generalized eigenvector of the estimated time delay whose elements contain the information of the frequency behavior after interpolation. The estimated frequency behavior of the backscattered echoes can be expressed as $\mathbf{B}^{-1}\mathbf{k}_{min}$.

Experiment

The studied pavement is made of three rough interfaces separating media. The first and the third layers are asphalt layers. The second layer is a sand layer with a thickness about 1 cm and a relative permittivity about 5. In far field, a step frequency GPR is applied, with studied frequency band $f \in [0.8;\ 10.8]$ GHz. The experiment setup is shown in Fig. 1.

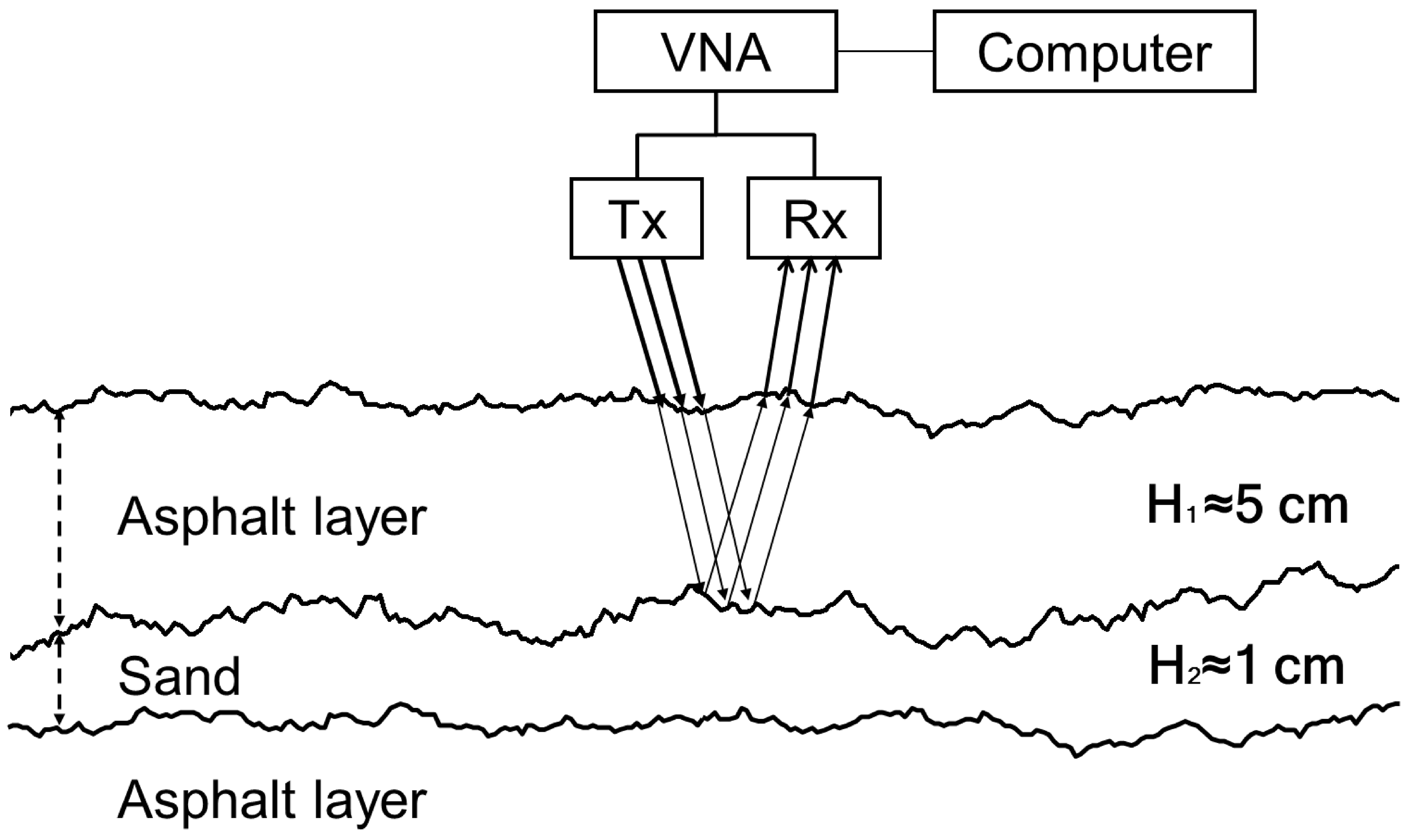

Figure 1: GPR and pavement configuration.

Preprocessing

1. Time filtering. In this case, we focus on the zone where echoes are overlapped (second and third echoes). By operating a time filter, the first backscattered echo is filtered, thus only the second and third backscattered echoes are used.
2. Data whitening. In order to apply the modified MUSIC, a whitening procedure by the pulse is necessary. The radar pulse can be measured as a backscattered echo from a metallic plane.
3. Sub-band averaging. In our study, the backscattered echoes are highly correlated. Thus, ISS is used to decorrelate the correlation between the echoes.

Results

In the experiment, the modified MUSIC is tested in the frequency band $B = [0.8;\ 10.8]$ GHz (401 samples), with $L = 200$. The second and third time delays are **4.017** ns and **4.143** ns, respectively. Consequently, the estimated thickness of the second layer is about **8.5** mm. Fig. 2 shows the frequency behavior of backscattered echoes (representing the roughness). From this experiment, we can conclude that the proposed algorithm is able to estimate the time delays and interface roughness.

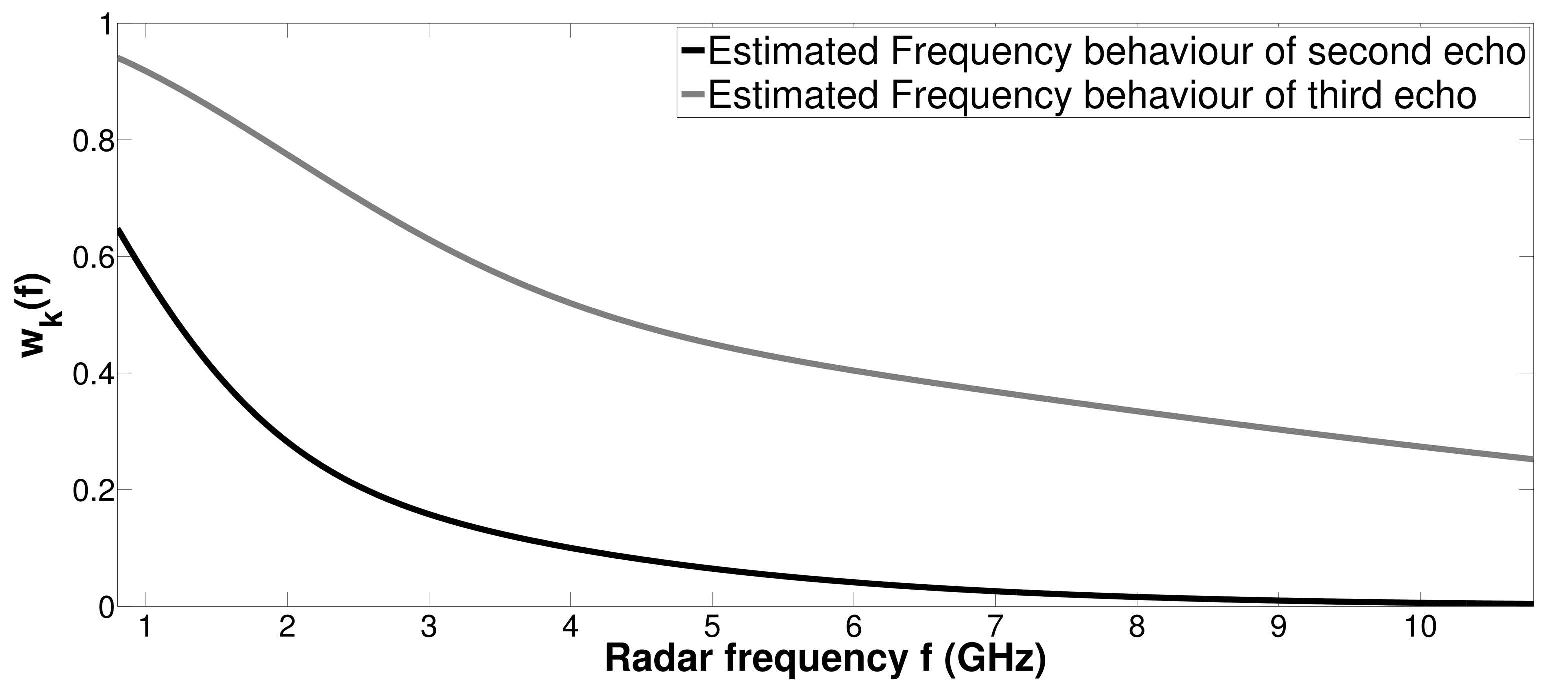

Figure 2: Estimated frequency behavior of backscattered echoes, $k = 2, k = 3$.

Conclusions

- ISS can decorrelate the corrleation between the backscattered echoes (with different frequency behaviors).
- The modified MUSIC is applicable for both time delay and interface roughness estimation.

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