Signal processing for optimisation of low-powered GPR data with application in transportation engineering (roads and railways)

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ABSTRACT: High-frequency air-coupled ground-penetrating radar (GPR) systems are used in road engineering for achieving high-resolution and fast imaging of the shallow layers of pavements. Regulatory policies on the permitted radiated power enacted by some international agencies for information and communication technologies, such as, the Federal Communications Commission operating in the United States, have led manufacturers to market low-powered GPR systems to comply with the standards.

The signal collected by these systems is more unstable than ordinary-powered GPRs, with the interpretation of the raw data being misleading or, mostly, totally subjective or even impossible. Thereby, the use of relevant signal processing techniques combined purposely within procedural schemes may help to reach reliability and effectiveness levels close to those granted by standard systems. In this study, a post-processing scheme aimed at maximising the correlation between signals collected by low-powered and standard 2 GHz antenna systems in railway and road surveys is presented.

1 INTRODUCTION

Different forms of energy can be recognized within the electromagnetic spectrum, due to their wavelengths and frequencies. Frequencies ranging between 3 kHz and 300 GHz define the Radio Frequency (RF) part of the spectrum. Ground-penetrating radar (GPR) is an electromagnetic tool operating within the RF spectrum.

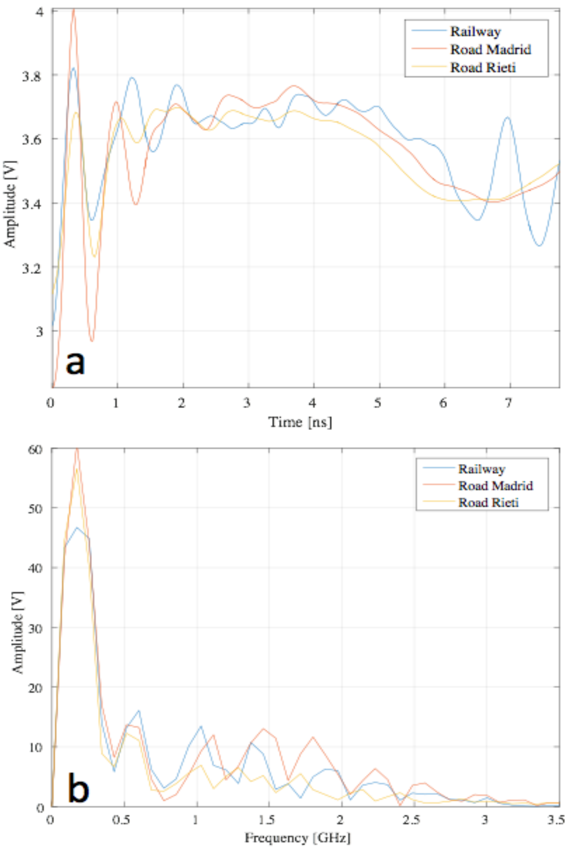
The RF spectrum composes part of the Non-ionizing radiations (NIR). The NIR radiative energy is able to only excite the ions contained within a medium when passing through it, instead of charging them. The most remarkable effect from this excitation is the heating of the medium. Other effects are generally referred to as non-thermal. The power of penetration of a NIR into a body, as well as its rate of absorption, is highly frequency-dependent (Kwan-Hoong 2003).

To date, the non-thermal effects of NIR on human health are not completely understood, and several international institutions payed attention on the free use of radiative instruments, especially in the case of uncontrolled environment, such as in GPR surveys of roads. This fact, as reported in many national and international research programmes (Dimbylow & Bolch 2007, Gluszcz 2009, ICNRPI 1992, Health Protection Agency 2006, 2008, Mobile Telecommunications and Health Research Programme, 2007), is raising attention in the field. To this effect, several guidelines and standards have been published in the last decades, with the aim of regulating the use of NIR in both controlled and uncontrolled environments. Broadly, United States (US) and Western Europe refer to (IEEE Standards Coordinating Committee on Non-Ionizing Radiation Hazards 1992, ICNRPI

Figure 1. The three survey sites: road surveys conducted in the district of Rieti, Italy (a); road surveys conducted in the district of Guadalajara, Spain (b), Railway surveys conducted in laboratory at Roma Tre University (c).

1992) whilst Russia, China, and Eastern Europe comply with (Sanitary Norms and Regulations. 1996). Typically, these science-based standards set a maximum permissible exposure (MPE) in terms of field strength, power density and time-averaged rate of energy transfer. Particularly, the US Federal Communications Commission (FCC) integrated the most common standards into a regulatory policy (FCC 1997).
More specifically in the area of GPR, manufacturers have to comply with different regulations on the power emission limit, and the challenge is mostly in countries like US where the threshold for maximum power emission is very low. As a consequence of a lower radiative power, these types of GPR systems exhibit worst performances in terms of signal-to-noise (SNR) ratio.
This work aims at evaluating the potential of low-powered systems in civil engineering applications. In particular, a dataset of GPR signals have been gathered from surveys carried out on different transportation infrastructures with both standard and low-powered systems. In this study, the results coming from the different systems have been compared, and a post-processing scheme for optimizing the information from the low-powered signals is proposed.Getting started

2 THE DATASET



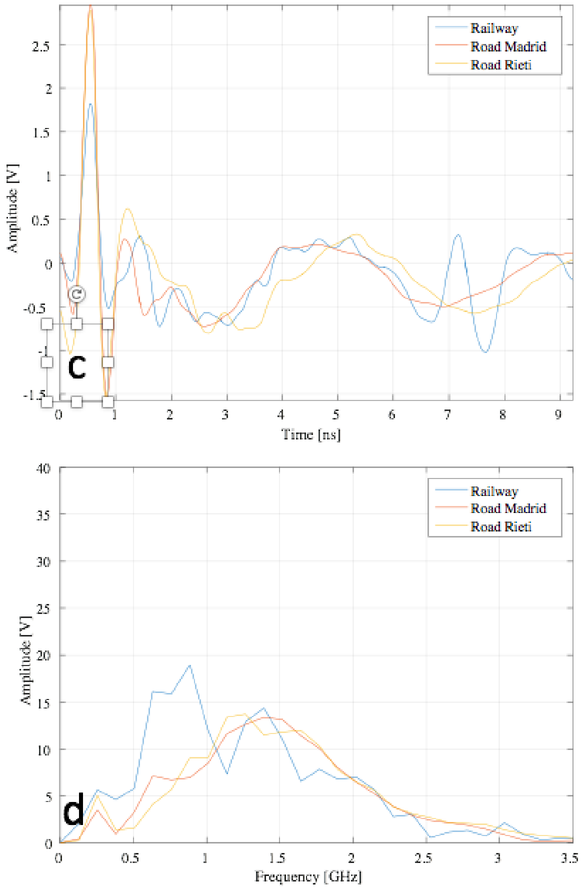


Figure 2. – Low-powered (a-b) and standard (b-c) raw GPR signals.

In order to evaluate different conditions that are most likely to be encountered on site in transportation engineering applications, both road and railway GPR surveys have been performed. According to the scope of this study, the same road and railway sections have been surveyed by means of both standard and low-powered systems. Pulsed GPR systems equipped with horn antennas and central frequency of 2000 MHz, were used. They were set to operate suspended in the air at 0.40 m height from the road/railway surface. The systems are manufactured by IDS Georadar and are actually identical in the whole set of components, with the exception of the radiative power. As far as the experimental frameworks are concerned, GPR surveys have been carried out at three different sites. In particular, road surveys have been performed over two different sections, located in the district of Rieti (Italy) and in the district of Guadalajara (Spain). In these surveys, the antenna was mounted onto an instrumented vehicle, and supported by a wooden framework. A third static data collection for railway engineering applications has been carried out in laboratory environment at Roma Tre University, over an experimental setup reproducing a ballasted railway track-bed. The data collections from the three survey sites are depicted in Figure 1. For sake of consistency, since the tests collected over the railway track-bed were static and, hence, produced a single A-scan, a single trace was also selected along the scanned sections for both the aforementioned road surveys. To ensure that the A-scans collected with the different

GPR systems, are referred to the same geographical position, GPS coordinates have been matched.

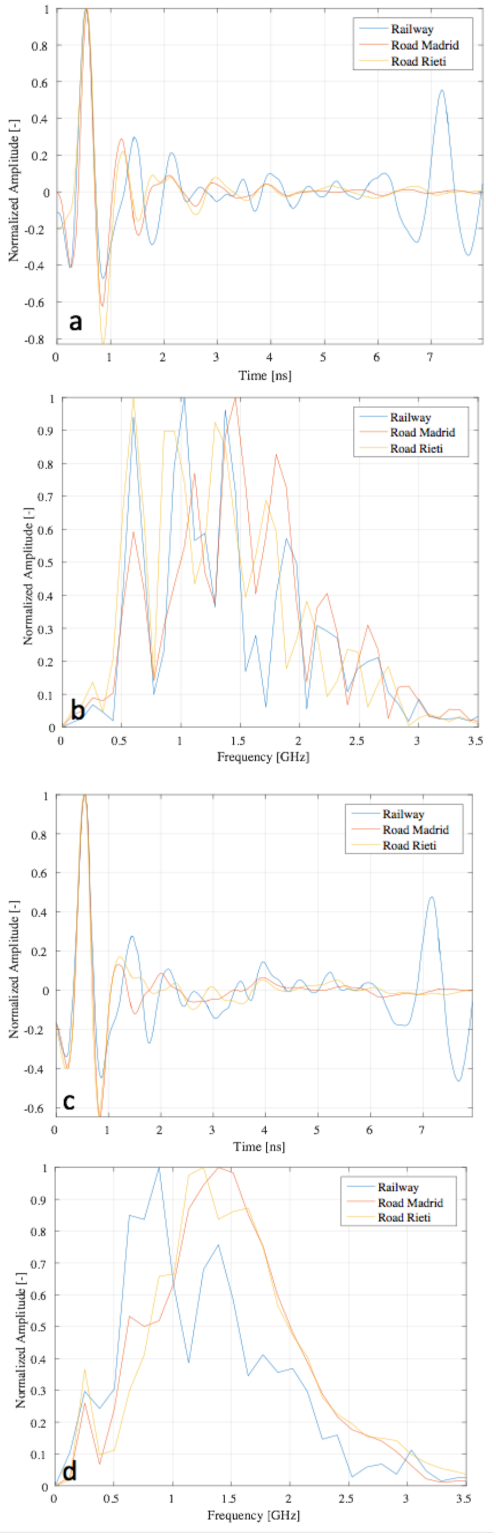


Figure 3. – Low-powered (a-b) and standard (b-c) GPR signals, after the standard band-pass filter application.

3 DATA POST-PROCESSING

Figure 2 shows the raw GPR traces, collected with the two antennas, both in the time and frequency domains. As clearly visible, low-powered signals are much more affected by noise, to the point that it is almost impossible to recognize the reflection peaks related to the dielectric discontinuities (Figure 2a). In more detail, it is worth noting the peaks of amplitude back-received at approximatively 200 MHz in the low-powered spectra (Figure 2b), which are to be related with noise and tend to “blind” the signal contributes.

Thereby, the analysis of the raw data suggested that, by filtering out the lower frequency components from the spectra, useful information could have been retrieved. Accordingly, after a preliminary zero- offset removal, a band-pass filter was applied to the whole dataset. As a common practice (Benedetto et al. 2016), the bandwidth included between the two cut-off frequencies has been set, in both cases, as 1.5 times the nominal frequency. As a result, the high-pass and low-pass frequencies have been set as 500 MHz and 3500 MHz, respectively. For sake of comparison, the amplitude has been normalised. In Figure 3, the effect of the band-pass filtering on the signals is shown. The benefit led by the procedure is clearly noticeable, especially for the low-powered case. It is now possible to recognize different amplitude peaks, deriving from the reflections at the interfaces of layers (Figure 3a). On the other hand, the low- powered spectra appear more chaotic than the regular ones, which is most likely due to the lower SNR ratio. Also, Figure 3b still shows a low-frequency peak at 550 MHz, hardly linkable with informative content. Accordingly, in order to maximise the likelihood between the two systems, a specific high-pass frequency needs to be set when processing low-powered data.

4 POST-PROCESSING OPTIMISATION

Using the data collected by GPR with standard radiated power as a reference, new band-pass filters were applied to the low-powered signals with differently

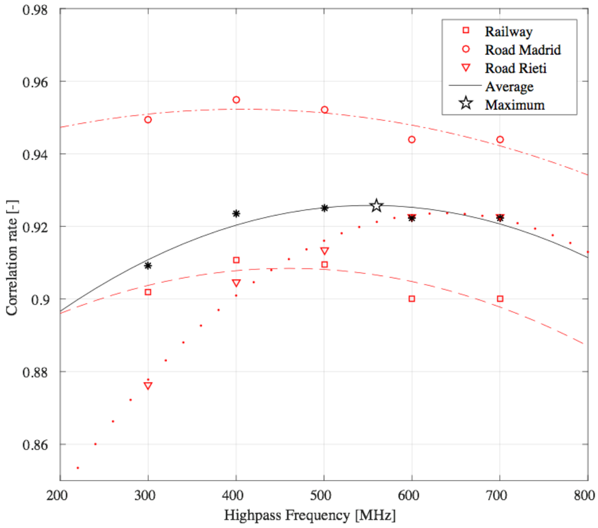


Figure 4. – Curves fitting the correlation coefficients calculated for different high-pass frequencies.

set high-pass frequency values, in order to reach the best matching between the data collected by the two systems. In particular, the range spanning between 200 MHz and 700 MHz has been tested, with steps of 100 MHz.

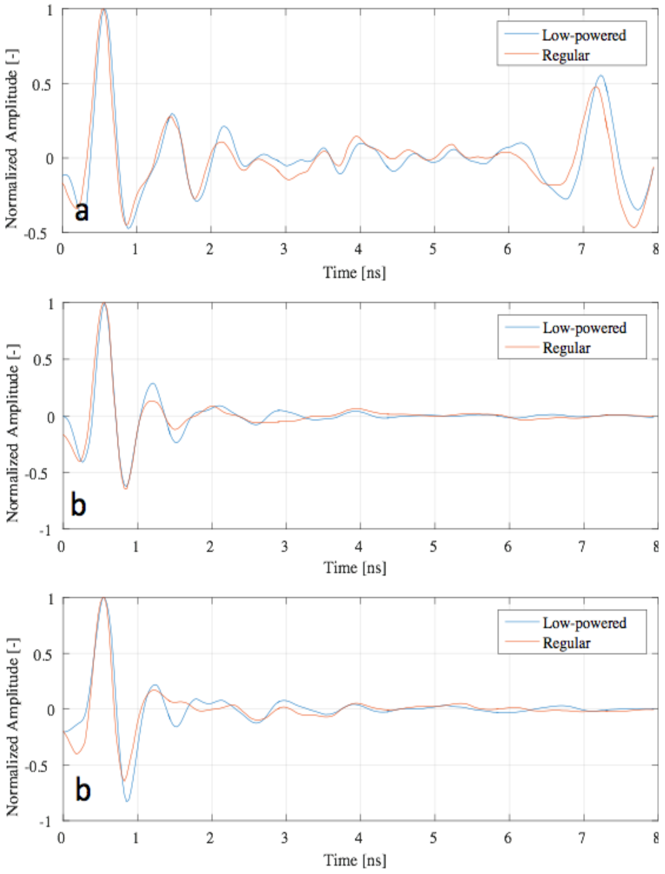


Figure 5. – *Comparison between Low-powered and standard signals for Railway (a), Road Madrid (b) and Road Rieti (c) tests.*

As reference parameter for the maximisation procedure, the correlation coefficient (*CC*) between the signals collected with different systems was taken and calculated as:

$$CC = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \quad (1)$$

with X being the low-powered system signal, Y being the standard system, σ_x and σ_y being their standard deviations, and σ_{xy} being their covariance. For each test condition, five correlation rates have been computed, with respect to the five tested high-pass frequencies. The curves fitting these five values are representative of the effectiveness of the filter in reducing the discrepancy between the two signals.

In order to reach a processing scheme suitable for every conditions that can be tested in the transportation infrastructures surveys, a fourth curve, fitting the average correlation rates calculated for each processing condition, has been calculated. Accordingly, the frequency related to the maximum of this curve indicates the optimal high-pass frequency required to maximise the effectiveness of the low-powered systems. The optimisation procedure is depicted in Figure 4, and a maximum band-pass frequency value of 560 MHz is defined. This implies a shrinkage of the bandwidth from 1.5 to 1.45 times the central frequency. In Figure 5, instead, the comparison between the low-powered and standard processed signals is shown, for each test. As clearly visible, the application of such a scheme led to encouraging results.

5 CONCLUSIONS AND FUTURE PERSPECTIVES

This study deals with the performance analysis of low-powered GPR systems, equipped with horn antennas with central frequency of 2000 MHz. In order to evaluate the capability of such devices to detect targets in transportation engineering surveys, three experimental activities have been arranged for collecting GPR data with low-powered and standard systems, in both railway and road environments. The analysis of the raw data emphasized the need for using bandpass filters, to cut the noise contribution, which was very significant for the utilised low-powered system, especially at lower frequencies. Furthermore, the study highlighted that different filter bandwidths are required, whether the low-powered or the standard system are considered. Accordingly, by taking the standard signal as a reference, an optimum procedure has been developed for defining the best high-pass frequency to use in low-powered systems. The main purpose of this was to minimize the discrepancy between the signals, and maximising the effectiveness of low-powered antennas. As a result, an optimal high-pass frequency value of 560 MHz was defined.

Future efforts in the field are to be focused on a similar identification of the high-pass frequency for GPR systems with different central frequencies, as well as on widening the range of test conditions and reaching a higher statistical significance.

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