Looking into concrete and masonry structures – usage of multiple frequency radar products to detect structural parameters and defects

Guido Tronca, Samuel Lehner, Isaak Tsalicoglou
Proceq SA, Switzerland, guido.tronca@proceq.com

Abstract

Traditional impulse Ground Penetrating Radar (GPR) systems use time-domain measurements of radar waves travelling in investigated objects. A Stepped Frequency Continuous Wave (SFCW) system collects data in the frequency domain and converts the data to time-domain data through digital processing. Until recently, the time-consuming calculations associated with the real-time Fourier transforms in SFCW systems limited their real-time usability in real-world applications. With the advent of faster processing capabilities, this limitation no longer applies to GPR.

Experimental work has been carried out on representative real-life concrete and masonry structures to provide a systematic comparison of a new SFCW GPR system with traditional impulse radar systems. In this paper, distinct evidence is given that SFCW technology combines the highest resolution in the detection of shallow targets with a very broad detection range. At the same time, the test system is characterized as very fast, both in terms of data display as well as data sharing.

The authors are concluding that industry and academic experts, civil engineers and contractors will be able to rely on a higher probability of detection and shorter time from their arrival to the construction site until the final inspection result is ready. Hence, by using SFCW test systems, the global construction industry is expected to gain higher safety standards and higher productivity levels.

1. Introduction

The widespread use of Ground Penetrating Radar (GPR) in Civil Engineering investigations is essentially due to the large variety of imaging applications that can be quickly addressed on concrete, masonry and rock structures. Each GPR application, however, is characterized by the range of properties of the typical objects to be inspected and of the potential targets to be identified. These ranges typically determine the antenna frequency to be employed, in order to increase probability of detection of targets, and its accuracy. As such, the choice of a single operating frequency turns into a trade-off between resolution of target sizes and depth penetration of the object.

In general practice, it is accepted that the full range of applications in civil engineering requires the use of different antennas, each with a central frequency ranging from 1.0 to 2.7 GHz. As a result, covering the full range of applications has so far been impossible with a single GPR device. Therefore, users typically choose one device among many in the market. This choice is often made without enough a-priori knowledge of the trade-off the user is getting into. Even worse, for many users it remains unclear that this trade-off will negatively impact some of their use-cases and their ability to serve customers.
In recent times, new integrated hand-held units have become available on the market, as opposed to the traditional wired antenna configurations. The use of high central frequencies can grant in this case sharp detection of shallow objects. However, it often does not combine with the desirable depth penetration often required by the user to fully investigate the object and locate all relevant targets.

Traditional GPR devices operate by broadcasting electromagnetic pulses at one specific central frequency, and then measuring the resulting arrival times of reflections at discontinuities of relative permittivity within the object and at its physical boundaries and interfaces to other objects. A Stepped-Frequency Continuous-Wave (SFCW) GPR continuously broadcasts electromagnetic waves and receives reflection signals by cycling through frequency steps across a certain frequency range. From each step, reflection data is collected in the frequency domain. The combination of frequency-domain data of all steps is then converted to the time-domain A-scan using an inverse Fourier transform. A series of A-scans along a line, i.e. a B-scan / radargram, can then be interpreted in the same way as B-scans of traditional pulse radar systems.

Until recently, the time-consuming calculations associated with the real-time inverse Fourier transforms drove costs up and thus limited the application of SFCW to large-scale scanning and military-grade systems. Thanks to faster processing capabilities available nowadays, a new hand-held GPR device was recently launched on the market by Proceq, bringing for the first time the SFCW technology into higher-frequency applications in structural concrete scanning and imaging. The expected benefits of this technology implementation derive from the combination of a very wide frequency range and a very high dynamic range. These two characteristics of the SFCW system deliver high resolution on shallow targets and large detection range at the same time, essentially invalidating the hitherto-accepted trade-off from a user point-of-view.

Some results taken from the validation work done on the SFCW system were already discussed in a recent paper (1). There, superior performance was reported in terms of detection range on concrete elements, when compared to state-of-the-art hand-held high-frequency traditional GPR devices with central frequencies of 2.0 and 2.7 GHz. In the current work, the comparison is extended to different real-life scenarios traditionally addressed by antennas with a single central frequency of 1.0 GHz and 2.7 GHz.

2. Experimental

2.1 Instrumentation

- GSSI StructureScan Mini XT: pulsed radar, central frequency 2.7 GHz, max. acquisition time 9 ns
- ERA: pulsed radar, central frequency 1.0 GHz, max. acquisition time 25 ns
- Proceq GPR Live: SFCW radar, ultrawideband (0.2-4.0 GHz), central frequency 2.4 GHz, max. acquisition time 20 ns

2.2 Investigated objects
• Concrete pillar (Case 1): useful for evaluating the vertical resolution capabilities on two close mats of steel reinforcement.
• Masonry vault (Case 2): floor above a brick pavilion vault laying at a depth between 20 and 80 cm

2.3 Measuring procedure

Linear scans were collected along 10x10 cm grids (Case 1) and a 25x25 cm grid (Case 2). The time window was set according to the maximum value allowed by each instrument, and overall up to the maximum of 20 ns.

2.4 Data processing

All data were imported and processed on GPR-SLICE software. The comparison of the B-scans involved the following steps:
• File import, time-zero compensation and de-wobble. Common linear gain was used for comparison purposes.
• Band-pass filter was needed only for ERA and GSSI systems to remove some low and high frequency noise components.
• No background removal filtering was applied, to prevent loss of information and grant a more objective comparison.
• Boxcar filter for horizontal smoothing.
• Migration and Hilbert transform.

Further processing was then performed to generate volume views and time slices: independent volumes calculations were done on x and y lines, followed by volume math and depth slices extraction at intervals of 1 ns width.

2. Discussion

3.1 Case 1 – Concrete pillar

The performance on the thin concrete element (see Figure 1) challenged the instruments’ capabilities of resolving multiple closely-spaced layers of steel reinforcement.

![Figure 1. Case 1: scan positioning on concrete pillar](image)
In Figure 2, three representative scans along the vertical direction of the pillar are displayed. The detection of the first mat was granted for all systems, as expected. However, for the ERA system, the resolution of the first mat is far worse than for the other two systems. Furthermore, for the ERA system the second mat proved to be indistinguishable from the back wall. Both issues result from the ERA system’s lower central frequency.

Figure 2. Case 1: longitudinal B-scans of (a) ERA, (b), GSSI, (c) Proceq GPR Live systems

The two other instruments detected all steel targets. However, when comparing all scans combined in a time-slice view (see Figure 3), the SFCW system (Proceq GPR Live) delivers a sharper resolution of both rebar mats. Meanwhile, in the scans with the GSSI system, the last layer of stirrups is mainly seen as low-intensity stripes obscuring the strong reflection of the back wall.
Figure 3. Case 1: time-slice views of GSSI (a, b, c) and Proceq GPR Live (d, e, f) systems corresponding to the first mat, second mat and backwall, respectively.

3.2 Case 2 – Masonry vault

We initially intended to compare all three systems on this very interesting case, due to the complex, featureful geometry. However, the full definition of the vault geometry (see Figure 4) required an extended time window way beyond 9 ns. This could only be delivered by the ERA and Proceq GPR Live systems.

Figure 4. Case 3: structure of the investigated pavilion vault

It can be seen in the example of Figure 5 how the time-slicing of SFCW system was able to provide a clear imaging of the shallow utility network (Fig. 5a), the full profile of the vault between the crown and the supporting wall (Fig. 5b and 5c), and the bottom plasterboard ceiling with its electrical installations (Fig. 5d). Similar information was also collected by the ERA system. In both cases, the depth positioning of the second backwall needed to be further corrected for the travel time in air between the vault and the bottom ceiling.
Figure 5. Case 3: Proceq GPR Live time-slice views focusing on (a) the utility network, (b) the vault crown, (c) the vault support, and (d) the plasterboard ceiling with electrical installations.

Furthermore: the Proceq GPR Live system was able to provide a high-resolution view of the vault texture. Comparable results were achieved by the GSSI system, due to its central frequency. As a reference, please refer to the net hyperbolas at the vault-air interface visible in Fig. 6 on two selected scans compared for the three systems.

Figure 6. Case 3: two B-scans located at mid-section and on top of the vault respectively; ERA (a, b), GSSI (c, d), Proceq GPR Live (e, f) systems
3. Conclusions

SFCW GPR technology has recently been made available for the first time to the civil engineering industry in the form of a portable, handheld GPR system. Prior benchmarking of this system took place in 2017 (1) in the form of as-built verification of concrete test-blocks. The system was then compared to state-of-the-art high-frequency pulsed GPR systems. Evaluation of system performance was synonymous with detection probability of known features. Analysis of the gathered data verified that SFCW technology overcomes the trade-off between target resolution and depth penetration that has traditionally plagued pulsed GPR systems, regardless of their single central frequency.

To extend the investigation of SFCW GPR from test blocks to real-world use-cases, in our current work a comparison was made in both concrete and masonry scanning use-cases. Furthermore, the comparison was extended to a lower-frequency pulsed GPR system, to better determine the SFCW system’s capabilities. Compared to the prior benchmark, these use-cases represent structures investigations, in which the targets embedded in the objects are not known in advance. As such, evaluation of system performance was synonymous with comparative detection probability of unknown features, as well as with image clarity as deep as possible within the scanned objects. For an objective comparison of the three very different systems, their resulting data was analysed with external software based on a common data-processing pipeline.

The use-cases addressed involved the need for high resolution (precise steel reinforcement and utility detection, definition of wall and vault texture) combined with a large detection range for the definition of the structural details of the entire investigated object. As expected, only a limited number of features could be verified with a single pulsed-GPR system at a time. For example, the low-frequency system lacks the resolution required resolve the second-layer rebar mat, while the higher-frequency system lacks the penetration depth needed to image the entire geometry of the vault.

Meanwhile, the SFCW GPR system fully addressed all applications, systematically delivering equivalent or better performance in terms of all detected features and image quality. As such, we conclude that SFCW GPR technology has now reached a commercially-significant stage of maturity for its use in structural concrete scanning applications. The technology enables users to scan both known and unknown structures, and reliably detect targets of various sizes, even deep within concrete.

Most importantly, SFCW technology turns the debate regarding the “correct” central frequency of a GPR device into a moot point. It also makes irrelevant the trade-off of target resolution vs. penetration depth of traditional pulsed GPR systems.

In the grander scheme of things: adopters of SFCW GPR in the civil engineering industry can now shift their focus away from debating system specs (such as the central frequency), and towards fulfilling the “job-to-be-done” their end-customer really cares for; be that as-built verification, structural investigation, or enabling coring/drilling/sawing applications.
Acknowledgements

Proceq wishes to thank Radar Geoservizi, Turin, Italy for the precious assistance provided with instruments and expertise.

References