

Looking into concrete – multiple frequency usage in radar products to detect structural parameters and defects faster and more accurately

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Abstract

Traditional impulse Ground Penetrating Radar (GPR) systems use time-domain measurements of the reflected waves within the investigated objects. A Stepped Frequency Continuous Wave (SFCW) system collects data in the frequency domain and converts the data to time-domain data through computer processing. Until recently, the time-consuming calculations associated with the real-time inverse Fourier transforms in SFCW systems limited its application. Thanks to faster processing capabilities available nowadays, this limitation no longer applies to GPR. The experimental work on representative concrete structures presented in this paper shows a systematic comparison of a new SFCW GPR system with traditional impulse radar systems. The results illustrate that SFCW technology combines the highest resolution in the detection of shallow targets, with a very broad detection range. At the same time, the system is very fast, both in terms of data display as well as data sharing. Therefore, we are concluding that experts, civil engineers and contractors will be able to rely on a higher probability of detection and higher productivity using just one SFCW test system in the future.

Keywords: Stepped Frequency Continuous Wave Structural GPR

1 Ground Penetrating Radar (“GPR”)

The goal of utilizing a GPR device is the reliable detection of flaws or features (hereafter called “targets”) hidden within optically opaque objects. In structural GPR investigations, targets include metallic reinforcements, ducts, plastic pipes, air voids, as well as the boundaries of the object itself.

The operating principle of GPR is based on detecting discontinuities of dielectric properties that are caused by one or more targets at different depths and orientations within the object under investigation. At the boundaries of such discontinuities, electromagnetic energy is partially transmitted through the targets and partially reflected in various directions, among which also towards the surface of the object. There, it can be detected by the receiving antenna of the GPR device, recorded and amplified by the device’s electronics, and post-processed to generate insights for the user. Traditional devices rely on time-domain measurements of the reflections from targets. I.e., they measure the wave’s round-trip travel time between the transmitting antenna, the reflecting target, and the receiving antenna.

The dielectric properties of the object determine the speed of the electromagnetic waves within it. This enables the user to estimate the absolute depth of the reflecting targets. Precise speed estimation depends on knowledge of tabulated values of dielectric properties, such as those of wet or dry concrete.

Estimated depths and locations are then graphically represented in 2D or 3D views. Further physical effects within the object itself, its embedded targets and their interfaces, such as attenuation, scattering, and losses, affect the signal strength adversely. The strength some of these unwanted effects depends on the frequency of the transmitted electromagnetic wave.

As such, a device operating at higher frequencies (1.0 – 2.5 GHz) can detect targets of smaller sizes, if these are not hidden at depths from where the reflected signal cannot be reliably acquired and amplified. Higher frequencies are used whenever high resolution is required, as in the case of structural investigations. However, they cannot usually deliver extended detection range, due to the more significant signal attenuation. Inversely, operating at lower frequencies (0.2 – 0.9 GHz) enables the detection of larger targets at greater depths, yet at the expense of smaller targets closer to the object's surface. Lower frequencies are typically used for soil applications and utility mapping, as they allow a broader detection range — however, this comes at the cost of high resolution.

Traditional GPR devices operate by broadcasting electromagnetic pulses at one specific center frequency. This has been chosen by the system supplier to optimize the product for a specific application. Each GPR application is characterized by the range of properties of the typical objects to be inspected and of the potential targets to be identified. 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.

2 Stepped-Frequency Continuous Wave (“SFCW”) GPR

Recent innovations in the field of structural GPR now enable us to largely resolve the long-standing trade-off between resolution and penetration depth. These also enable us to increase the human interpretability of the analyzed data in applications such as in as-built verification, integrity assessment, and hit prevention in the construction industry.

Proceq GPR Live uses SFCW technology, i.e. it continuously broadcasts electromagnetic waves and gathers data from the reflected component of the waves in the frequency domain. Until recently, the time-consuming calculations associated with the real-time inverse Fourier transforms in SFCW systems limited its application. Thanks to faster processing capabilities available nowadays, this limitation no longer applies to GPR. Additionally, through electronics design optimization, the maximum signal acquisition time has more than doubled compared to traditional GPR systems, as shown in the next section. Effectively, this enables a longer period during which signals can be gathered with a high signal-to-noise ratio from deeper within the object. Moreover, instead of operating using pulses centered around a single nominal frequency, it relies on multiple frequency steps with a transmitter frequency response that corresponds to the full range of modulated frequencies between 0.2 and 4.0 GHz. In a more realistically representative setup with the system fully coupled to a concrete structure, an ultra-

wide net component between 1.0 and 3.5 GHz has been established to be practically available in the field, and immune to lower and higher frequency noise effects.

These technological features provide a distinct advantage compared to traditional GPR devices: target detection is now possible with a higher accuracy without the need of a priori expectations of what could be detected and at which depths within the object. Additionally, the received data is processed by the onboard electronics and then visualized in 2D and 3D using a state-of-the-art tablet. The user-friendly interface enables the user to mark and identify the detected targets. This effectively makes it possible to “look into concrete” faster, more accurately, and with less effort. Finally, the data and the user’s annotations of the detected targets are dispatched to cloud storage and made available from anywhere, anytime, thus reducing the effort for subsequent data handling and reporting.

3 Comparison to traditional GPR devices

Validation testing of the Proceq GPR Live involved a systematic comparison with other GPR systems that utilize both hand-held integrated and traditional antennas with separate processing and indicating devices. The cases that follow are taken from the direct comparison of Proceq GPR Live with two hand-held systems that have, until now, represented the state of the art:

- **Hilti PS-1000:** nominal center frequency 2.0 GHz; max. acquisition time 6 ns
- **GSSI StructureScan Mini XT:** nominal center frequency 2.7 GHz; max. acquisition time 9 ns
- **Proceq GPR Live:** SFCW 0.2 – 4.0 GHz; max. acquisition time 20 ns

In terms of data processing, both datasets of the Mini XT and the Proceq GPR Live were treated using GPR-SLICE software with the same processing sequence. The data from the PS-1000 were processed using PROFIS Detection software, as the Hilti system does not support exporting raw data.

The comparison is demonstrated using the non-migrated ((a), shown on the left) and migrated ((b), shown on the right) B-scans for each GPR device in different cases. Each case represents a realistic configuration of targets present in concrete blocks. The four cases together represent a wide range of complexity in configuration, and therefore also of detection difficulty.

3.1 Case 1

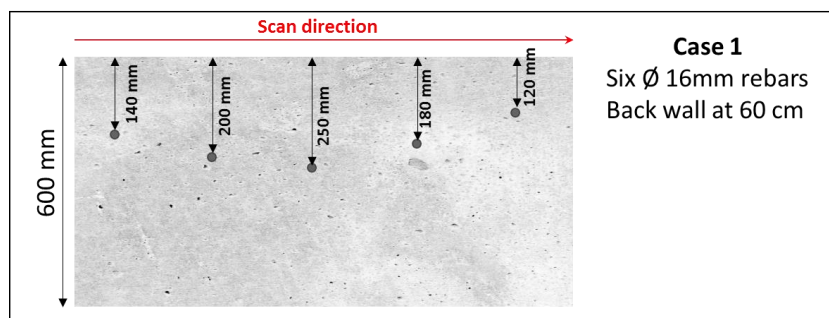


Figure 1: Concrete block with rebars and a flat back wall

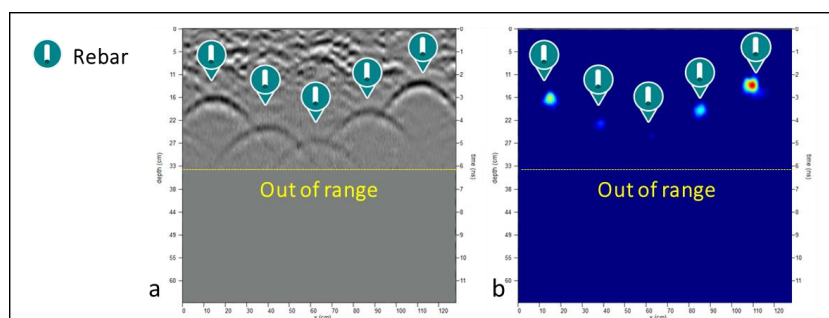


Figure 2: Hilti PS-1000 detects all rebars; however, the back wall is out of range

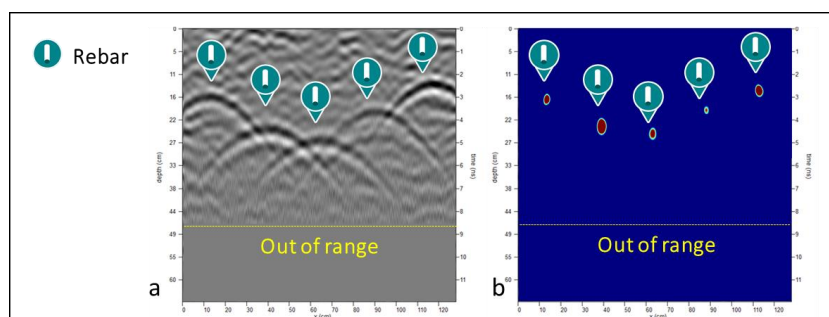


Figure 3: GSSI StructureScan Mini XT detects all rebars, but not the back wall

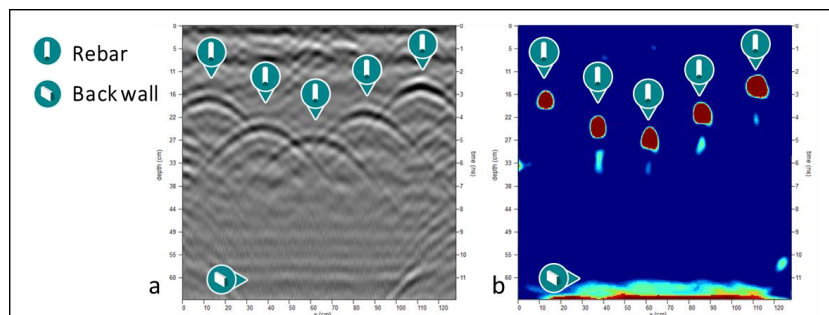


Figure 4: Proceq GPR Live detects all rebars, as well as the back wall

3.2 Case 2

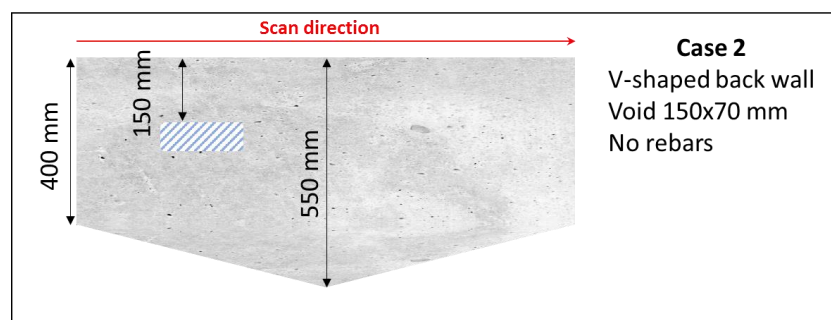


Figure 5: Concrete block with a V-shaped back wall and a void

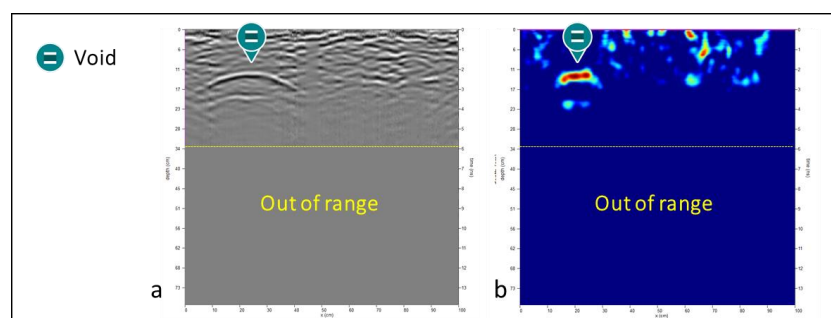


Figure 6: Hilti PS-1000 detects the void with spurious noise on the right-hand side; however, not the back wall

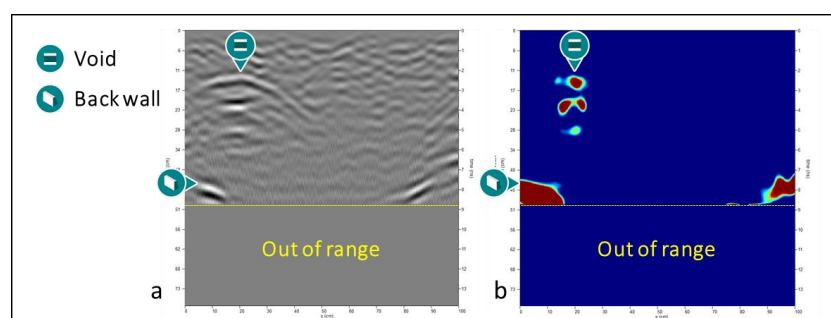


Figure 7: GSSI StructureScan Mini XT detects the void, but not most of the V-shaped back wall (out of range)

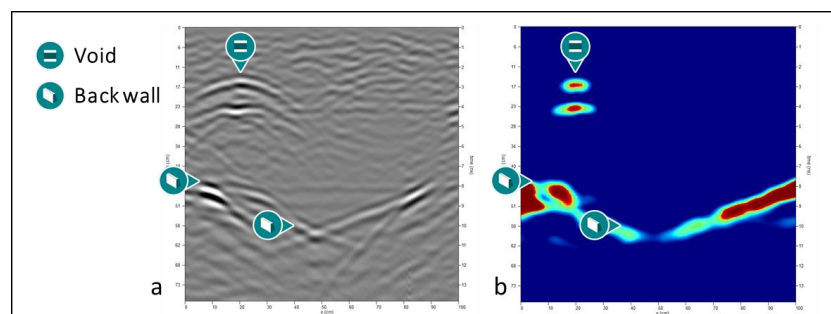


Figure 8: Proceq GPR Live detects all targets without spurious noise

3.3 Case 3

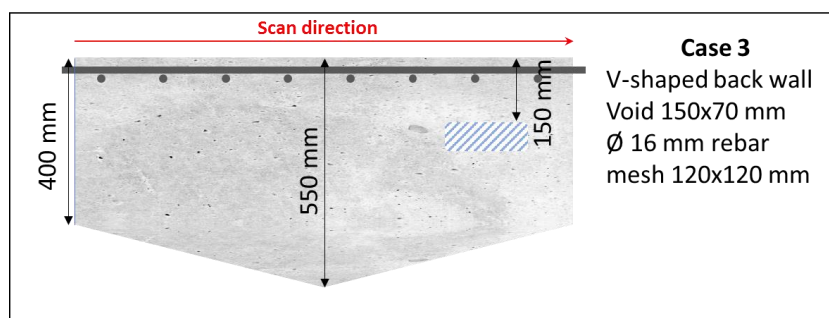


Figure 9: Concrete block with a V-shaped back wall, rebar mesh, and a void

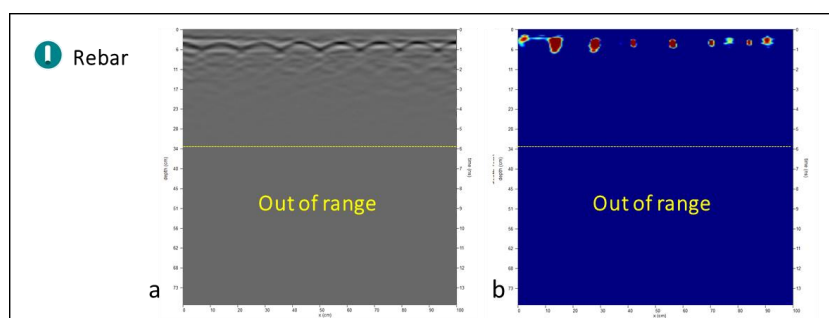


Figure 10: Hilti PS-1000 only detects the shallow rebar mesh

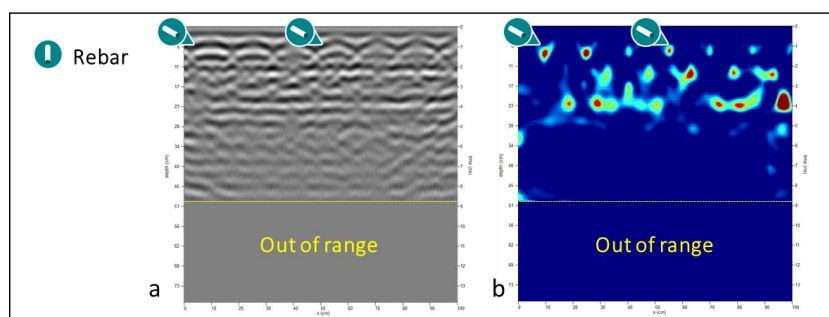


Figure 11: Beyond the rebar mesh, GSSI StructureScan Mini XT reports inexistent targets

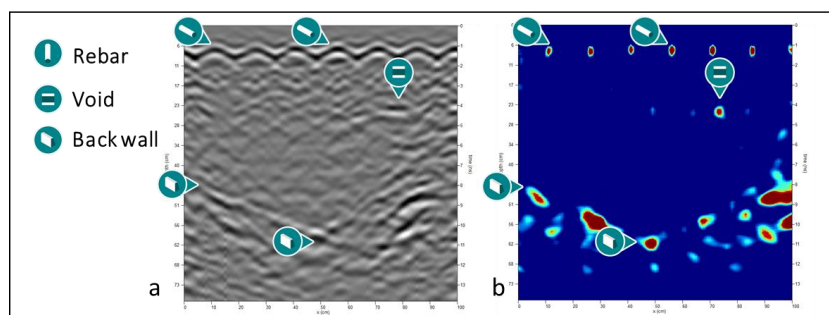


Figure 12: Proceq GPR Live detects all targets unambiguously

3.4 Case 4

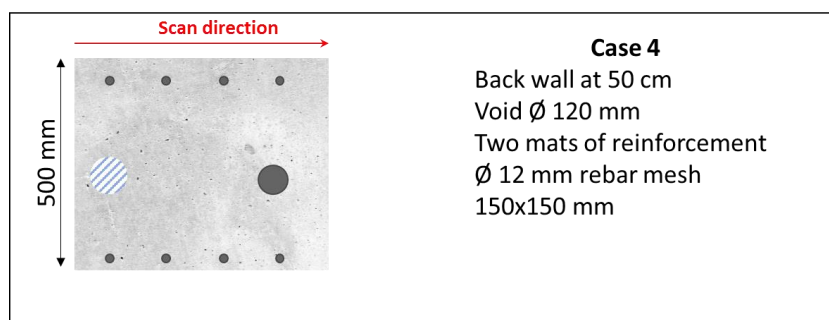


Figure 13: Concrete block with rebar mesh at the front and back walls, a void, and a post-tensioning (PT) duct

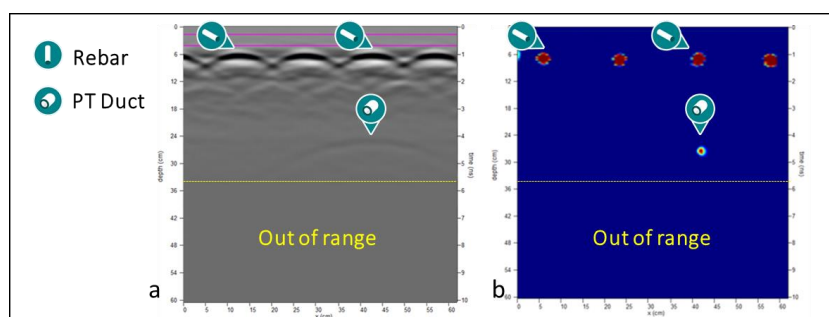


Figure 14: Hilti PS-1000 fails to reach the back wall and its rebar mesh, and to detect the void

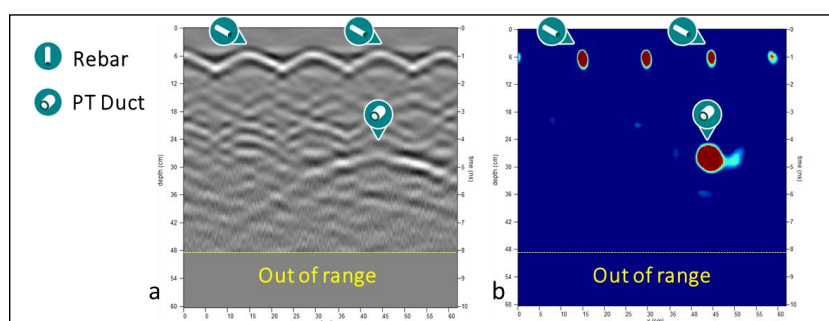


Figure 15: GSSI StructureScan Mini XT covers a larger depth than Hilti PS-1000, however with similar results

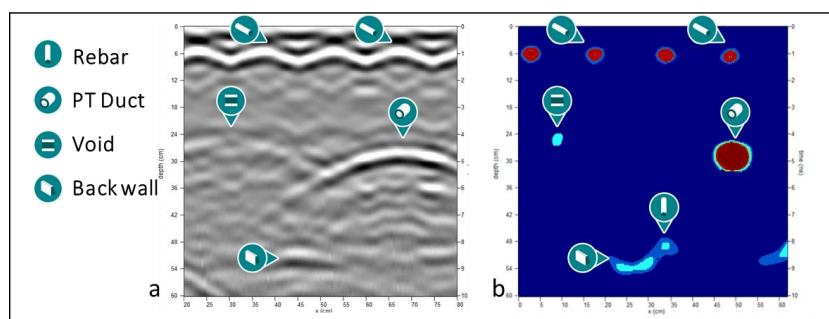


Figure 16: Proceq GPR Live detects all targets, including the second layer of rebar mesh at the back wall, and the back wall itself

3.5 Observations

The first observation relates to penetration depth for the detection of deep features. In situations of non-reinforced objects or of weakly-reinforced objects with shallow features, the traditional GPR devices perform comparably to Proceq's new SFCW solution. However, the low maximum acquisition time of Hilti PS-1000 and GSSI StructureScan Mini XT set a significant limit to the acquisition time, and hence the potential detection range. This results in any target deeper than 30 cm and 50 cm respectively to remain undetected. As evidenced in all four cases, both traditional GPR devices failed to fully detect the objects' backwall, as well as any deep features in their proximity.

The second observation relates to resolution, accuracy, and clarity in detecting targets in more complex configurations, i.e. in cases 2, 3, and 4. In this situation, Proceq GPR Live accurately and unambiguously detects all targets on these blocks. In stark contrast, the two traditional GPR devices report spurious noise (cf. Case 2, Figure 6), or even inexistent targets (cf. Case 3, Figure 11). Furthermore, the shielding effect of steel reinforcements makes some of the features — such as voids — undetectable by traditional GPR devices (cf. Case 4, Figures 14 and 15) in the illustrated cases. In contrast, as evident in the comparisons within cases 3 and 4, the first layer of reinforcement does not prevent Proceq GPR Live from detecting weak reflectors (voids) or deep targets (second layer rebars, back walls).

5 Conclusions

Handheld SFCW technology has been applied for the first time to structural GPR investigations and has been proven to deliver an ultra-wide bandwidth, effectively resolving the resolution/penetration trade-off observed in established structural GPR systems.

Electronics design optimization has resulted in a high antenna gain, for an increased maximum acquisition time thanks to a very high SNR. High quality of the received reflected signal reduces the amount of heavy post-processing likely to cause loss of information or even false artifacts in the scan that may lead to false positives.

These technological features afford the technology carrier, Proceq GRP Live, a distinct advantage compared to traditional pulse-based, single-frequency GPR devices. Structural GPR users can now “look into concrete” and detect structural features and defects faster and more accurately than ever before, and up to penetration depths previously unseen in portable structural GPR units.