



Review of Applications of Ground Penetrating Radar as an NDT Tool

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ABSTRACT

Ground-penetrating radar (also referred to as GPR, ground probing radar, or georadar) is a near-surface geophysical tool with a wide range of applications. Over the past 30 years, GPR has been used successfully to aid in constraining problems in diverse fields such as archaeology, environmental site characterization, glaciology, hydrology, land mine/unexploded ordinance detection, sedimentology, and structural geology. In many cases, however, GPR surveys have been planned or executed with little or no understanding of the physical basis by which GPR operates and is constrained. As a result, many unsuccessful GPR studies have also been presented or published over the past 30 years. The objectives of this primer are to (1) provide an introduction to the important variables pertinent to GPR and (2) explain the relevant aspects of these variables in GPR acquisition, in an attempt to provide fundamental knowledge for improving GPR usage in the future.

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1. INTRODUCTION

Ground Penetrating Radar (GPR) is a single technique that could render the ground and its contents visible is potentially so attractive that considerable scientific and engineering effort has gone into devising suitable methods of exploration (Bristow & Jol, 2003). As yet, no single method has been found to provide a complete answer, but seismic, electrical resistivity, induced polarization, gravity surveying, magnetic surveying, nucleonic, radiometric, thermographic, and electromagnetic methods have all proved useful. Ground-penetrating, -probing or surface-penetrating radar is a specially attractive option. The subject has a special appeal for practicing engineers and scientists in that it embraces a range of specializations such as electromagnetic wave propagation in lossy media, ultra-wideband antenna technology, and radar systems design, discriminate waveform signal processing, and image processing. Most ground penetrating radars is a particular realization of ultra-wideband impulse radar technology (Wu et al., 2019). The terms 'ground penetrating radar (GPR)', 'ground-probing radar', 'sub-surface radar' or 'surface-penetrating radar (SPR)' refer to a range of electromagnetic techniques designed primarily for the location of objects or interfaces buried beneath the earth's surface or located within a visually opaque structure (Knight, 2001). The term 'surface penetrating' is preferred by the author as it describes most accurately the application of the method to the majority of situations including buildings, bridges, etc. as well as probing through the ground (Anderson et al., 2007). The technology of GPR is largely applications-oriented and the overall design philosophy, as well as the hardware, is usually dependent on the target type and the material of the target and its surroundings. The range of applications for GPR methods is wide and the sophistication of signal recovery techniques, hardware designs, and operating practices is increasing as the technology matures. The ground-penetrating radar survey process can be seen in **Figure 1**.

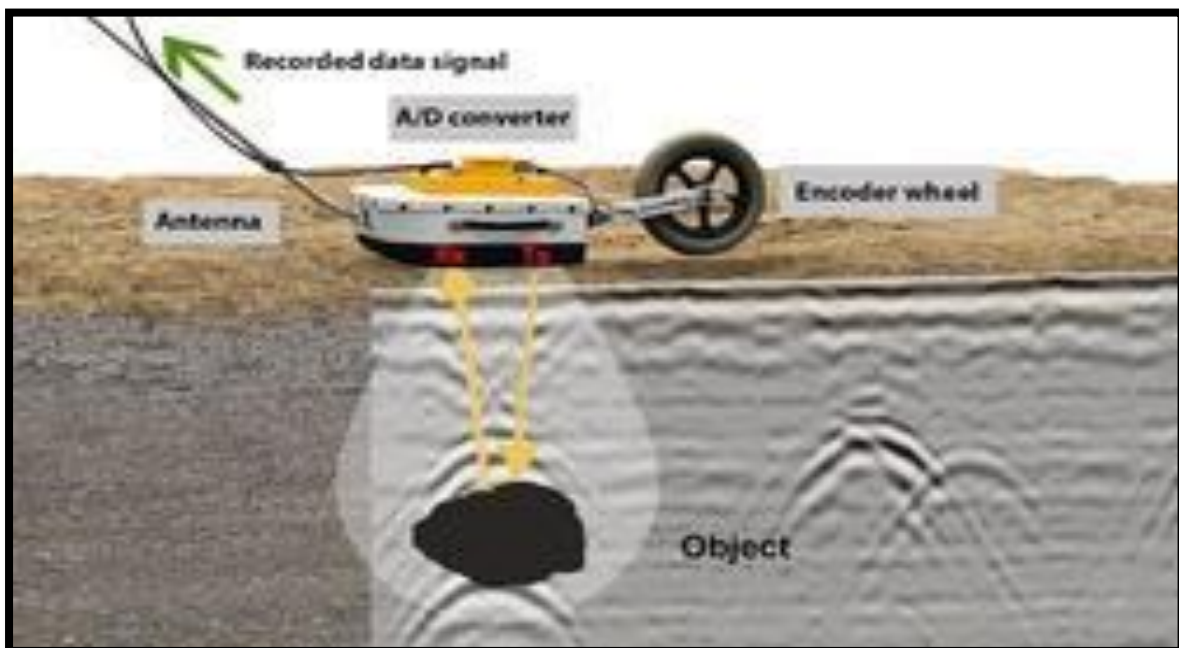


Figure 1. Ground-penetrating radar survey. The figure was adopted from <https://3.imimg.com/data3/QX/YB/MY-7261747/ground-penetrating-radar-survey-250x250.jpg>

The objectives of this primer are to (1) provide an introduction to the important variables pertinent to GPR and (2) explain the relevant aspects of these variables in GPR acquisition, in an attempt to provide fundamental knowledge for improving GPR usage in the future.

2. HISTORY

The first use of electromagnetic signals to determine the presence of remote terrestrial metal objects is generally attributed to Hiilmeyer in 1904, but the first description of their use for the location of buried objects appeared six years later in a German patent by Leimbach and Lowy. Their technique consisted of burying dipole antennas in an array of vertical boreholes and comparing the magnitude of signals received when successive pairs were used to transmit and receive. In this way, a crude image could be formed of any region within the array which, through its higher conductivity than the surrounding medium, preferentially absorbed the radiation. These authors described an alternative technique, which used separate, surface-mounted antennas to detect the reflection from a sub-surface interface due to groundwater or to an ore deposit. An extension of the technique led to an indication of the depth of a buried interface, through an examination of the interference between the reflected wave and that which leaked directly between the antennas over the ground surface. Remote transducers are possible because the dielectric impedance ratio between free space and soil materials, is very much less than the corresponding ratio for acoustic impedances, by a factor that is typical of the order of 100. From the 1970s until the present day, the range of applications has been expanding steadily, and now includes building and structural nondestructive testing, archaeology, road and tunnel quality assessment, location of voids and containers, tunnels and mineshafts, pipe and cable detection, as well as remote sensing by satellite. Purpose-built equipment for each of these applications is being developed and the user now has a better choice of equipment and techniques.

3. WORKING OF GPR

GPR is non-destructive testing. GPR is a geophysical locating method that uses energy waves in the microwave band, ranging in frequency from 1 to 1000 MHz. GPR requires two main pieces of equipment a transmitter and a receiving antenna. The transmitter sends electromagnetic energy into the soil and other material. Ground Penetrating Radar works by emitting a pulse into the ground and recording the echoes that result from subsurface objects. GPR imaging devices also detect variation in the composition of the ground material (Santos-Assunção *et al.*, 2014).

If the electromagnetic impulse hits an object, the density of the object reflects, refracts, and scatters the signal (Walubita *et al.*, 2009). The receiver detects the Ground returning signals and records variations within them. The GPR system has software that translates these signals into images of the objects in the subsurface. This is how it is used to map structures and utilities buried in the ground or man-made structures. Ground Penetrating Radar signals can be used to find a wide range of items. This subsurface tool is most effective when there is a large difference between the electromagnetic property of the target and surrounding material. GPR is often used to map items made of the following materials metal, plastic, PVC, concrete, and natural materials (see **Figure 1-5**).

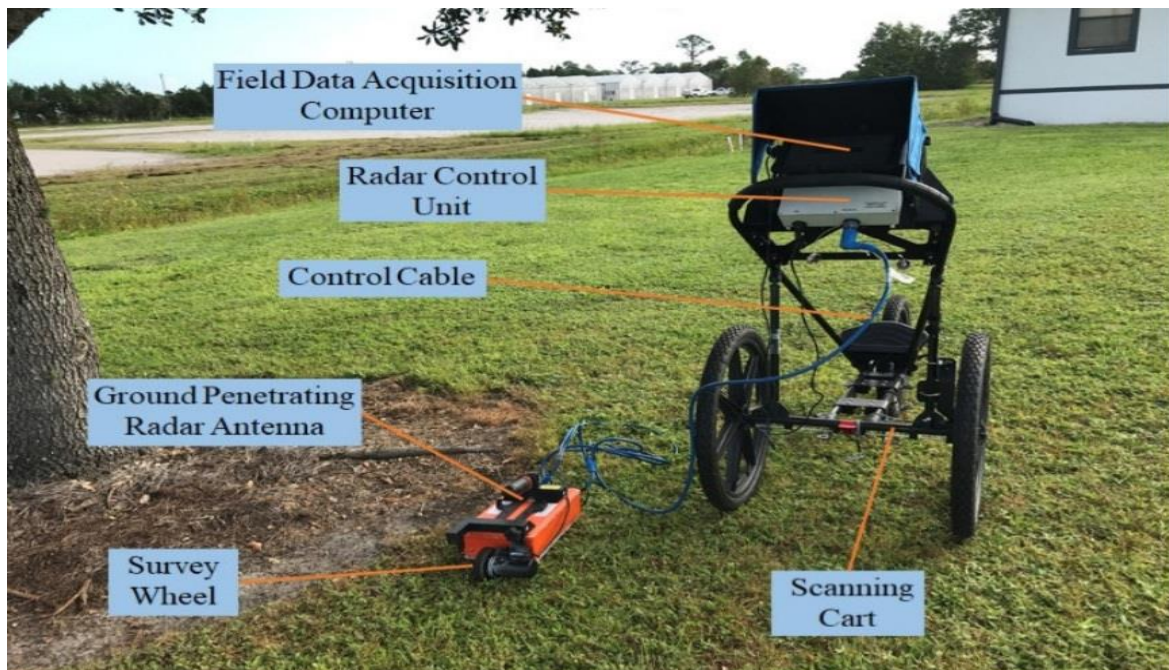


Figure 2. GPR appearance. The figure was adopted from <https://images.app.goo.gl/Z4aeVmVF3C2JMrtu8>.

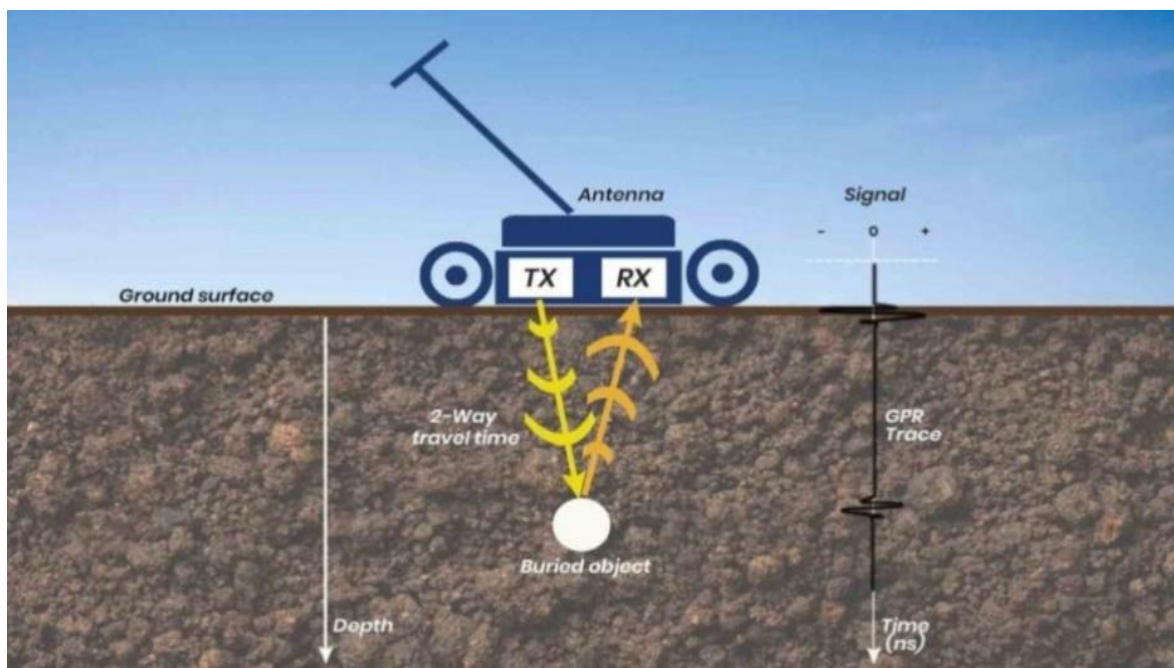


Figure 3. GPR Working. The figure was adopted from <https://images.app.goo.gl/YcvsvZnwGKa1fyaL6>.

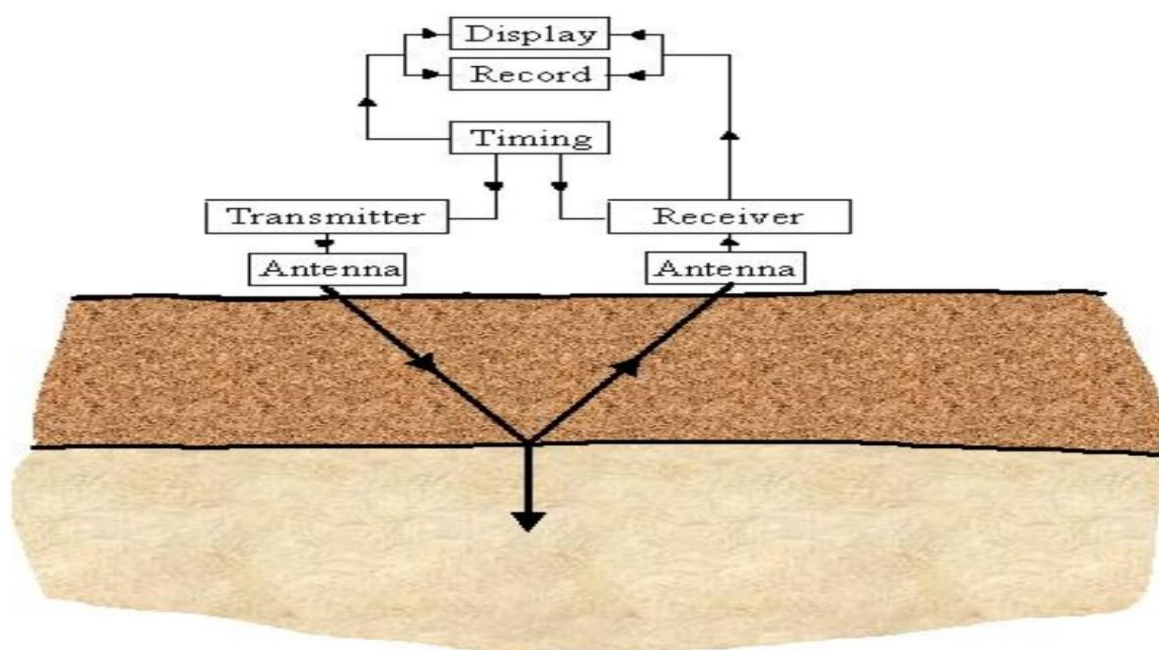


Figure 4. GPR Working Principle. The figure was adopted from <https://images.app.goo.gl/YHHmjctErvotXSyV7>.

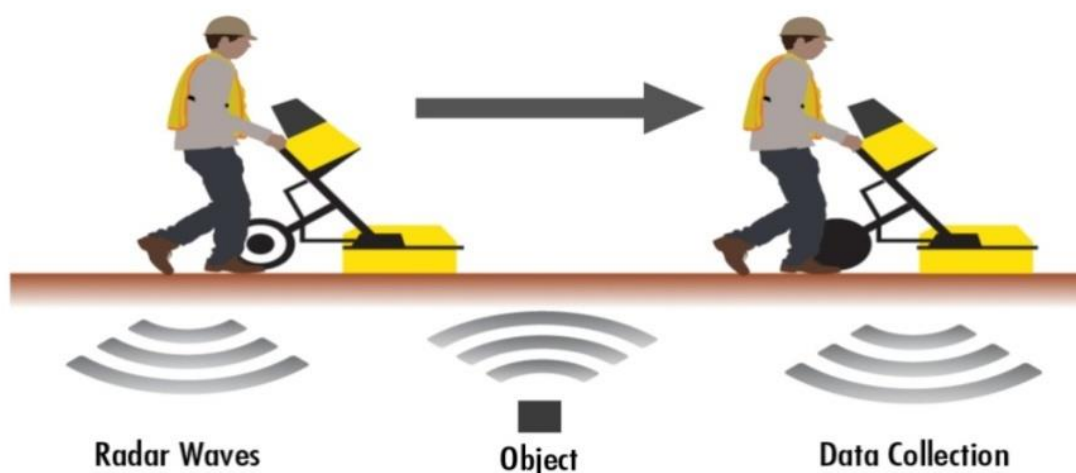


Figure 5. GPR concept when working. The figure was adopted from <https://www.slideshare.net/Gauravate/ground-penetrating-radar-392848>.

4. ADVANTAGES OF GROUND PENETRATING RADAR

GPR is an extremely cost-effective and non-invasive way of surveying. It provides invaluable information before workers even break ground or start excavating (Plati *et al.*, 2020).

- (i) GPR is safe for use in public spaces and a wide variety of project sites.
- (ii) It detects metal and non-metal objects, as well as voids and underground irregularities.
- (iii) It makes it possible to measure the dimensions, depth, and thickness of targets.

- (iv) Data is provided quickly and can cover a large site area.
- (v) Only one side of the surface needs to be scanned to provide data.
- (vi) Frequencies can be regulated to deliver a range of resolution and penetration depths.
- (vii) Data collected during the survey can be seen immediately or used in later projects.
- (viii) No digging, excavating, or ground disturbance is necessary.
- (ix) Landscaping, structures, lawns, etc. are left undisturbed by the survey process.
- (x) It's less expensive than other methods.

5. COMPARISON BETWEEN GPR AND SEISMIC REFLECTION

Differences between GPR and Seismic Reflection are (Hildebrand et al., 2002)

- (i) The principles of GPR are similar to those of seismology. The main difference is that ground-penetrating radar uses electromagnetic energy, rather than acoustic energy of seismic waves, to detecting subsurface structures.
- (ii) Seismology refraction surveys record signals that bend within the ground and arrive back at the surface. Increasing seismic velocity in the ground, related to the ground's elastic properties and density, bends these acoustic signals back towards the surface. Seismic imaging is popular for mapping horizontal structures beneath the ground, but not very effective for characterizing vertical features.
- (iii) GPR uses electromagnetic energy in the form of high-frequency radio waves, which effectively detect changes in electrical properties below the surface. Seismic energy, on the other hand, detects changes in subsurface mechanical properties.

6. RESEARCH APPROACH

In this section, GPR is an effective tool for subsurface inspection and quality control on engineering construction projects. The numerous applications of GPR include the following:

The traditional method of subsurface investigation, coring, is destructive and provides information only at single random points. GPR, a proven technology, offers a continuous image of the subsurface providing invaluable information for asset management planning (Anderson et al., 2007).

- (i) Pavement structures. Measure pavement structure – obtain continuous subsurface imaging to delineate the top and thickness of asphalt, base, and sub-base layers. Quickly generate pavement structure reports highlighting pavement layer thicknesses. Determine construction practices, including concrete under pavement, joints, and road cuts that are not visible from the surface.
- (ii) Pavement Scanning. Cross-sectional view of a portion of the shoulder lane on an interstate highway in California, the USA as shown in **Figure 6**. The colored lines indicate subsurface boundaries with the blue line interpreted as the bottom of asphalt. The road data was collected with a GPS, so it is possible to plot the survey on Google Earth and pinpoint areas of interest.
- (iii) Optimizing Core Location. Records of construction and repair may not exist or be hard to locate. GPR systems enable highway engineers to easily assess subsurface conditions over vast lengths of the road as shown in **Figure 7**. Using GPR to determine core locations is an effective way to understand the structure of the road, especially exceptional areas that may not be discovered with

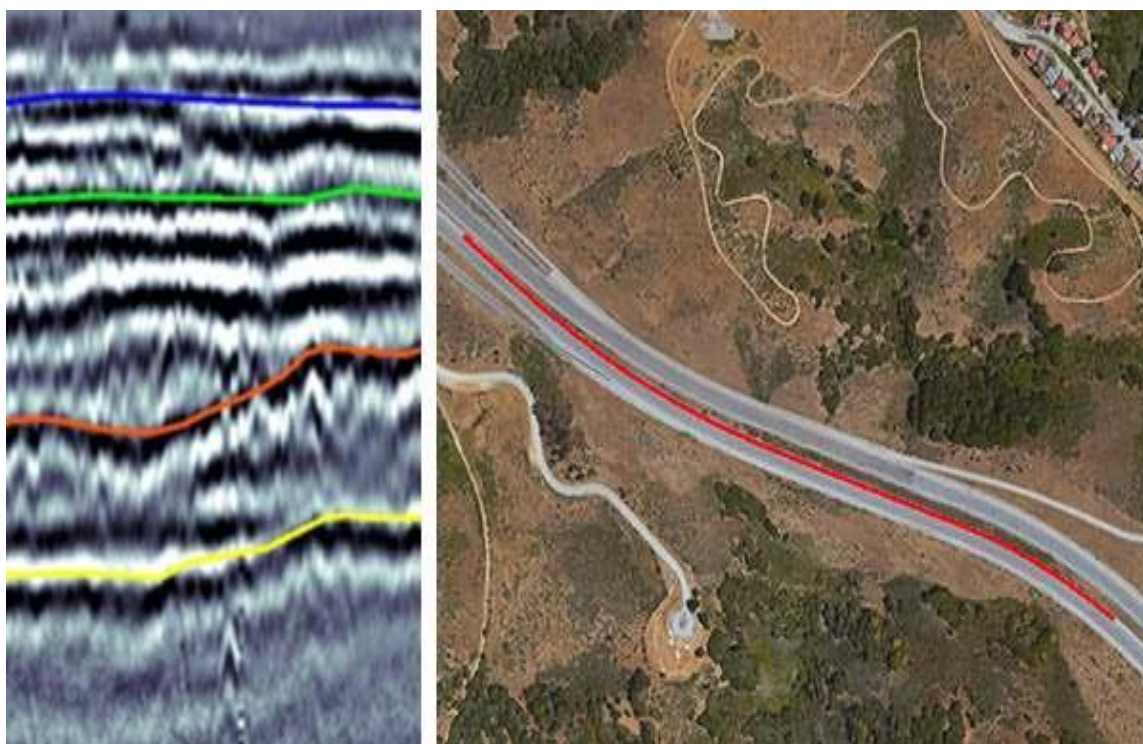


Figure 6 Cross-sectional view. The figure was adopted from <https://www.sensoft.ca/georadar/roads-bridges/>

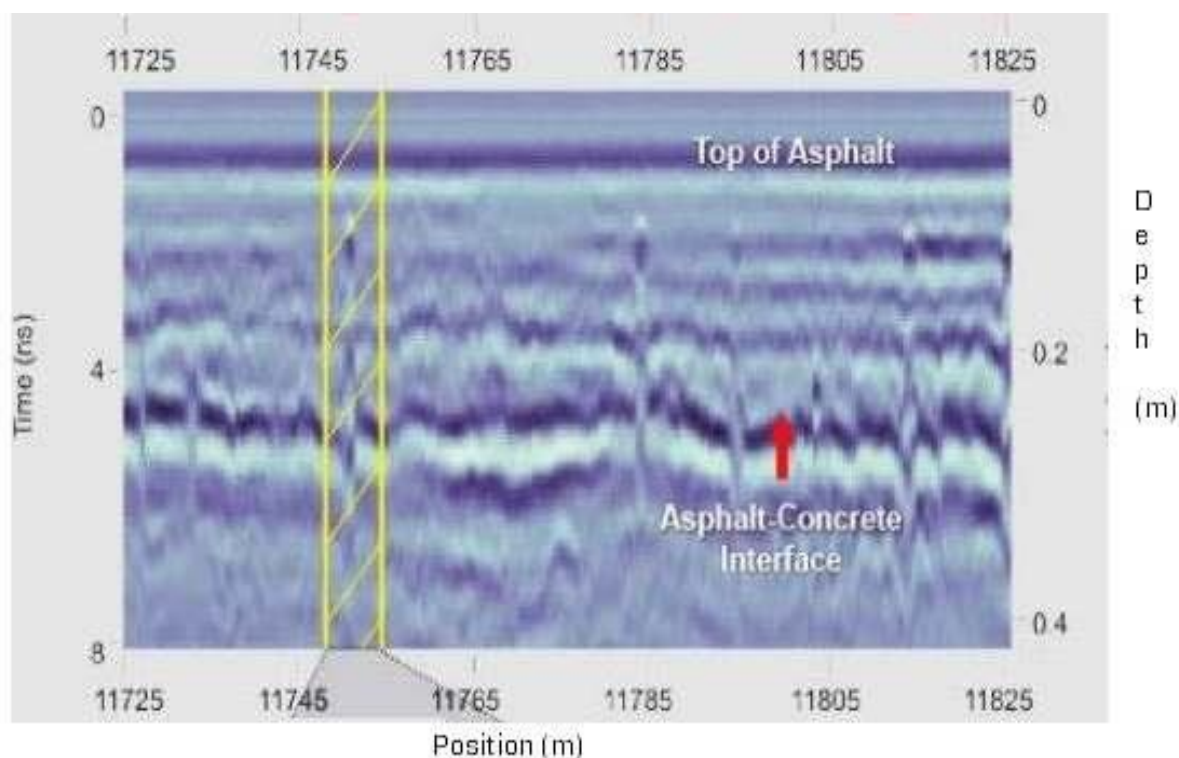


Figure 7. roads with GPR provides information about where the substructure changes. The figure was adopted from <https://www.sensoft.ca/georadar/roads-bridges/>

- (iv) Bridge Condition Assessment. The degree of corrosion of metal reinforcing is a major concern for bridge decks and similar concrete structures. Since the presence of saline water and corrosion by-products causes strong attenuation of GPR signals, measuring and mapping the variations in GPR signal attenuation has become an accepted practice to assess the condition of concrete structures.
- (v) Bridge Deck Condition Report. The Bridge Deck Condition Report module outputs a PDF report that includes a GPR response amplitude map and the statistical summary of all the picked rebar in a bridge deck. Map images are generated as either a Raw Amplitude map or a Deterioration Index map that uses the processing outlined in ASTM 6087 (Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar).

7. RESULTS AND DISCUSSION

7.1. Concrete Scanning and Assessment

GPR can safely and non-destructively provide information about the internal structure of concrete, including the position, amount, and cover depth of rebar, evidence of corrosion, locations of structural elements including post-tension cables, and indications of potential voids (Santos-Assunção et al., 2014). This is critical for confirming the quality of newly built structures, assessing the safety and condition of existing structures, and planning for future renovation projects (Masini et al., 2010).

- (i) Voids under concrete. GPR can be used to locate voids that sometimes form under concrete. Voids under concrete produce a strong reflection, due to the large contrast between the properties of concrete and the air or water-filled void underneath (see Figure 8).

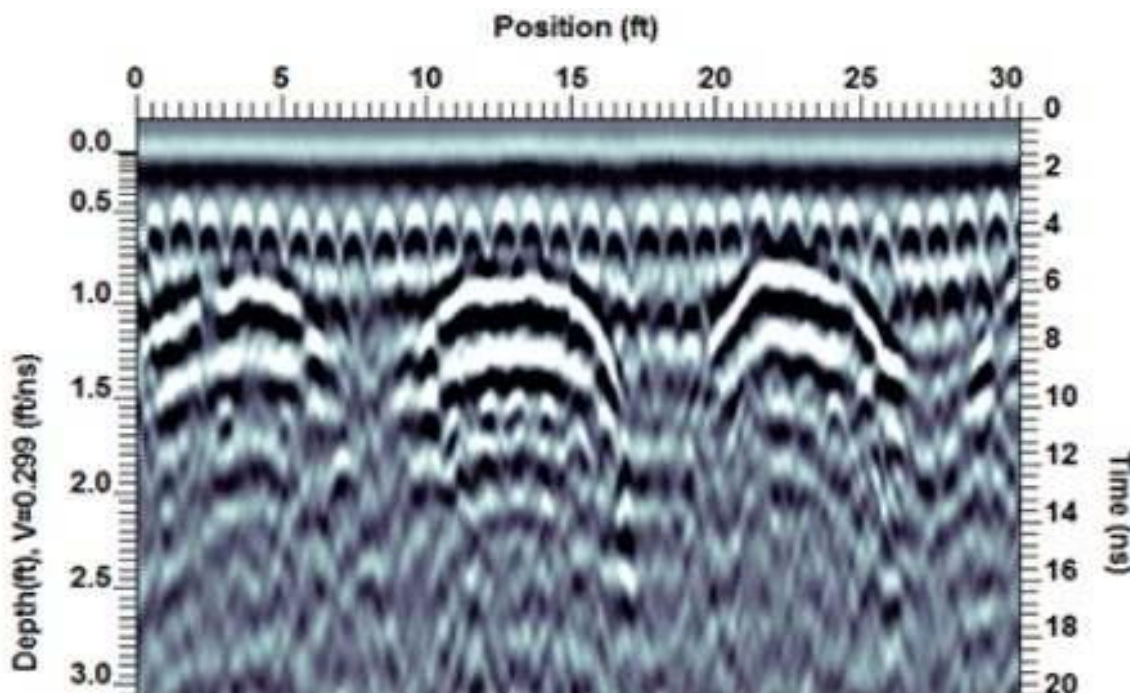


Figure 8. GPR line across a slab-on-grade concrete floor reveals voids. The strong contrast between the concrete and air-filled void produces a strong reflection at the bottom of the slab. The figure was adopted from <https://www.sensoft.ca/georadar/concrete-scanning-assessment/>.

- (ii) **Corrosion Inspection.** GPR is used to find deterioration in concrete because GPR waves are attenuated and scattered by an area of concrete that is deteriorated (see **Figure 9**).
- (iii) **Bottom of Concrete.** GPR can provide an estimate of the thickness of the concrete slab by imaging the bottom of the concrete; this is very useful when access to only one side of the concrete slab is possible (see **Figure 10**).

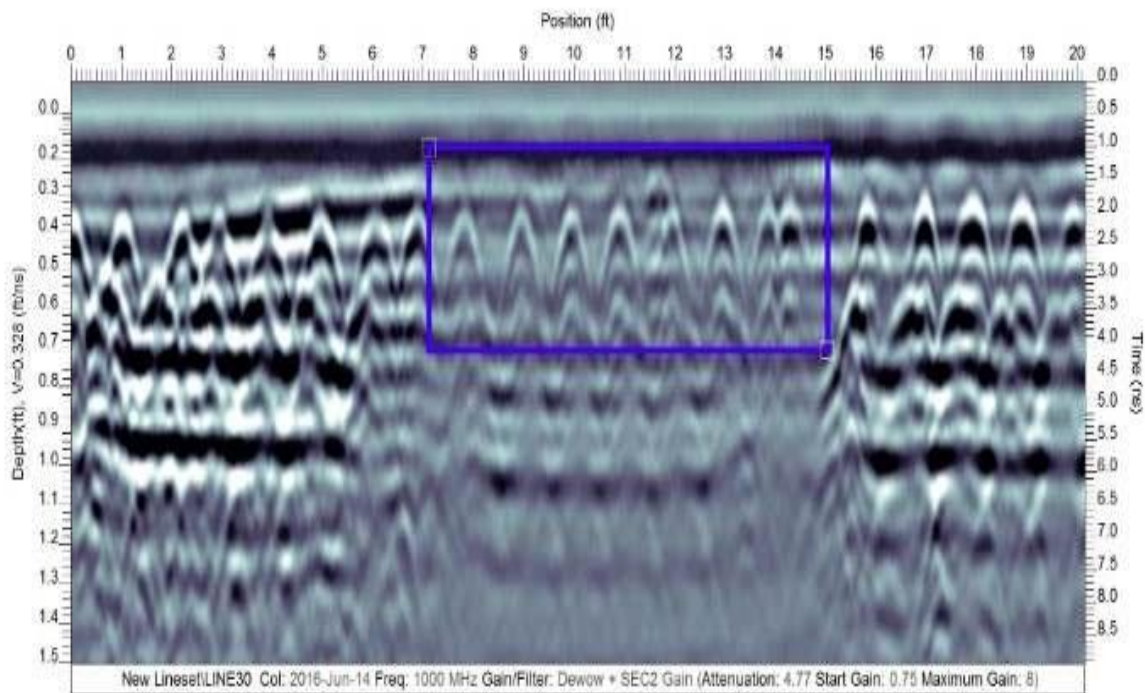


Figure 9. GPR line on a bridge deck shows an area of weaker rebar reflections between 8 and 15 feet compared to the surrounding area, suggesting a potentially corroded area. The figure was adopted from <https://www.sensoft.ca/georadar/concrete-scanning-assessment/>.

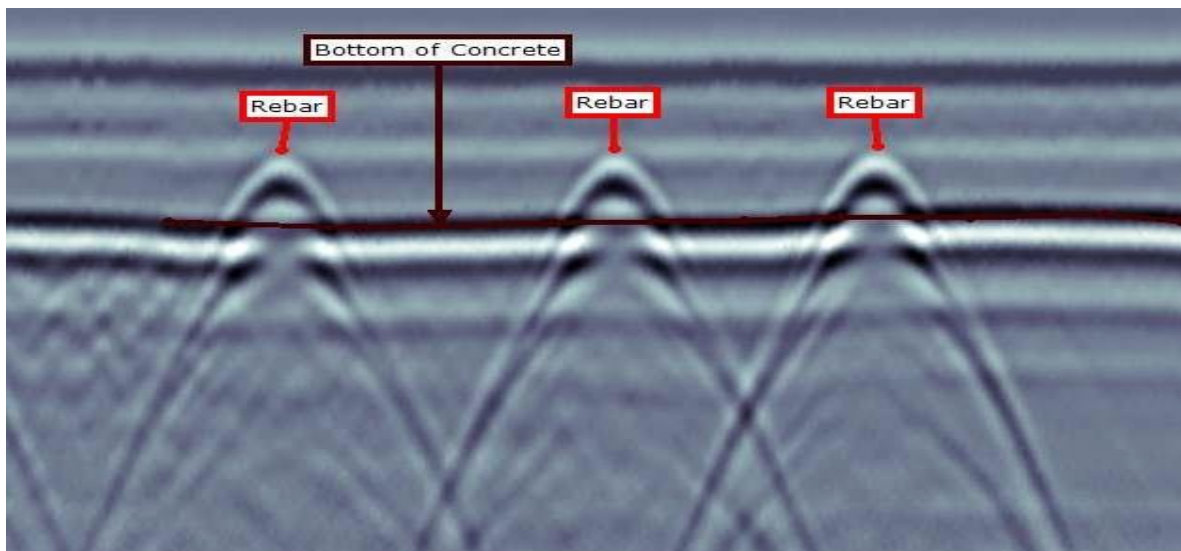


Figure 10. GPR cross-section image showing the top of the rebar cover as well as the bottom of a concrete slab. The figure was adopted from <https://www.sensoft.ca/georadar/concrete-scanning-assessment/>.

7.2. Geotechnical and Environmental

There are several factors:

- (i) **Geology.** Engineered development and assessment of groundwater conditions demand a solid definition of subsurface conditions. GPR's ability to define geologic strata and detect anomalous geologic structures makes it a regular tool in the engineering geophysicist's arsenal of methods. In addition, GPR is one of the few methods that are directly sensitive to water content and chemistry. Applications range from route selection for roads, railways, and pipelines to karst evaluation. GPR's ability to provide a high-resolution subsurface geological structure leads to widespread geotechnical uses of GPR (Li et al., 2010). Applications are wide-ranging such as the determination of bedrock depth, the definition of soil stratigraphy, identification of karstic features, and location of buried groundwater channels.
- (ii) **Hydrogeology.** GPR's sensitivity to soil water content and geologic structure make it a natural method for hydrogeology investigations. From delineating water table to stream and river bed structure to borehole monitoring of contaminant flow, the spectrum of GPR uses is broad and varied.

7.3. Mining and Quarrying

Several parameters must be considered:

- (i) **Placer and Mineral Exploration.** GPR is used worldwide for mineral exploration. The most common use is exploration for fluvial deposits of gold and diamonds as well as beach deposits of titanium and iron-rich heavy minerals. Other GPR uses include detection and tracking of mineral-rich veins, major fault zones, and lateritic nickel exploration.
- (ii) **Tunneling and Underground Mines.** A number of geologic challenges can be addressed with GPR. Whether attempting to examine rock mass stability or locate mineralized zones, GPR provides a powerful method of looking into the subsurface. Salt and potash present highly favorable settings for using GPR.
- (iii) **Quarry Rock Quality.** Extraction of rock for building stone requires the selection of sound and workable rock. GPR's ability to detect structure integrity and undesired jointing and cracking prior to extraction deliver major economic benefit. Marble, granite, and limestone quarrying operations worldwide use GPR for critical development decisions.

7.4. Infrastructure

GPR is now widely used for assessing the interior of concrete structures (Tarussov et al., 2013). When cutting and coring for renovation and repair, avoiding reinforcing, post-tension cables and embedded conduits is a priority. GPR can sense both metallic and non-metallic features making it a versatile imaging tool. Construction records for many buildings are not readily available and construction often differs from design resulting in GPR being the only way to assure what is there.

- (i) **Utility locating.** Prevent damage by accurately locating all buried pipes and cables prior to excavation. GPR can be used as part of the utility locating workflow to provide more complete locates and reduce risk.
- (ii) **GPR can detect traditionally non-locatable subsurface features** including metallic and non-metallic pipes (PVC, asbestos cement, concrete storm, and sewer systems); utilities with broken or damaged tracer wires; underground storage tanks; drainage tiles; non-utility structures (vaults, foundation walls).

- (iii) **Locate and Mark traditionally “non-locatable”.** GPR can locate both metallic and non-metallic pipes and cables. This provides a complete picture of the underground and helps to ensure that nothing was missed using traditional locate methods (**Figure 11**).
- (iv) **Gather depth information on buried infrastructure.** This example shows the location of a concrete storm sewer. GPR was able to find this “non-locatable” and determine the depth of the utility and that it was on a slope, aiding with horizontal direction drilling planning (**Figure 12**).
- (v) **Utilities close to each other.** GPR can map all utilities in a single survey. With the availability of in-field interpretations and viewing options, the multiple utility lines can be mapped easily on-site (**Figure 13**).
- (vi) **Verify locates with GPR.** GPR is often used to verify locates performed using other technologies. Many companies hire GPR service providers for peace of mind that their site is fully cleared and accurately marked prior to beginning excavation
- (vii) **Locate abandoned or untraceable utilities.** GPR can locate abandoned and non-locatable utilities that may not be detected with traditional methods. In this example, the utility on the left could not be located using an EM pipe and cable locator. The GPR easily mapped the two utilities in the area, to ensure proper action could be taken prior to excavation.
- (viii) **Find all buried infrastructure.** GPR can also locate non-utility features, such as underground storage tanks (UST). The example here shows 5 storage tanks (**Figure 14**).

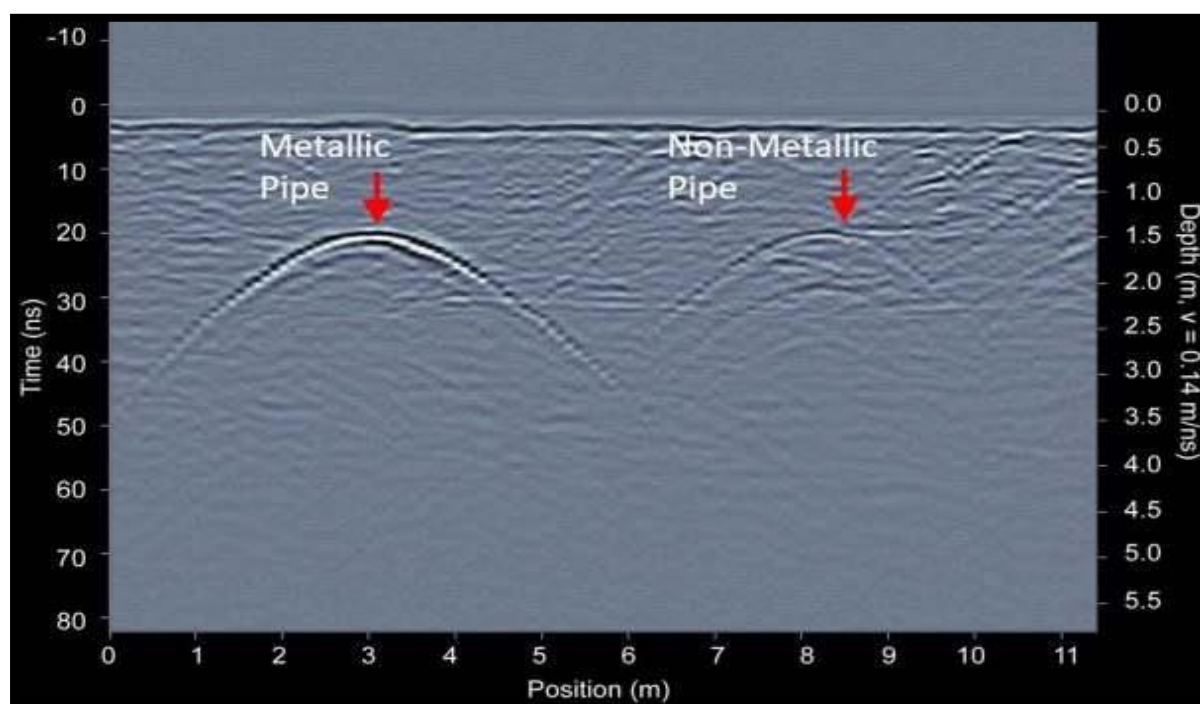


Figure 11. Metallic and Non-Metallic Pipes. The figure was adopted from <https://www.senssoft.ca/georadar/utility-locating/>

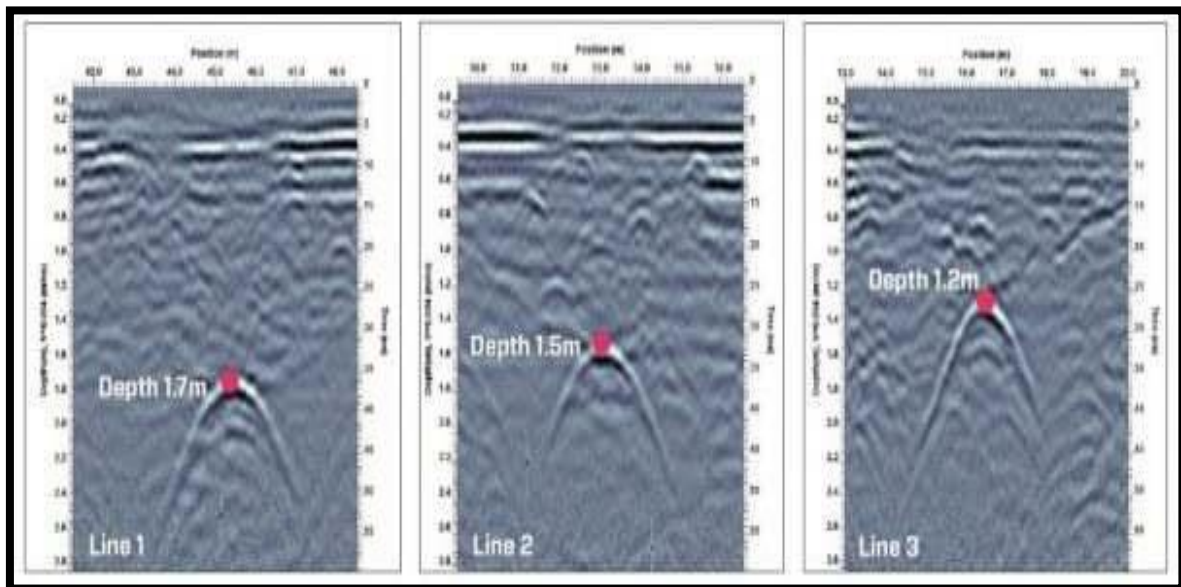


Figure 12. Gather depth information on buried infrastructure. The figure was adopted from <https://www.sensoft.ca/georadar/utility-locating/>

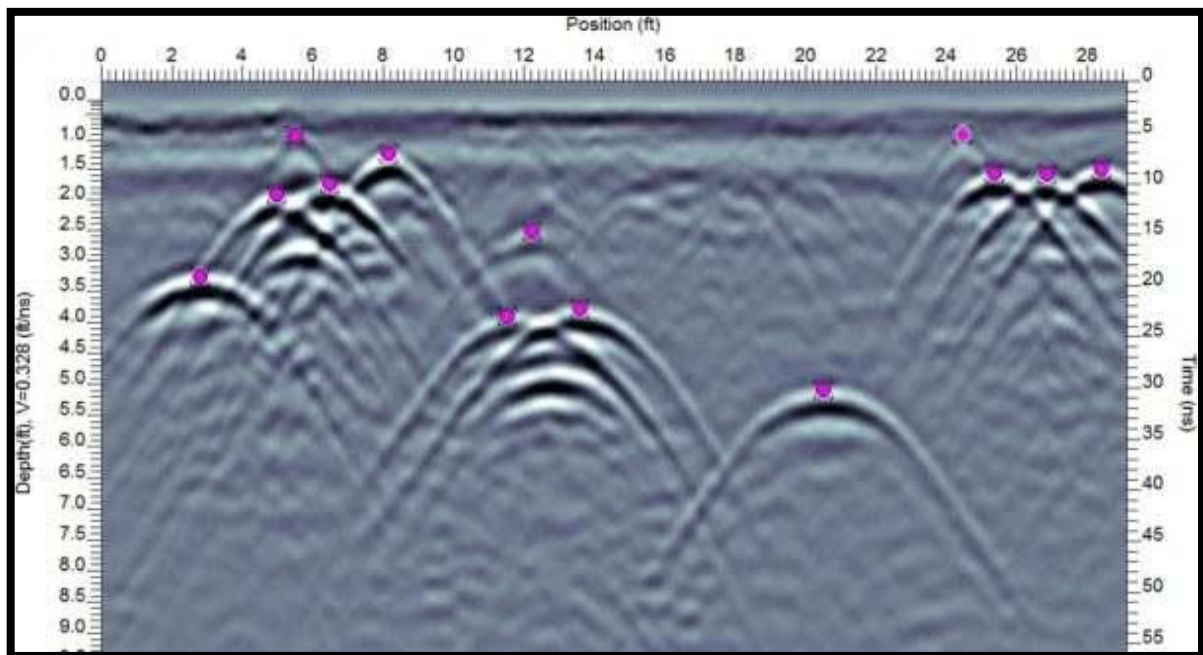


Figure 13. Utilities close to each other. The figure was adopted from <https://www.sensoft.ca/georadar/utility-locating/>.

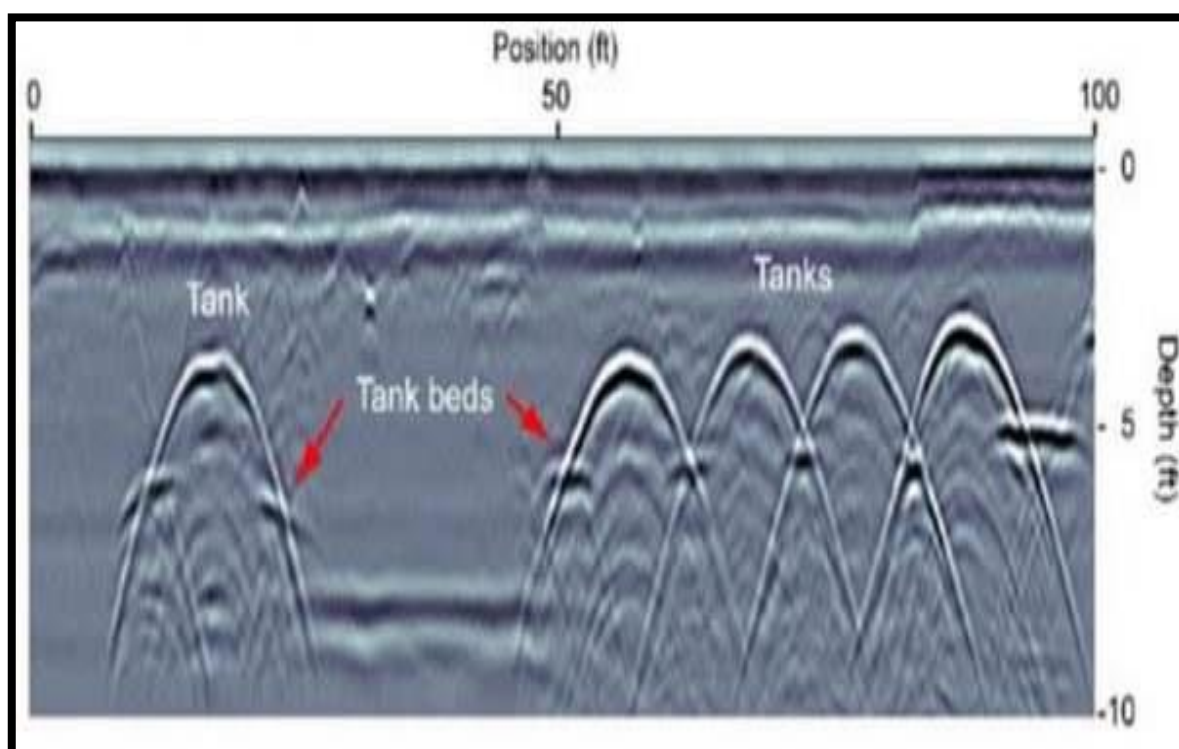


Figure 14. Line scan of 5 buried storage tanks. The figure was adopted from <https://www.senssoft.ca/georadar/utility-locating/>

8. CONCLUSION

GPR is not a major source of electromagnetic radiation. As most GPR systems radiate into the ground the likelihood of interference is very low. For these reasons the licensing authorities appear to have been persuaded that GPR poses little threat. However, both the FCC and ETSI will be supervising the use of GPR more strictly in the future, and manufacturers, developers, and users should ensure that they comply with all of the statutory requirements. The vast majority of GPR systems radiate at levels well below the internationally agreed limits for radiological hazard. Care should be taken by users of GPR that mobile phones and other sources of possible interference do not contaminate the data being gathered, but fairly simple filtering can be used to post-process the data and remove the effects of interference.

9. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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