Urban underground infrastructure mapping and assessment

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ABSTRACT

This paper outlines and discusses a few associated details of a smart cities approach to the mapping and condition assessment of urban underground infrastructure. Underground utilities are critical infrastructure for all modern cities. They carry drinking water, storm water, sewage, natural gas, electric power, telecommunications, steam, etc. In most cities, the underground infrastructure reflects the growth and history of the city. Many components are aging, in unknown locations with congested configurations, and in unknown condition. The technique uses sensing and information technology to determine the state of infrastructure and provide it in an appropriate, timely and secure format for managers, planners and users. The sensors include ground penetrating radar and buried sensors for persistent sensing of localized conditions. Signal processing and pattern recognition techniques convert the data in information-laden databases for use in analytics, graphical presentations, metering and planning. The presented data are from construction of the St. Paul St. CCTA Bus Station Project in Burlington, VT; utility replacement sites in Winooski, VT; and laboratory tests of smart phone position registration and magnetic signaling. The soil conditions encountered are favorable for GPR sensing and make it possible to locate buried pipes and soil layers. The present state of the art is that the data collection and processing procedures are manual and somewhat tedious, but that solutions for automating these procedures appear to be viable. Magnetic signaling with moving permanent magnets has the potential for sending low-frequency telemetry signals through soils that are largely impenetrable by other electromagnetic waves.

Keywords: underground infrastructure, mapping, ground penetrating radar, water supply, smart cities

1. INTRODUCTION

The motivation for this research lies in the combination of the societal importance and tractable technical challenges associated with mapping and sensing the condition of urban underground infrastructure. Underground utilities are critical infrastructure for all modern cities. They carry drinking water, storm water, sewage, natural gas, electric power, telecommunications, steam, etc. This infrastructure reflects the growth and history of the city. Many components are aging, in unknown locations with congested configurations, and in unknown condition. ASCE gives drinking water and waste water infrastructure in USA grades of D [1].

Managing leaks in fresh water supply systems is a typical example of some of the issues. Figure 1 shows water loss for the past three years for a municipal utility in northern Vermont. The amount of water loss has been increasing and ranges up to 50%. Despite concerted efforts with meter tracking and conventional leak detection equipment, the problem remains largely unresolved. Figure 2 shows a leak in a fresh water pipe. Locating the leak was difficult and required expensive excessive trenching.

1.1 Smart cities approach

A smart city information-centered approach has the potential to help with more effective management of limited resources for the upkeep and growth of underground infrastructure. The goal is to address fundamental technical issues relating to building a smart database map and sensor network for infrastructure buried in cities. Figure 3 shows a long-term vision with the underlined items corresponding to tasks planned for this project. Some of the key ingredients are:

1. *Urban underground 3-D utility mapping and sensor network database* – Assemble databases that contain both 3-D mapping and condition assessment of underground infrastructure.

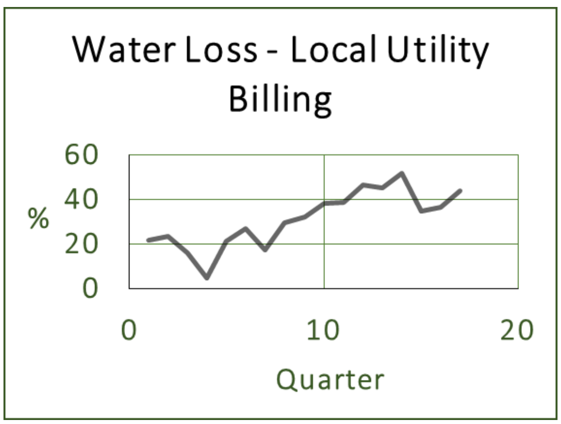
2. H*igh-speed tomographic ground penetrating radar (GPR) system* – Design, fabrication and use of a system that can quickly scan and produce tomographic 3-D images of underground infrastructure.

3. *Underground water pipe monitoring sensor system* – The sensors need to be connected to network. Possibilities include a high-speed fiber optic telemetry network, as available in Gigabit cities; and lower speed wireless systems, such as LoRa. Technical challenges include energy supply and the high attenuation of wireless signals by most soils.

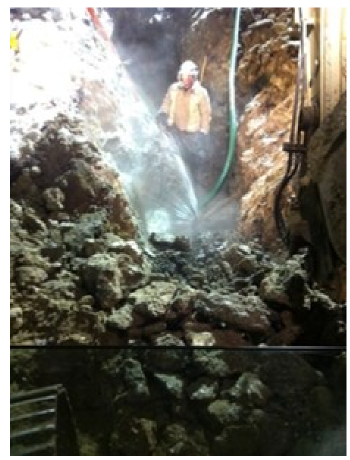
4. *Digital and automated analysis tools* – Both the GPR and sensor network data streams are multichannel, complicated and voluminous. A dashboard style presentation of the data requires automated data processing methods for mapping and condition assessment.

5. *Field test ground truthing* – Most underground infrastructure is buried and out of sight. Easy verification of the mapping and sensing is not possible. It is imperative that consistent efforts be made to verify the accuracy of sensory information, usually by observing conditions before and after excavations.

This is a long term multi-faceted undertaking. Activities described below are some of the requisite pieces and include improved GPRs for locating, mapping and assessing underground infrastructure, and a possible approach to sensor telemetry with low-frequency earth-penetrating magnetic fields.



a. Water loss from municipal utility in northern Vermont



b. Water leak with excess trenching required to determine location

Figure 1 Typical problems with water supply leaks: a. high losses in a system, and b. difficult to locate leaks

1.2 Ground penetrating radar

GPR offers virtually the only available technique for determining underground features and conditions without digging or inserting robots. Using GPR in an urban environment poses some severe technical challenges: 1. need for rapid broad coverage of streets; 2. key features often buried at depths of 2 m or more; 3. clays and wet soils prevent deep penetration with electromagnetic waves; 4. variable dielectric properties produce lensing effects, and 5. cluttering underground pipes causing multipath effects – both distort tomographic methods; Detection of dielectric anomalies corresponding to the wet soil conditions of leaks.

Most GPRs use ground-coupled sensing, with the antennas placed closely to the ground surface for improved penetration, and operating in a monostatic or bistatic mode. The result is that the GPR scanning speed is very slow, typically 5 to 10 miles per hour and with a coverage is limited to vertical transmission and receive paths. Broad urban coverage with slow speed GPR is impractical. Most of the presently-available GPR systems are single channel, equipped with one transmitter antenna and one receiving antenna, and have a small antenna footprint.

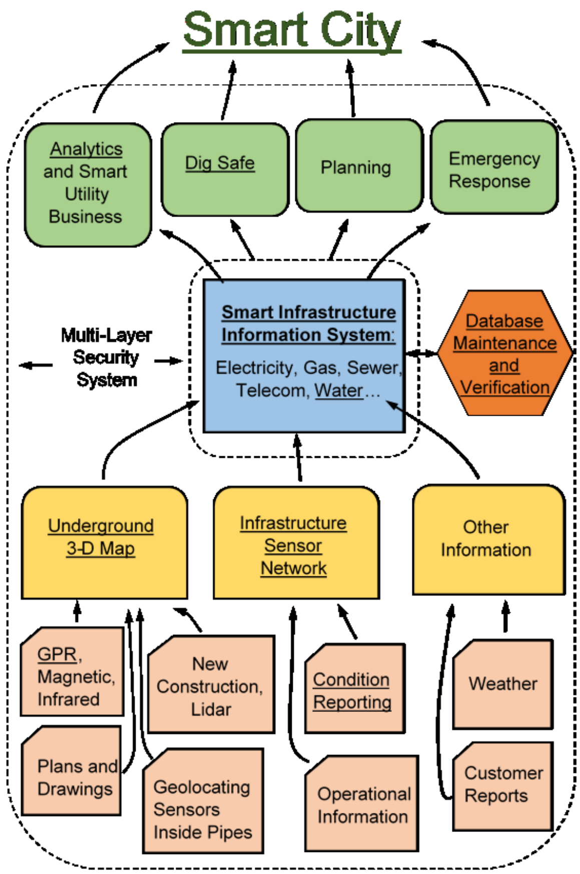


Figure 2 Long term vision of smart cities underground infrastructure mapping, monitoring and management system. Underlined items are those planned for inclusion in this project.

Innovations in GPR on two fronts can resolve some of these issues: 1. Phased array multichannel source methods with polarization control – These methods have the potential for electronically steering GPR source signals in a manner that is similar to traditional airborne phased array radar systems, but must account for the near-field geometries of GPR systems. A primitive phased-array GPR scanning system has been demonstrated [2]. Polarization control is important for pipe locating as evidenced by data collected from steel reinforcing bars in concrete, Figure 4; and 2. Full waveform multi-static data acquisition methods – GPR signals are high-speed, i.e. travel at the speed of light, with frequencies often ranging up into multiple GHz. These signals are difficult to sample with ordinary analog-to-digital converters. Typically, subsampling methods using hundreds and thousands of send/receive cycles provide the necessary sampling, at the expense of reduced overall sampling time and increased unwanted radiated emissions. It is possible to increase the sampling speed with full-waveform digitization [3].

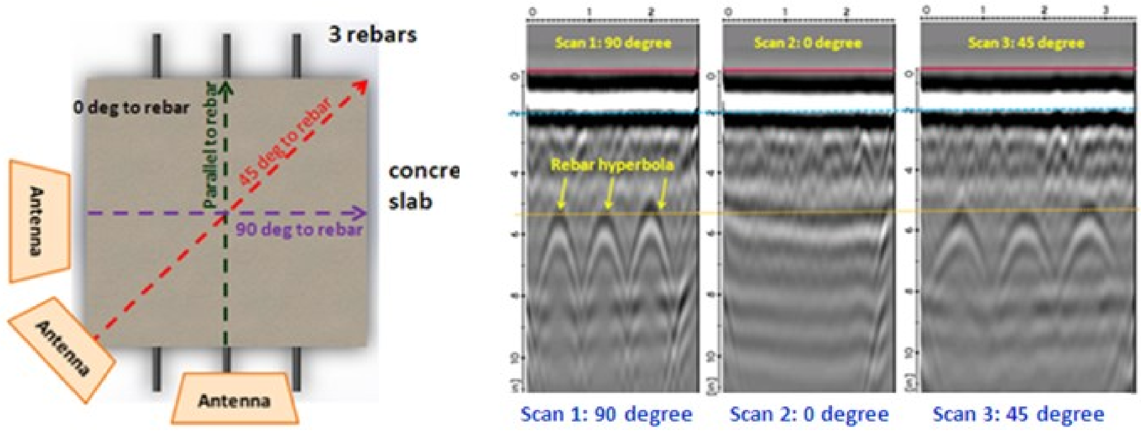


Figure 3 GPR measurements of rebars in concrete slab: 3-different scanning angles and the resulting B-scan images

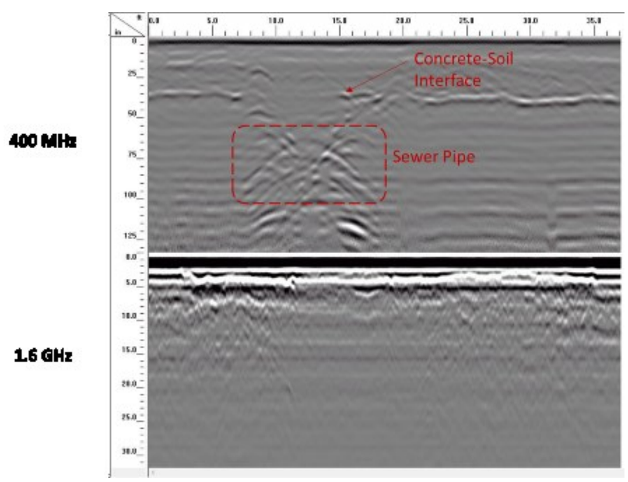
2. GPR FIELD TESTS

Recent measurements of buried infrastructure at sites in Vermont elucidate some of the possibilities and issues. Most of these measurements were taken with a tri-band GPR system, using channels at: 1. 400 MHz, 2. 1.6 GHz and 3. 2.3 GHz. In most cases, the 400 MHz band proved to be the best for subsurface sensing due to the combination of resolution and depth of penetration.

2.1 Drainage pipe under bike path

The installation of a water drainage pipe under a bike path at the University of Vermont is an easily located target due to noticeable subsidence in the pavement and nearby drains. Figure 4 shows the pipe and associated GPR scans. The results from the 400 MHz scan show both the pipe and the soil disturbance caused by the cut and cover installation.

a. Bike path and drainage pipe direction



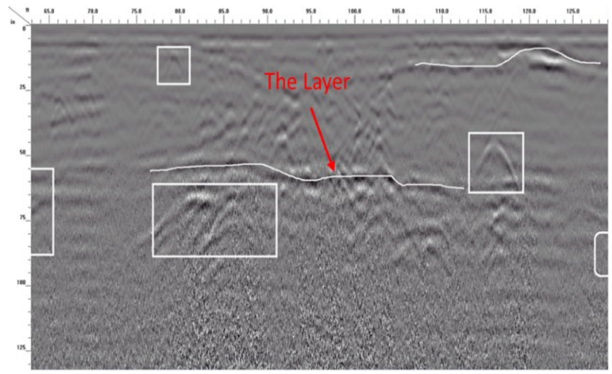
b. B-scans at 400 MHz and 1.6 GHz with the GPR traversing the pipe.

Figure 4 GPR scan of drainage pipe under bike path. The 400 MHz scan shows pipe and soil disturbance due to cut and cover installation

2.2 St. Paul St. bus station

A small scale example of some of the possibilities includes a subsurface investigation of the CCTA Bus Station project on St. Paul St. in Burlington, VT during the summer of 2016. Figure 5 shows an excavation of St. Paul St. and a soil layer approximately 2 m deep that was detected by the 400 MHz GPR. Figure 6 shows a sheet pile wall at the same site restrained by 25 mm diameter steel nails. The GPR could detect the nails, but the image was somewhat cluttered. It is not obvious that the nails would have been discovered with these instruments without prior knowledge of their existence.

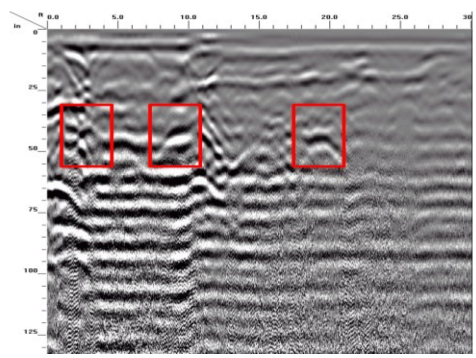
a. St. Paul St. excavation showing soil layer



b. Ground penetrating radar scan of site prior to site showing soil layer and various buried pipes.

Figure 5 Excavation of St. Paul St. in Burlington, VT showing: a. soil layer, and b. detection of soil layer in GPR B-scan

a. Sheet piles with soil nails providing lateral support

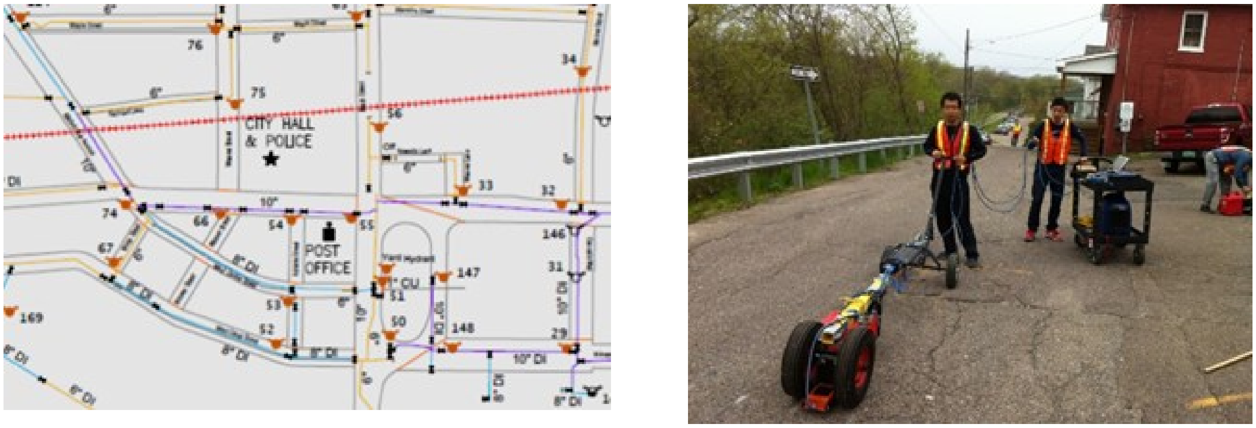


b. Detection of soil nails by GPR

Figure 6 Sheet piles on St. Paul St. excavation with 25 mm diameter steel soil nails detected by GPR in a cluttered scan

2.3 Railroad Lane water leak detection

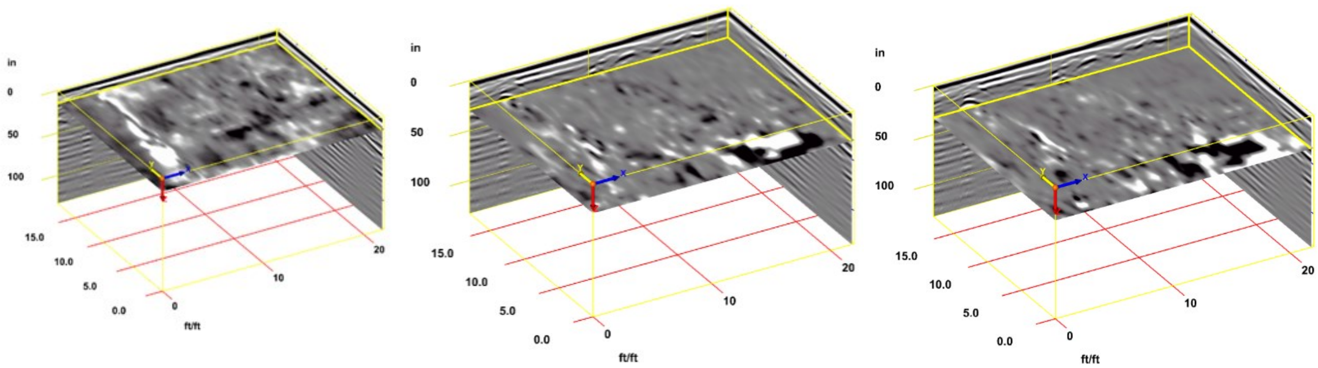
Railroad Ln. in Winooski, VT was suspected of having a serious leak in a water supply pipe running underneath. A set of tests in the summer of 2016 attempted to locate the leak with GPR, Figure 7. A grid-based GPR scan resulted in a volumetric C-scan representation of the subsurface conditions and producing an anomaly corresponding to a probable leak.



a. Map of Winooski, VT with Railroad Ln.

b. Dual-band GPR instrument on Railroad Ln.

Figure 7 GPR Scan for water leak on Railroad Ln in Winooski, VT



a. Depth Slice 1 – 15.3 inch

b. Depth Slice 2 – 29.2 inch

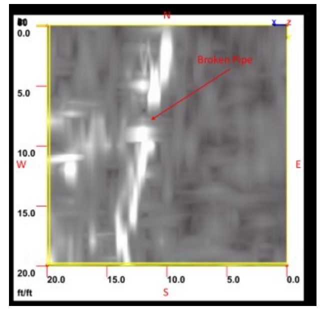
c. Depth Slice 3 – 33.2 inch

Figure 8 C-scan horizontal slices from GPR scan of Railroad Ln showing an anomaly corresponding to the site of a probable water leak

2.3 Orchard Terrace storm sewer assessment

Orchard Terrace in Winooski, VT is scheduled for a complete replacement of water and wastewater pipes in the next year. As part of a ground truthing effort, a scan was taken of various items of interest, including a cul-de-sac with a possible break in a storm water sewer. The GPR scan identified an anomaly that may correspond to a break in the pipe. This remains to be verified.

a. Orchard Terrace cul-de-sac with pavement distress indicating possible storm sewer issue



b. C-scan of Orchard Terrace with anomaly locating possible break in storm sewer.

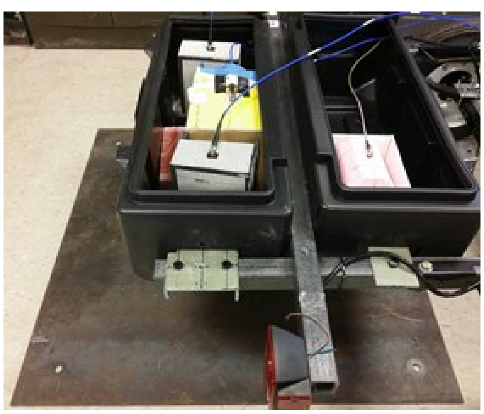
Figure 9 Orchard Terrace in Winooski with possible storm sewer break detected by GPR

3. TECHNOLOGY IMPROVEMENTS

The above GPR measurements and related sensor monitoring of underground infrastructure is tedious, time consuming and, as presently practiced, largely impractical on a large urban scale. A series of technical improvements will help to speed up the measurement processes and analyses.

3.1 Multi-static GPR system

A multi-static GPR uses a single antenna as a source and multiple antennas as receivers that collect the response simultaneously from a signal produced from the source antenna. The simultaneous collection of reflected pulses provides a potential speed up of data acquisition and an added degree of freedom through angled and off-axis measurements. A key feature is to use a low-cost multi-channel receiver, based on a waveform sampling ASIC developed for high-energy physics that is capable of simultaneous full waveform signal capture on multiple channels, i.e. multi-static capability, has recently been demonstrated using s developed for high-energy physics [4]. The combination of full-wave and multi-static sampling in an integrated low-cost receiver unit offers a unique opportunity to build a high-speed, yet modest cost, multi-channel GPR system, Figure 10. The simultaneous, single-shot, full waveform capture of three channels in a multistatic GPR configuration appears in Figure 11.



a. Four-channel multi-static antenna array

b. GPR cart with multi-static array

Figure 10 GPR trailer cart with four-antenna simultaneous multi-static GPR array

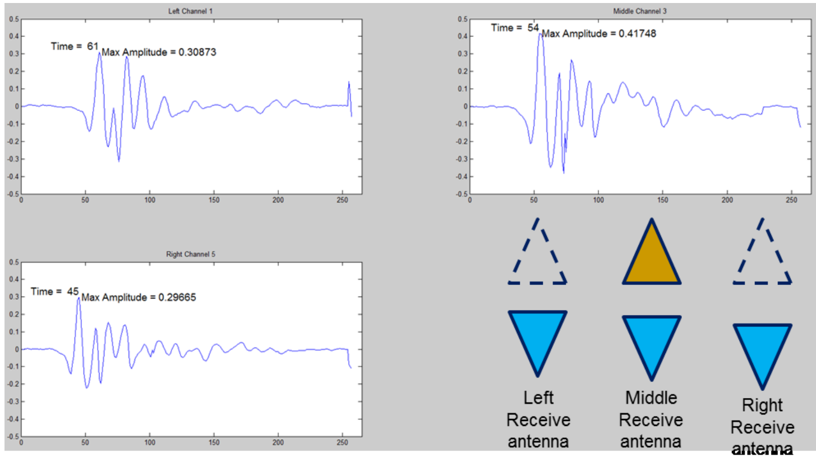
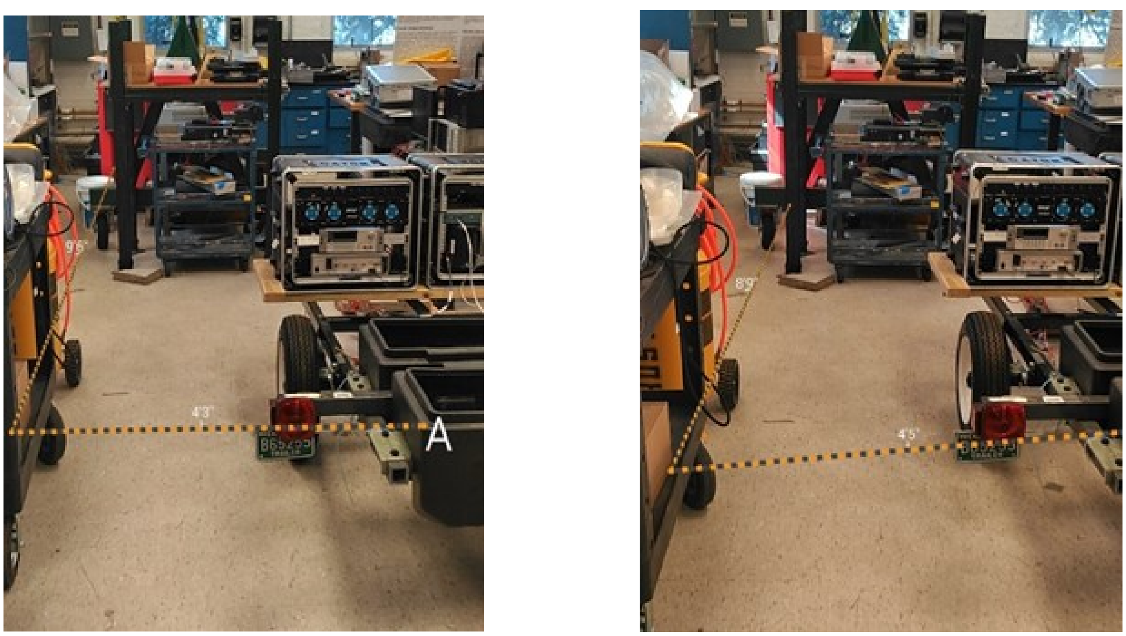


Figure 11 Three channels of single-shot fully digitized waveform captured with multi-static GPR system

3.2 Smart phones for position registration

Position registration is a primary concern with sensing large areas with a GPR. The difficulties are compounded in urban environments with measurements during moving traffic in GPS-denied conditions. Smart phones have onboard sensing and computational ability that makes them potentially viable tools for vehicle trajectory estimation with Kalman filtering of acceleration, heading and GPS signals that arrive at different update rates [5]. The continued increase in processing power and algorithmic development has enables the use of video processing for position registration. One possibility is in the Tango environment, as shown in Figure 12, with the distances measured to landmarks produced with an out-of-the-box app.



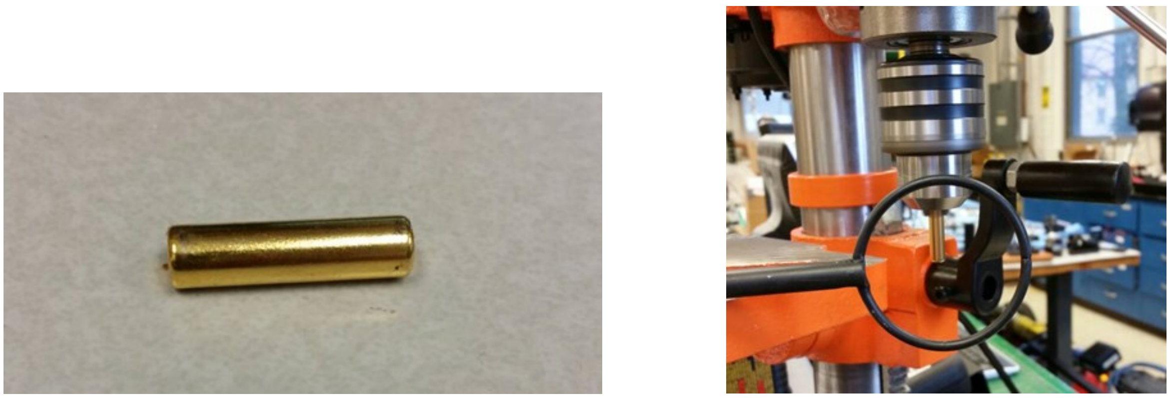
a. Cart in position A

b. Cart in position B

Figure 12 Tango-based registration of position of GPR cart

3.4 Magnetic signaling

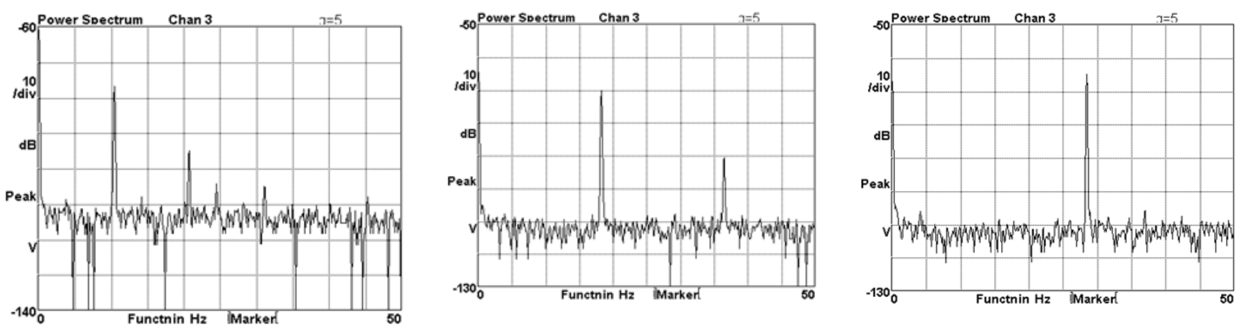
Difficulties with telemetry hamper the use underground pipe sensing systems. Most soils attenuate electromagnetic waves at a high rate. Low-frequency (3 kHz or less) EM waves can penetrate long distances through earth and sea water. Generating the low EM waves by traditional antennas carrying large electrical currents is impractical due to the large size of the antennas and associated power consumption. An alternative approach is the mechanical movement of permanent magnets. A series of tests with moving magnets indicates that it is possible to generate measurable dynamic magnetic fields at low-frequencies. Figure 13 shows a bar magnet with a nontraditional magnetic field orientation transverse with respect to the magnet axis. Rotating the magnet with a drill press creates a rotating magnetic field, Figure 14. Linear oscillatory motion of magnets can also produce oscillating magnetic fields, Figure 15 and Figure 16.



a. Bar magnet with polarity transverse to axis

b. Magnet in drill press with electromagnetic probe

Figure 13 Test of rotating magnet producing an oscillating magnetic field



a. 600 RPM (10 Hz)

b. 1,100 RPM (18.3 Hz)

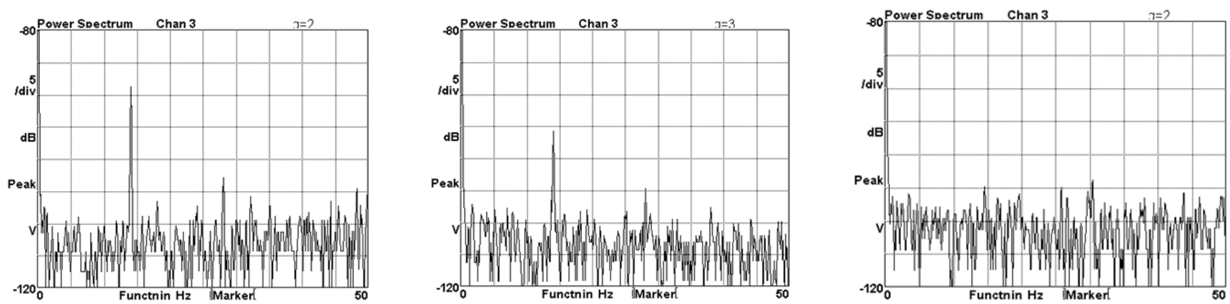
c. 1,700 RPM (28.3 Hz)

Figure 14 Spectra of fields produced by rotating magnet

a. Steel plate with array of bar magnets

b. Plate with array vibrating at 80 Hz

Figure 15 Plate with array of vibrating magnets



a. With 1 magnet attached to center post of shaker and an array of magnets attached to steel plate

b. With 1 magnet attached to center post of shaker and an array of magnets attached to steel plate

c. Verification test with just the shaker alone with no magnets

Figure 16 Measurement of magnetic field emanating from plate vibrating with and without magnet array

4. CONCLUSIONS

Maintaining and assessing the health of underground infrastructure can be challenging. Most items of interest are buried underground. Remote sensing with GPR is potentially viable, but technical improvements are needed for the technique to become practical for use on a wide scale. The improvements include improved position registration, and facile multichannel operation. Interaction with buried sensors is hampered by the high attenuation of electromagnetic waves by most soils. The use of moving permanent magnets may be a means of generating low-frequency magnetic waves capable of penetrating soils.

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