EFFICIENT LARGE-SCALE UNDERGROUND UTILITY MAPPING WITH A MULTI-CHANNEL GROUND-PENETRATING IMAGING RADAR SYSTEM

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ABSTRACT

Ground-penetrating imaging radar ("GPiR") combines standard GPR with accurate positioning and advanced signal processing to create three-dimensional (3D) images of the shallow subsurface. These images can reveal soil conditions and buried infrastructure. A commercial GPiR called the CART Imaging System was designed for mapping urban infrastructure. The CART system covers a 2m swath on the ground and can collect data while moving at speeds up to about 1km/h. The system collects enough data in a single pass to form a 3D image beneath its track; side-by-side passes are stitched together to create a seamless image of the subsurface.

INTRODUCTION

Numerous publications describe how standard GPR systems can be used to obtain images of the subsurface on a small scale (for a review of early work, see Daniels [1]; also Ciochetto *et al.* [2]; Grandjean *et al*. [3]). In this paper, GPiR is introduced as a standard term for GPR surveys (or systems) that combine efficient radar surveying with precise positioning control and advanced signal processing to create high-resolution 3D images of the subsurface on a large scale. By "large-scale" and "high-resolution," we mean surveys covering thousands of square meters with a resolution of centimeters. Such underground images take on the quality of satellite radar images or 3D seismic images.

A commercial GP*i*R called the *CART Imaging System* has been tested during the past two years in major cities of the US and Europe. The CART system uses an efficient new GPR array, which can be towed by a vehicle (Fig. 1 left) or pushed in front of a modified commercial lawnmower at speeds up to about 1 km/h.

The CART radar array, developed by Malå Geoscience (Johansson *et al.* [4]), has 9 transmitters and 8 receivers in two parallel rows (Fig. 1 right). Each antenna is an ultra-wideband bowtie with a bandwidth from about 50 MHz to 400 MHz. Transmitters broadcast an impulse with a peak frequency of about 200 MHz. Control electronics with special timing circuit fire the transmitters and control the receivers in sequence to create 16 GPR channels covering a 2 m swath on the ground (Fig. 1 right). In this "bi-static" mode of operation, each transmitter fires twice in sequence, with each firing being recorded by an adjacent receiver.

The CART system uses a laser theodolite to track the position of the array at all times (GPS was also considered, but is not yet accurate and fast enough in city environments). As the CART array moves along the ground a laser theodolite locks on and follows a prism mounted on the CART. The CART system records the geometry data independently from the radar data and merges the two data streams using information provided by a trigger wheel that controls firing of the radar antennas (Burns *et al.* [5]; for a different approach, see Lehmann and Green [6]). The theodolite is also used to map surface features—such as curbs, manholes, valve covers, fire hydrants—to provide a local reference map for the 3D radar images.

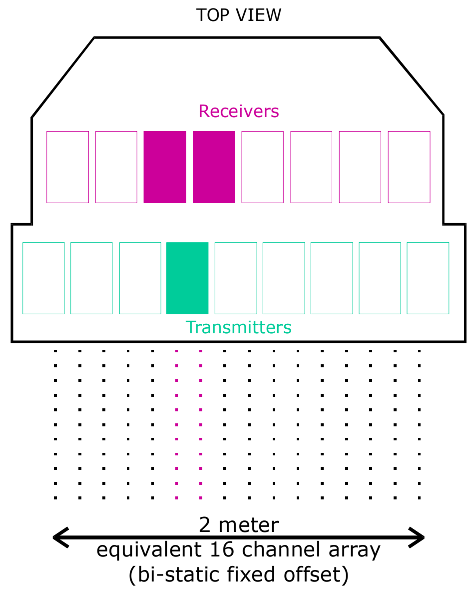

Figure 1: (Left) Photo of the CART Imaging System towed by a vehicle. (Right) Schematic top view of CART antenna array, which distributes 16 standard GPR channels over a 2 m swath, considering a bi-static fixed offset data acquisition

Processing the raw radar data into images involves several steps. Data are filtered with pre-processing algorithms that align traces in each channel and balance channels with filters that remove static shifts and match the mean (or median) response across channels. The pre-processed data are then merged with geometry data, gridded and migrated to produce 3D radar images of the subsurface (Oristaglio *et al*.[7]; Hansen and Johansen [8]). A typical final product consists of slices through the radar image, along with extracted features (e.g., interpreted utility lines coded in depth) that are rendered in a CAD (Computer Aided Design) system. These final maps can be merged with client CAD drawings if available.

CON-EDISON AND WORLD TRADE CENTER SURVEYS IN NEW YORK CITY

A pilot project to test GP*i*R on a large-scale in New York City was carried out for ConEdison in December 2000. Data were collected during four nights; each night covered about 3000 m^2 (30,000 ft^2) of road surface for a total of about 12,000 m^2 (120,000 ft^2 or nearly 3 acres). The final acquired data grid (after merging geometry information) had a spacing of 10 cm in-line (i.e. in the direction of individual channel profiles) and 15 cm crossline. Positions of surface features—curbs, street signs, valve and manhole covers—were mapped to provide a reference grid for the radar images.

The feature of most interest to ConEdison for mapping was a high-voltage transmission line ("*oil-o-static*") that runs along 149th Street and up Prospect Avenue. Many other utility conduits crisscross the intersection. In addition, tests pits dug in May 2000 had uncovered buried trolley tracks along 149th Street, west of the intersection with Prospect. The dense and complex underground network poses a huge challenge to precision mapping on such a large scale. A merged image covering the entire area surveyed was produced on a 3 in (7.6 cm) horizontal grid down to a depth of 96 in (2.4 m) in 1 in (2.54 cm) depth increments. Figure 2 shows a typical large-format depth slice.

The most prominent features in the shallow images slices are pairs of buried trolley tracks running along 149th Street and along Southern Boulevard. The full pattern of branching and intersecting trolley tracks under 149th Street—especially the complex junctions near the three-way intersection—is especially impressive in the full image at 12 in depth (Fig. 2). The buried trolley tracks along Southern Boulevard show up most clearly in the slice at 18 in depth. The presence of buried tracks along 149th Street was known from test pit records; there were no (available) records of the tracks along Southern Boulevard.

Also prominent in these slices are numerous trenches containing buried utilities. The trench containing the *oil-o-static* line runs east to west along 149th Street (near the south curb) and then curves north up Prospect Avenue, best seen in the 36 in depth slice. Clearly visible at this depth and scale is the trench of a second *oil-o-static* line along Prospect Avenue, east of the first one.

One more trench (unidentified in the conduit map) runs between the two islands in the intersection and crosses both the *oil-o-static* and gas lines. Many other trenches and conduits crisscross the intersection. In addition, most (if not all) of the test pits previously dug by ConEdison are clearly visible as rectangular patches in the image (e.g. the pit just west of the intersection of 149th Street and Prospect Avenue).

Another large-scale project was initiated to help in recovery and engineering work at the World Trade Center. Streets surrounding the World Trade Center were surveyed with the CART system to map utilities and assess damage to subsurface structures that may have been caused by the collapse. Large-scale images similar to the one in Fig. 2 were produced from these surveys.

SUMMARY AND CONCLUSIONS

This paper introduces ground-penetrating *imaging* radar (GP*i*R) as a new technology (and terminology) for efficient radar mapping of the shallow subsurface on a large scale. GP*i*R combines standard GPR with precise positioning control and advanced signal and image processing to create high-resolution 3D radar images of the first 2 to 3 m below the surface (in typical organic soils; penetration in dry, sandy soils can be as deep as 6 to 7 m). Radar images of the subsurface—and features extracted form them—can provide permanent digital records to monitor infrastructure in place or plan new installations.

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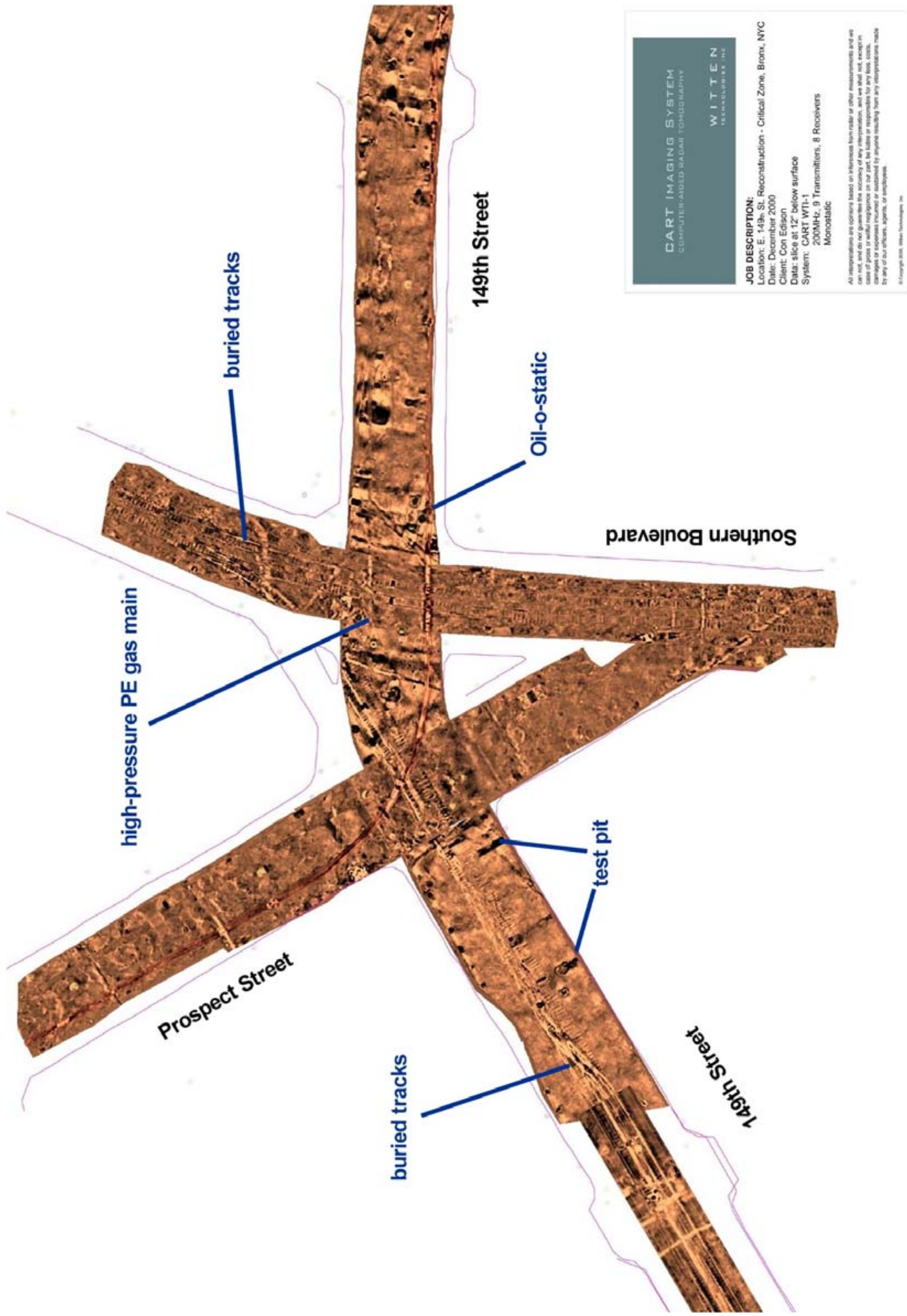

Figure 2: Twelve inch depth slice of migrated CART radar data from Bronx survey. Area covered is approximately 12,000 m^2.