A new WebGIS approach to support ground penetrating radar deployment

Mémoire

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Résumé

En raison de l'agglomération complexe des infrastructures souterraines dans les grandes zones urbaines et des préoccupations accrues des municipalités ou des gouvernements qui déploient des systèmes d'information foncière ou des industries qui souhaitent construire ou creuser, il devient de plus en plus impératif de localiser et de cartographier avec précision les pipelines, les câbles d'énergie hydroélectrique, les réseaux de communication ou les conduites d'eau potable et d'égout. Le géoradar (Ground Penetrating Radar ou GPR) est un outil en géophysique qui permet de produire des images en coupe du sous-sol desquelles de l'information utile sur les infrastructures souterraines peut être tirée. Des expériences antérieures et une analyse documentaire approfondie ont révélé que les logiciels disponibles pour réaliser des levés GPR qui sont utilisés directement sur le terrain et hors site ne reposent pas ou très peu sur des fonctionnalités géospatiales. En outre, l'intégration de données telles que la visualisation de données GPR dans des espaces géoréférencés avec des orthophotos, des cartes, des points d'intérêt, des plans CAO, etc., est impossible. Lorsque disponible, l'ajout d'annotations ou l'interrogation d'objets géospatiaux susceptibles d'améliorer ou d'accélérer les investigations ne proposent pas des interfaces conviviales.

Dans ce projet de recherche, une nouvelle approche est proposée pour déployer le GPR et elle est basée sur quatre fonctionnalités issues du Web et des systèmes d'information géographique (WebGIS) jugées essentielles pour faciliter la réalisation de levés GPR sur le terrain. Pour démontrer la faisabilité de cette nouvelle approche, une extension de la plate-forme logicielle existante GVX (conçue et vendue par Geovoxel) appelée GVX-GPR a été développée. GVX-GPR propose aux utilisateurs d'instruments GPR quatre fonctionnalités soit 1) intégration de cartes, 2) géo-annotations et points d'intérêt, 3) géoréférencement et visualisation de radargrammes et 4) visualisation de sections GPR géoréférencées. Afin de tester l'approche WebGIS et GPX-GPR, deux sites d'étude ont été relevés par deux professionnels différents, un expert et un non-expert en géophysique, ont été sélectionnés. Une première expérimentation réalisée sur le campus de l'Université Laval à Québec prévoyait l'identification de trois objets enterrés soit un câble électrique, une fibre optique et un tunnel dont leur position XYZ était connue. Le deuxième essai s'est passé à l'Universidade Federal do Rio de Janeiro (Rio de Janeiro, Brésil), avec un professionnel expert en géophysique. Ce 2^{e} site cherchait à reproduire un environnent plus réaliste avec une quantité inconnue d'objets enterrés.

Les quatre fonctionnalités proposées par GVX-GPR ont donc été testées et leur intérêt discuté par les deux utilisateurs GPR. Les deux utilisateurs GPR se sont dits très intéressés par l'outil GVX-GPR et ses nouvelles fonctionnalités et ils aimeraient pouvoir l'intégrer à leur travail quotidien car ils y voient des avantages. En particulier, l'approche et GVX-GPR les a aidés à découvrir de nouvelles cibles, à délimiter le territoire à couvrir,

à interpréter les données GPR brutes en permettant l'interaction entre les données géospatiales (en ligne) et les profils de données GPR, et finalement pour la cartographie à produire tout en respectant la norme CityGML (donc utile au partage éventuel des données). De même, une fois le système maitrisé, GVX-GPR a permis d'optimiser la durée du levé.

Ce projet de maitrise a donc permis d'élaborer une nouvelle approche pour effectuer des levés GPR et proposer un outil logiciel pour tester la faisabilité de celle-ci. Une première étape de validation de la faisabilité et de l'utilité a été réalisée grâce aux deux tests effectués. Évidemment, ces deux tests sont des premiers pas dans une phase plus large de validation qui pourrait s'effectuer, et ils ont ouvert la porte à des ajustements ou l'ajout d'autres fonctionnalités, comme la manipulation des outils de visualisation 3D et l'ajout de filtres et traitement de signal. Nous estimons néanmoins ces premiers tests concluant pour ce projet de maîtrise, et surtout ils démontrent que les instruments GPR gagneraient à davantage intégrer les données et fonctionnalités géospatiales. Nous pensons également que nos travaux vont permettre à des communautés de non spécialistes en géophysique de s'intéresser aux instruments de type GPR pour les levés d'objets enfouis. Notre approche pourra les aider à préparer les données géospatiales utiles à la planification, à effectuer le levé terrain et à produire les cartes associées.

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Abstract

Due to the complex agglomeration of underground infrastructures in large urban areas and accordingly increased concerns by municipalities or government who deploy land information systems or industries who want to construct or excavate, it is imperative to accurately locate and suitability map existing underground utility networks (UUN) such as pipelines, hydroelectric power cables, communication networks, or drinking water and sewage conduits. One emerging category of instrument in geophysics for collecting and extracting data from the underground is the ground penetrating radar (GPR). Previous experiments and a thorough literature review revealed that GPR software used in and off the field do not take advantage of geospatial features and data integration such as visualization of GPR data in a georeferenced space with orthophotographies, map, point of interest, CAD plans, etc. Also missing is the capability to add annotation or querying geospatial objects that may improve or expedite the investigations. These functions are long-lived in the geospatial domain, such as in geographic information system (GIS). In this research project, a new approach is proposed to deploy GPR based on four core WebGIS-enabled features, used to support field investigations with GPR. This WebGIS is based on an existing platform called GVX, designed and sold by Geovoxel as a risk management tool for civil engineering projects.

In this proposed approach, a generic guideline based on GVX-GPR was developed which users can follow when deploying GPR. This approach is based on four core features which are missing on most GPR software, (1) map integration, (2) geo-annotations and points of interest, (3) radargram georeferencing and visualization, and (4) georeferenced slice visualization. In order to test the designed WebGIS-based approach, two different professionals, an expert in geophysics and a person without any background in geophysics, used the proposed approach in their day-to-day professional practice. The first experiment was conducted at Université Laval (Québec – Canada) when the subject undertook an area to a survey in order to identify 3 possible targets pre-mapped. The second, with a Geophysics-specialist, took place in Rio de Janeiro, at Universidade Federal do Rio de Janeiro's campus. This study covered an area counting on an unknown number of buried objects, aiming at reproducing a realistic survey scenario.

Four new feature were added and discussed with GPR practitioners. Both GPR user declared to be very interested by the proposed by the tool GVX-GPR and its features, being willing to apply this software on their daily basis due to the added advantages. Particularly, this approach has aided these professionals to find new buried objects, delimit the survey area, interpret raw GPR data by allowing geospatial data interaction and GPR profiles, and, finally, to produce new maps compliant with standards such as CityGML. Also, once mastered, the technology allowed the optimization of survey time.

This project enabled the development of a new approach to leverage GPR surveys and proposed a new tool in order to test the approach's feasibility. A first step into the validation of this proposal has been taken towards a feasibility and utility evaluation with two tests accomplished. Unmistakably, these are the first steps of a likely larger validation process, opening up new possibilities for the continuity of the project such as the addition of signal processing techniques and 3D data handling. We nevertheless consider these conclusive for this master's project, above all demonstrating the value add by geospatial data integration and functions to GPR instruments. This work is also intended to the community of newcomers, or interested in GPR, to further explore this technology, since this approach shall facilitate the preparation, execution, and post-processing phases of a GPR survey.

Table of contents

List of Figures

List of Tables

List of abbreviations and acronyms

ADE – Application Domain Extension

ASCE – American Society of Civil Engineers

CAD – Computer-Aided Design

CSA – Canadian Standards Association

ETL – Extract, Transform, and Load

GIS – Geographic Information System

GPR – Ground Penetrating Radar

MVC – Model, View, Controller

MVP – Minimal Viable Product

UML – Unified Modeling Language

UUN – Underground Utility Networks

XP – Extreme Programming

A goal is a dream with a deadline.

Napoleon Hill

Acknowledgements

First, I would like to thank the people who actively helped me to pursue my studies and help me in this journey of coming to a new country, learning a new language, and being introduced to a culture I didn't know.

First of all, I would like to wholeheartedly thank Ms Jacynthe Pouliot, my professor, research director, and, most of all, friend, for every minute spent helping me out, correcting my errors, guiding me through the steps of carrying out a research project of this magnitude. Without you guidance and your trust, I wouldn't have succeeded.

A special thanks to Louis-Martin Losier, for having indicated me, worked with me, actively participated in my studies and research subjects, and also being a friend, with a lot of compassion through the roughest moments.

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Finally, thanks to my family and friend (in Brazil), who even far far away, never let me have the feeling of being alone.

Paulo G. Tabarro

Foreword

This dissertation presents a novel approach to the deployment of Ground Penetrating Radar in order to properly locate and map underground utility networks. Initially, this research was projected to develop a technology which would be an integrating part to a real-time display of GPR's. Finally, in the beginning of 2017, with my conversations with Prof. Jacynthe Pouliot, vice dean of research at the faculty of forestry, geography, and geomatics at Université Laval, and Louis-Martin Losier, PhD in environmental geotechnics, we noticed the potential to have Geovoxel's existing solution developed until a level that it would not be a real-time display for GPR's but a tool to help the end-to-end process. With the help of Prof. Richard Fortier, co-director of research, professor, and director of the Centre d'études Nordiques, and his expertise in GPR, we were able to delimit a project and scope for this Master's project. This project is framed within the research of Prof. Jacynthe Pouliot, funded by the Natural Sciences and Engineering Research Council of Canada. Along this funding, Geovoxel Inc. has also contributed to its funding through a Mitacs Accelerate scholarship.

All the results presented in this dissertation were obtained during experiments, with openly accessible data sources, and open license software/tools. Some of the assumptions utilized as basis for its problematics and motivation were conducted by the research team in the past years previous the project debut. For instance, Prof. Jacynthe Pouliot's contribution to the evaluation of user needs when visualizing underground utility networks on cartographical interfaces and Jean-Michel Lavoie's research based on the use of GPR for land information systems. From their results and conclusions, the research team and I, we have designed, planned, executed, and tested the software and approach in question.

After the first user experiment conducted in the autumn 2017, we submitted a first conference publication, which took place in October 2017, in Melbourne – Australia. This first extended abstract presented the first results obtained and the evaluation process which guided us through our proposition. The published extended abstract information is found below.

Title: A WebGIS to Support GPR 3D Data Acquisition: A First Step for the Integration of Underground Utility Networks in 3D City Models
Conference: 12th 3D Geoinfo Conference
Date: 26-27 October, 2017
Type: Extended Abstract
Authors: Paulo Guilherme Tabarro, Jacynthe Pouliot, Richard Fortier, Louis-Martin Losier
Open access: Yes
Status : Accepted and Published

Available online: https://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XLII-4-W7/43/2017/isprs-archives-XLII-4-W7-43-2017.pdf

Publisher: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences

Volume/Issue: XLII-4/W7

A second user experiment, providing more solid results for the research was conducted in January 2018, at Universidade Federal do Rio de Janeiro (Brazil) with the partnership of Geovoxel Brazil. These results along with data processing and interpretation provided the team with further material for a second manuscript which has been submitted to an international journal presenting a closer to complete overview of the research project. The information about this manuscript are presented below.

Title: Detection and location of buried infrastructures using ground penetrating radar: An original approach based on GIS and data integration

Journal: International Journal of 3-D Information Modeling (IJ3DIM)

Date: under review (accepted with major modifications)

Type: Paper

Authors: Paulo Guilherme Tabarro, Jacynthe Pouliot, Richard Fortier, Louis-Martin Losier

Open access: No

Status: Under revision, previously accepted with major corrections

Publisher: IGI Global eEditorial Discovery

Chapter 1 - Introduction

1.1 Underground Utility Networks (UUN)

As the cities worldwide are keeping a fast-paced growth, the utilities supplied to the population such as Internet, hydroelectricity, sewerage, water, etc. are growing just as much (Aydin, 2008; as cited in Jeong et al., 2004, p. 225). Simplistically categorizing infrastructures, they can be found above the ground level and in the underground. Often, infrastructures under the ground such as cables, pipes, ducts, etc., are referred to as Underground Utility Networks (UUN). An example of a complex UUN located in downtown Rio de Janeiro, Brazil, is shown in Figure 1.1. Due to the increasing apprehension of underground utility's damage, a practice called Subsurface Utility Engineering, formalized by ASCE (2002), has been proposed, introducing a new framework to manage risk by identifying and assuring quality of underground utilities (CSA, 2011, p. 4).

When building houses, edifices, pavement as well as expanding these structures, it is of extreme importance to identify, beforehand and during trenching activities begin, how structures are laid on the subsoil (Costello et al., 2007; Lew and Anspach, 2000; Metje et al., 2007). This is related to social-economic impacts to business and inconveniences to the population when the unknown UUN are damaged during excavation. The awareness of UUN location upon digging ensures population of reliable supply of services such as hydroelectricity, internet, water pipes, water pipes, and gas pipelines (Info-excavation 2015; Tan and Looi, 2013). A great number of the functioning infrastructures were built years or decades ago, when mapping technologies were not as mature as nowadays and standards were not outlined or widespread. Due to this inherited lack of knowledge of what is under the ground, ground disturbances pose an imminent risk for governmental and private stakeholders as well as households when planning and executing developmental projects, since they can cause damages to UUN and disrupt essential services such as drinking water and electricity to the population. Ground disturbances are defined as digging, excavation, trenching, ditching, tunneling, boring/drilling/pushing, augering, topsoil stripping, land levelling/grading, and plowing for several purposes such as the installation of new UUN (CSA, 2011, pp. 3). In the province of Ontario, Canada, the Occupational Health and Safety Act and Regulation for Construction Projects imposes that any trenching activity exceeding certain limits such as $50,000 of project cost, 1.2 m deep, and 30 m long, etc., has to be notified by a Notice of Trench[1]. In Canada, the social-related costs due to damages to UUN have been estimated at almost one billion CAD/year (CCGA, 2016). In an assessment study of US/UK-based companies, contractors, and clients presented by Metje et al. (2007), seven companies have had 4017 utility-related incidents over a four-year period from 2010 to 2014. According to Bernold (2003), public and private services are experiencing negative effects from these incidents, and at least $1 is saved from every $1 spent in

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[1] https://www.labour.gov.on.ca/english/hs/sawo/pubs/fs_trenches.php

prevention when services keep running following a ground disturbance, without major impacts to population, businesses, and governmental organizations. In Figure 1.1, ground disturbances without a good mapping of the UUN available before the excavation would likely result in severe damages to the utilities and disrupting the services.

In addition, if none or inaccurate information is available about the UUN during ground disturbances and when an utility is affected, the question falls into who is responsible for the repairing costs and as well as the deficient service to the population, since 80% of the damage caused to subsurface infrastructure caused an interruption of service in Quebec (Info-Excavation, 2015).

Ideally, in order to avoid these extra costs, accidents, and damages to UUN, before the beginning of any ground disturbance, engineering companies and households should be able to have ample access to unified UUN database resources of the surrounding areas targeted to be disturbed (Girard and Pouliot, 2015). This mapping resources should offer enough spatial information for the operators of the construction to be able of avoiding any types of hazards. This information must give the users the ability to geographically identify objects and their characteristics. In other words, users have, with minimal effort, access to information on the objects' location, depth, gage, and function of the UUN belonging to the delimited project area.

Figure 1.1: A complex UUN underground environment (Courtesy of Geovoxel).

1.2 Detecting and Mapping UUN

The importance of properly locating and mapping underground infrastructures is brought, more and more, to public and private organizations. Two questionnaires on the innovation in locating and characterizing UUN from the Transportation Research Board in Washington D.C. illustrate some of the problems faced by utility directors, representing 34 states of the US (Sterling et al., 2009). In the first questionnaire, the issues for not accurately mapping underground utilities are discussed while, in the second one, the best practices in locating and characterizing the most problematic underground utilities are presented. Based on the results presented in these questionnaires, the cost, time, and lack of management are the largest issues related to the proper location of UUN. However, two statements seem extremely relevant for the purpose of the research undertaken herein. Nine among twenty six responders affirmed that getting accurate information on UUN from specialized consultants and current equipment to locate UUN are not enough good. The follow up comments in these questionnaires are of equal or higher relevance and strengthen the importance of the research project presented in this M.Sc. thesis (Sterling et al., 2009):

- Develop public geospatial databases.
- Get high-quality mapping early in any engineering project involving ground disturbances.
- Require professional survey to accurately locate UNN for as-built information.
- Mandate use of the Standard Guidelines for the Collection and Depiction of Existing Subsurface Utility Data.

This problematic presented by Sterling dates from 2009, however, this scenario does not seem to have been reverted. For instance, in 2017, Info-excavation reported over five damages per business day in the province of Québec, Canada, implying a raise of 11% in the number of damages relative to 2016, which already represented a CAD$123 million in social-economic-related direct and indirect costs (Info-excavation, 2017). According to Info-Excavation, from 2009 to 2017 (Figure 1.2), the number of damages per year has not yet represented any significantly drop. Despite current efforts, such as in the city of Montreal[2] where new procedures for the mapping of exposed structures are being made, numbers might still display a significant linearity before the results of these practices are yielded.

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[2] https://ville.montreal.qc.ca/executiontravaux/file/360/download?token=8Tphm90A

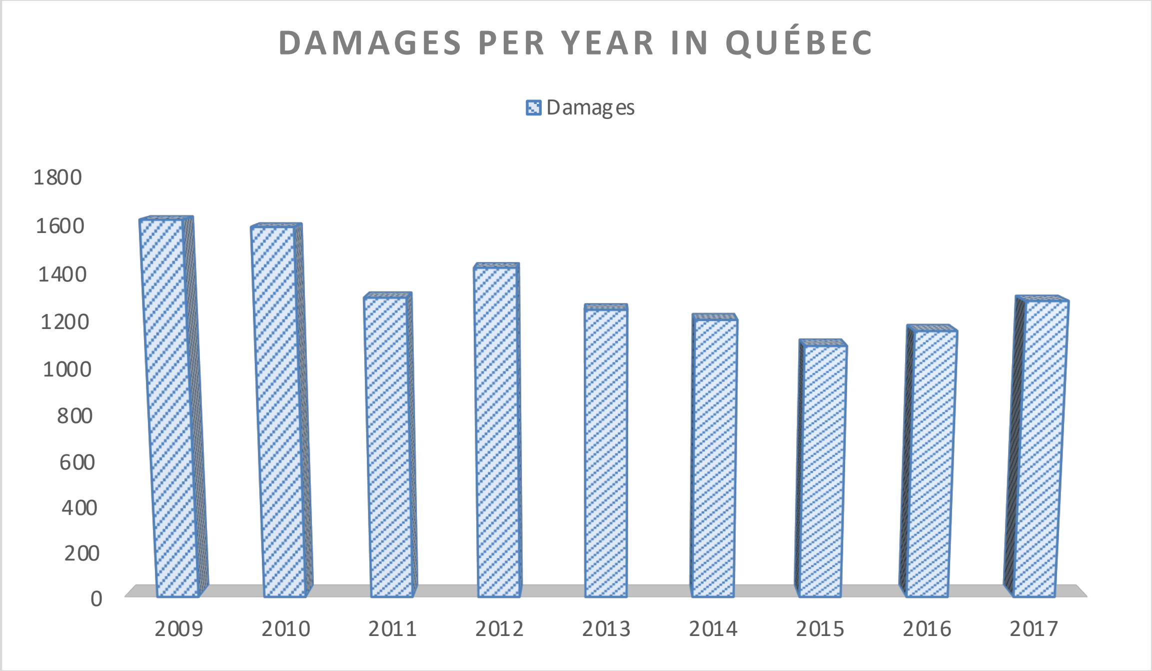

Figure 1.2: Damages per year in the state of Quebec according to Info-Excavation.

The linear behavior of the number of accidents can be attributed to multiple factors. However, it reveals that, to date, despite the standards and procedures being created, either the community is still absorbing/comprehending the importance and laying out strategies of best practices at their fullest. Another likely reason can also be the number of developments being conducted along the years, resulting in the market of SUE could not being able to provide enough proficient workforce to achieve better numbers. Moreover, outside the infrastructure and land management community, the population as a whole plays an important role in the awareness of the need for proper location of underground object prior excavation.

In case of non-existing documentation, a solution which has been largely adopted is to perform non-destructive surveys such as Ground Penetrating Radar (GPR) profiling, radio detection, and electrical resistivity tomography, aiming at collecting underground images or signals for geographical, dimensional, and compositional aspects of buried objects (Samet et al., 2017, pp. 1). With such information, it is possible to represent UUN georeferenced data in maps and geospatial software with the main goal of providing the users with a robust understanding of the UUN before ground disturbances.

The GPR is one of the widely accepted and most technological methods to gather subsurface data (Jaw and Hashim, 2013, p. 21). It uses electromagnetic signal transmitter and receivers to produce subsurface image under the form of cross-section along GPR survey line in which electromagnetic interferences due to UUN are identified. Prior to start GPR acquisition, a GPR practitioner, professional or non-professional GPR operator, has the needed documentation for identifying area of coverage, hypotheses, and possible targets. With these documents in hand, the GPR operator is expected to carry out data acquisition in a given region of interest. After understanding the survey goals to locate UNN and assessing the terrain accessibility, the GPR operator usually divide the area of coverage into blocks and, subsequently, determine a mesh, which depending on the covered area and the targeted utilities is spaced by regular intervals as guidelines (Figure 1.3).

Figure 1.3: A fictitious GPR mesh showing the line pattern followed by a GPR operator.

The need for a mesh can be explained by the orientation of objects buried in the underground. Porsani (2010) showed that some objects, such as a steel pipe, are not very reflective when the antenna orientation is in parallel with the object orientation. Jaw and Hashim (2013) carried out experiments and simulations to evaluate which methods to deploy GPR survey were the most appropriate (along the object, across the object) one. For given cases, GPR survey performed along the object orientation can provide clearer results depending on the amount of objects buried in the area.

During data acquisition in the field, as a rule a thumb almost independently applied on the nature of the project, the GPR operator follows equally spaced intervals but also avoids all obstacles found along the survey lines. The images generated from the equally spaced GPR survey lines are then interpolated and transformed from single 2D cross-sections (Figure 1.4).

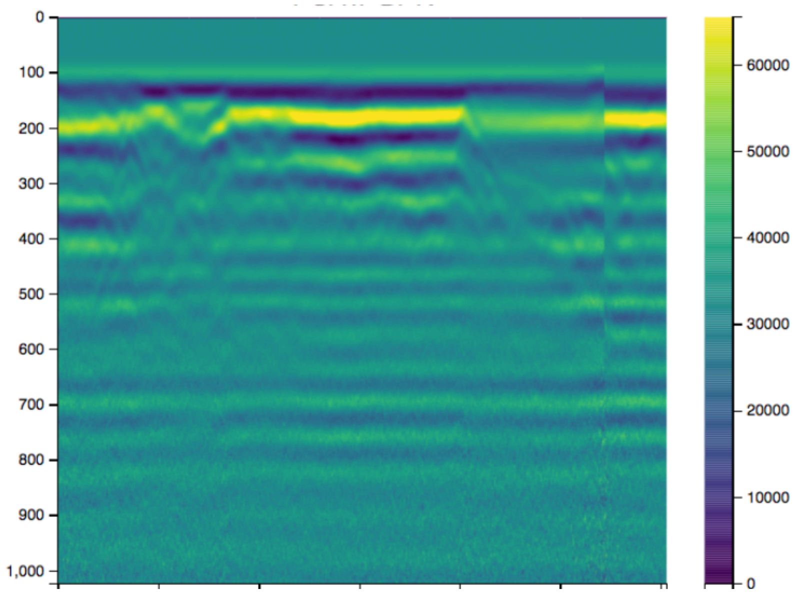

Figure 1.4: Example of a GPR radargram profile and a 3D cube generated from the interpolation of multiple profiles.

Currently, most of the GPR technologies count on annotations on profiles to demark likely targets on the profiles, feature which is usually combined with hyperbola fitting. Some companies have also taken steps forward and allowed users to directly translate these annotations into geo-annotated points, mitigating user error when translating a location from a GPR profile to a real-word coordinates. An example (Figure 1.5) IDS's Opera Duo, which displays on a map the points annotated by GPR users.

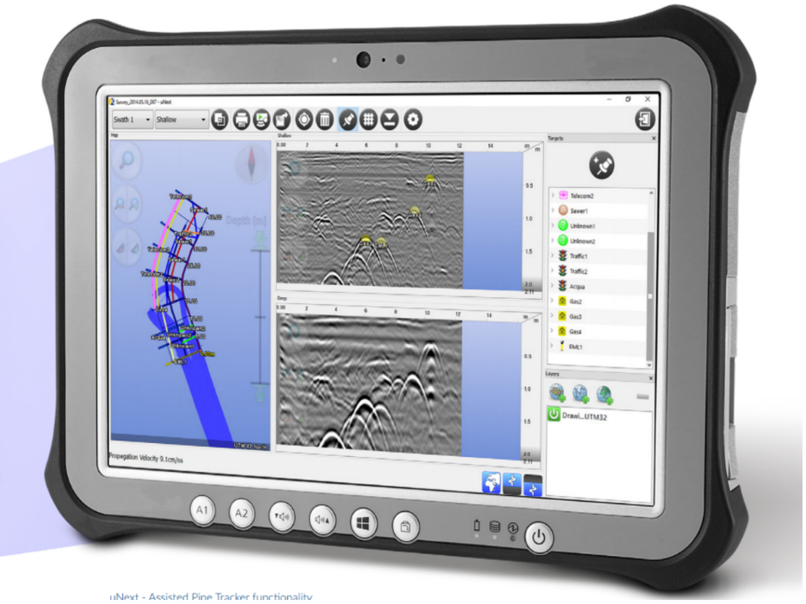

Figure 1.5: uNext by IDS displaying a multiple-view screen with geo-referenced features on the left side and GPR radargrams on the right-hand side.

With multiple profiles combined through interpolation methods and profiles annotated with targets, these electromagnetic signals become a 3D GPR cube. With these profiles as cross-sections and 3D cube in hands, the GPR operator perform the interpretation of electromagnetic interferences and may be able to draw conclusions about the presence of likely UUN. Figure 1.6 is the representation of interpreted results directly in a 3D cube environment with the software RADAN.

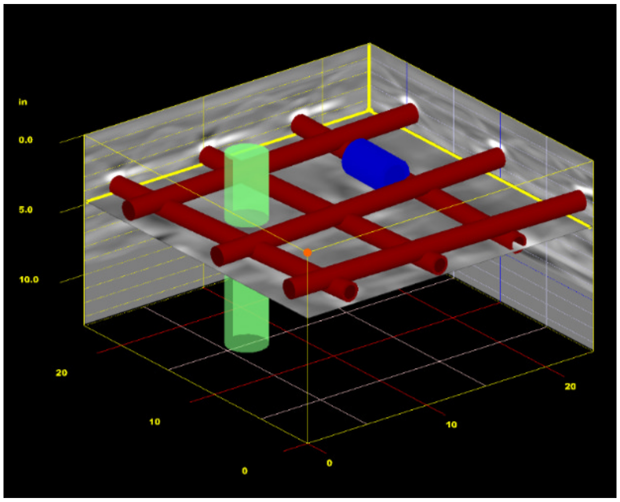

Figure 1.6: 3D data manipulation on RADAN[3] (Geophysical Survey Systems, inc.).

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[3] https://www.geophysical.com/software

Apart from GPR, other technologies are used independently or interchanged with each other (and GPR) when detecting underground utility networks (Desai et al., 2016):

1. Induction utility locators: the most common survey method for UUN, even though it requires either an existing background signal or an induced current. In a trial and error deployment, induction locators are capable of detecting most power cables but not water mains, PVC pipes, etc, if not added by an induction generator;
2. Acoustic location method: also trial and error-based, utilizes an acoustic to identify sounds introduced into the mean, which usually is a liquid or a gas;
3. Magnetic locators: use objects' magnetic properties to locate them, which can be applied to networks with limited applicability;
4. Magnetic surveys: measures soil disturbances to earth's magnetic field (using the magnetized materials).

1.2.1 Standards and Procedures

Worldwide, the initiatives for properly formalizing practices and quality of data for SUE have been emerging over the last decade. In the United States, the American Society of Civil Engineering has proposed the standard ASCE 38-02 which describes four levels of quality and their means of acquisition. Both Canada and Malaysia[4] have similarly followed the framework and implemented the respective standards CSA S250 and the Standard Guideline for Underground Utility Mapping. The American and Canadian standards not only propose methods but also standardize how data is represented (ASCE, 2002; CCGA, 2014; CSA, 2016).

These standards recommend that engineers have to talk and define with companies both the level of quality and the deliverable expected and recommend improvements of level of quality for certain areas that seem worth reviewing. According to ASCE 38-02, the levels of quality defined are as follows.

- Level of Quality A: The position and dimensions of the infrastructure are measured by the actual exposure of the infrastructure. A least-possible excavation is performed to avoid damage to these infrastructures. A recommended accuracy is usually of 15mm.
- Level of Quality B: Site undergoes survey(s) with geophysical methods. The tolerance of the accuracy is stablished by the project owner.
- Level of Quality C: Based on the visualization of external infrastructures (manholes, poles, etc.), a professional correlates these items to conclude where utilities are located.

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[4] http://pejuta.com.my/wp-content/uploads/2015/06/Standard-Guidelines-For-Underground-Utility-Mapping-JUPEM.pdf

- Level of Quality D: Information from existing records and oral collections

In the UK, BSI has proposed, alongside clients and contractors, a thorough guide for data acquisition of the underground. It lays a framework for quality levels' requirements and the procedure recommended to achieve so, in a more detailed manner, varying from verification of the exposed infrastructure to simply accessing previously mapped data on location analytics solutions. The standards proposes levels of quality ranging from A to D, like the previous ones. However, what differentiates this standard from the ones previously mentioned is the enforcement of survey-specific parameters in order to achieve expected qualities of data B, which is broken down to four new categories. This is done by categorizing which type of survey the site will receive. For instance, the standard describes that to achieve a level of quality for survey methods B1 (the highest), with single/multi-channel GPR, users would be required to perform a 1m grid. The quality levels are defined are follows:

- B1: Accuracy level of 15cm
- B2: Accuracy level of 25cm
- B3: Accuracy level of 50cm, with or without depth
- B4: No level of accuracy defined. Infrastructure is believed to be buried but without conclusive evidence

As what can be considered as the single most important point of converge between these standards is the fact that all of them proposing as the best practice, the mapping UUN's while they are still exposed, aiming to avoid costs and errors that are tightly correlated to other acquisition methods.

1.3 Problematic

Although the use of GPR to locate UUN is growing in popularity, their manipulation is not trivial and GPR data interpretation still stands as a great barrier for skilled and unskilled GPR practitioners (Cassidy, 2009; Jol 2008; Rahman and Zayed, 2016; Li, 2015). As claimed by Cassidy (2009) "Unfortunately, the ease of both use and data interpretation is also GPR's pitfalls, as many inexperienced practitioners fail to fully appreciate the true nature of GPR wave propagation and its interaction with the subsurface materials". Also, as noted by Rahman et al (2016) as "highly subjective and time consuming". According to previous experiments at Laval University and requirements' gathering with a specialist (Lavoie and Pouliot, 2016; Rodrigues, 2016), even the first steps of a survey, such as getting a GPR survey started, are not always a straightforward subtask and may be very toilsome due to the difficulties of identifying which area will be surveyed, lack of or poor documentation, and landscape changes. As mentioned by Rodrigues (2016), the vast majority of public organizations in South America still rely on paper CAD plans as database, where annotations are written on for updates in the project.

Taking the province of Québec as an example, a system called FITNO[5], which is the register of public service networks, provides information on which companies may own buried infrastructures in a given area, but this register does not offer a geographical interface to visualize UUN's on a map (Pouliot et al., 2015). Another source of information for underground cadastral data is a Quebec's "call before dig" service called Info-Excavation. This organization, formed as a consortium of companies but managed as a separate institution, offers a service free of charge which demands from utility owners to indicate, with ground marks or documentation, where their infrastructure is located. In the case of missing records or unprecise information, the area has to undertake re-surveying.

In the case of surveying being a requirement and GPR the choice for this data acquisition, a time-consuming interpretation process takes place and may last up to three times longer than the fieldwork, generally done with highly specialized software, in a stage called post-processing phase (Benedetto and Pajewski 2015; Jol, 2009; Rodrigues, 2016). As a result, during the interpretation phase, if a survey appears to be lacking information, the GPR operator has to return to the surveyed site to gather the missing information, adding costs and time to the project execution.

Based on previous experiments with various GPR instruments and software (Lavoie and Pouliot, 2016) and literature review revealing efforts for integrating GPR and GIS (Dallaire and Garneau, 2008; Li et al., 2015; Themistocleousa et al., 2015; Talmaki et al., 2013; Tischler, 2003; Zheng et al., 2004), only a limited number of GPR software offer capacities for spatial data visualization and overlaying GPR data with other sources of data. Even though most GPR's have an interface capable of showing the data collected in real time, operations using this interface such as signal processing, hyperbola fitting, geographic interaction such as adding annotation, attribute or metadata, drawing line and box, or querying spatial database are very limited, if they exist at all. GPR data are often not georeferenced in an official coordinate system, which limits the capability for integrating such data with multiple sources of valuable spatial data. Some GPR instruments allow GPS to be integrated for real-time georeferencing images (Li et al., 2014; Rial et al., 2006), but yet, GPS signal in urban areas is highly disturbed or even absent due to a dense number of buildings and interferences from radio emissions[6].

As debated in Lavoie and Pouliot (2016), besides the need of geospatial tools not only to empower GPR surveys but provide ample access to this information, a comparative assessment of the visualization of underground utility networks on map-based interfaces was performed by the research team. Four distinct issues have been identified: (1) cadastre mapping of UUN is missing geospatial data and put management of rights,

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[5] https://foncier.mern.gouv.qc.ca/Portail/notaires-avocats/inscription-au-registre-foncier/fitno/

[6] https://www.gps.gov/spectrum/

responsibilities, and restrictions associated to such objects at risk, (2) GPR data and instruments are very relevant for such data acquisition, (3) most land-surveyors have limited skills regarding manipulation of GPR instruments and data, and they are not able to appreciate the value of such source of information/equipment, (4) current GPR's operators do not really know/worry about having georeferenced data or applying integrated and standardized geospatial database or GIS approaches or innovative solutions like augmented reality visualization. Additionally, a market assessment, made by Geovoxel in Brazil, revealed that among 13 companies that offer GPR survey as a service, none of them offered to its customers geospatial deliverables, but CAD plans instead. CAD plans are a spread 2D/3D technology for technical drawing and annotation designs. In addition, industrial and governmental customers of GPR services' providers often rely on old-fashioned CAD documents as data source, frequently stored it in paper format or unstructured and unsystematic ways (Beck & Stickler 2009; Jeong et al., 2004).

Despite of CAD's acceptance and diffusion for representation of UUN outside the blueprint's world, manuals and standards provide proper guidelines for geospatial data collection, mapping, and representation of UNN (ASCE 2002; CCGA 2014; Chen and Cohn 2010; CSA, 2011, 2016; Metje et al., 2007). Some manuals go as far as outlining the density of survey lines required in order to achieve higher data accuracy levels (BSI, 2008). Following studies such as Thomas et al. (2009), stakeholders are not satisfied with levels of accuracy superior of 100 mm. Other requirements regarding depth show that GPR imposes limitations when targets are at depths larger than 3 m (in scarce cases), thus imposing even higher standards for data precision. Despite of their existence, studies still reveal a linear behaviour of the number of strikes (such as in Figure 1.2). This may be due to many reasons, but it is rational to conclude that either standards do not propose enough procedures or that GPR professionals are yet unaware of their importance. Currently, these communities (SUE engineers, geophysicists, geomaticians) do not frequently work collectively; even though the society in general would greatly benefit of such collaboration.

Finally, the partner in this research project presented herein, Geovoxel Inc., is a company that offers GPR expertise and also a platform-as-a-service called GVX for managing risk in construction sites and infrastructures at risk. This platform is a software which integrates real-time sensors and performs multidimensional analysis by crossing this data with existing underground map information such as geology, hydrology, etc. According to Geovoxel's needs and perception of its technological improvements for the future, integrating GPR data into GVX is a very appealing selling point. Currently, GVX does not support GPR data or its acquisition, and so it utilizes existing GPR software for carrying out data processing, extraction, transformation, and load (ETL). Geovoxel would like to offer a more complete solution to its clients such as more sophisticated ways to acquiring, processing, and visualizing GPR data.

To better identify the needs of GPR practitioners, a series of questions about the software used by their GPR operators when surveying and the deliverables which they have to provide to their clients have been submitted to two companies (not disclosed for privacy reasons). The answers to these questions are given in Table 1.1. According to the two interviewed GPR users, representing their respective company, they mostly perform simple surveys to find a single buried infrastructure in a parcel. However, the lack of geospatial software integration is an important limitation. In question 2, they use standalone software which requires the use of a computer in the field for processing and interpretation purposes if required. This is unpractical for production levels. In addition, only the GPR Slice software relies on geospatial features according to the available markers on site. This software also depends on internet connection and does not allow users to draw directly in a georeferenced environment to generate standard-compliant data. Most of the maps generated during surveys by both GPR practitioners are handmade maps and used to support a report when needed, but most of the time, the data lifecycle ends as a soil mark, and not in a structured database which has to be supplied to governmental agencies and notaries who may use it for cadastral purpose. And, finally, the users showed a great interest in trying the new proposed solution and would be willing to test this solution.

Table 1.1: Questions and answers about software and deliverables submitted to two companies.

	Company A	**Company B**
Role	GPR Operator	GPR Operator and Geophysicist
Area	Connecticut	New York
1) When you go on site for a survey, what do you take with you?	Not too many complicated products (not even processing software).	Most of the time only rebars take processing, since the other ones are a single buried object in the parcel.
2) Which software do you use to do data interpretation?	RADAN	RADAN and GPR Slice
3) What is your final deliverable?	Most of the time ground marks, but upon request, a report with handmade or sketch maps. Never CAD files.	Most of the time ground marks and handmade maps, and rarely, CAD files.
4) How do you or your customer keep record of this data?	They don't.	They don't, at maximum a report is provided.
5) Do you think that a geospatial tool[7] could help you to do the end-to-end process of a GPR Survey?	It depends on the nature of the project.	It depends on the nature of the project.

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[7] A map-based software such as a Geographical Information System.

Comments	Most of the time, the surveys are very straightforward and do not require any processing. In these cases, no software is required and also the customer does not need to have a lot of information resources on the surveyed area. However, the GPR practitioner has declared a lot of curiosity for the solution and would be interested to test it.	GPR user does very punctual work but he is very enthusiastic and he thinks that the proposition is very well arranged.

In summary, a series of problems related to UUN and GPR surveys to accurately locate UUN have been identified as a basis for this research project presented herein:

- Digging without enough map resources often leads to UUN damages and disruption of essential services;
- Not only underground cadastral mapping but also mapping resources in general are often incomplete for UUN risk management;
- GPR users arrive to survey sites with no or scarce information about the survey area (boundaries, properties, obstacles);
- When on site, GPR users do not have tools that support remote access to information and/or complete post-processing software solutions;
- Despite of GPR’s popularity, most users are able to handle it but not to interpret the data;
- GPR data interpretation is toilsome, ineffective (may not find all buried objects in the area), and inefficient (too much time and resources spent to carry out a single survey);
- Current GPR software relies minimally on geospatial tools, which have a large synergy with this domain;
- Surveys’ deliverables are often unstandardized and became paper reports, handmade maps, and soil marks, instead of digital maps and databases that comply with software and organizations standards across the industry and government.

1.4 Objectives

The overall objective of the research project is to improve the deployment of GPR investigation by supplying to users WebGIS capabilities available on a portable device in the field. To achieve this objective, a new innovative approach is proposed taking into account the workflow and needs of GPR users, specialists, and end users while performing an end-to-end survey. This approach aim at responding to the assessed need of geospatial tools with new features in a map-based, online, software provided by Geovoxel. This WebGIS module is called GVX-GPR. In this module, geographical features are exploited to improve the deployment of GPR survey in the field and assist the GPR specialists in the data processing and interpretation of GPR survey. A new WebGIS was developed and it provides to GPR operators multiple layers of structured spatial data including GPR scans and the ability to geo-annotate, in a controlled manner, points of interest. This module is easily operated on site through devices such as tablets and/or smartphones. The new WebGIS-based approach aims to help GPR operator to:

- Conduct GPR surveys that bring resources into more effective actions and results, increasing users' comprehension of the survey site and the interpreted data,
- Ease the GPR deployment for not only experienced professionals but also newcomers, increasing the usage of this geophysical tool for UUN detection and location,
- Achieve more complete interpretation with less technical effort, being as close as possible to identify and locate all UUN,
- Provide ample access to online information resources and tools, even though GPR practitioners may be outside the office,
- Perform more efficient production of subsurface maps, which support decision-making process for field work, and
- Deliver more reliable underground infrastructure data, available to a larger community of users.

As long-term contributions, the proposed approach for the deployment, processing and interpretation of GPR surveys intends to aid customers, industry, official authorities in proposing more rigorous and integrated procedures for locating and mapping UUN, and managing and disseminating geospatial information. In having more precise location of UUN, the impact for the society may be noticeable by possibly reducing the number of damages during ground disturbances, increasing the security for heavy equipment operators and citizens, lowering the disruption of essential services, and as proposing more efficient usage of land. Thus, unanticipated costs for repairing utilities or lessening risks of services' interruption due to trenching hazards can be also avoided. Finally, the outcomes of this research project may encourage the creation of a new market for geospatial technology industry since this segment of the industry is currently lacking businesses involving GPR handling and data processing. This projects' ambition is also to expand the knowledge base in both geomatics and geophysics by promoting an integrated and interoperable WebGIS-enabled solutions.

An important point to be made about this research and its scope is that the accuracy of GPR instruments and the performance characteristics of GPR such as signal quality or detection range, which vary in many ways as soil condition, conductivity property, kind of utilities, etc., are not addressed in this thesis. The proposal is focusing on adding GIS functionalities and spatial data integration procedure during the GPR investigation.

1.5 Methodology

As shown in Figure 1.7, the project follows an engineering approach from the identification of problems met by the GPR users to test and validation of the solution. A literature review has been also performed to review the current GPR survey solutions, best practices, and existing technology. Specific requirements have been assessed and validated in a series of interviews with companies offering GPR service as well as operators. A conceptual model has been created through the use of Unified Modelling Language (UML) case diagrams, with a data model integrating the necessities of the approach. Then, a GPR deployment methodology has been defined and validated again with users. With the conceptual modelling and requirements in hands, the MVP has been developed using a software development methodology and tested with two different categories of users.

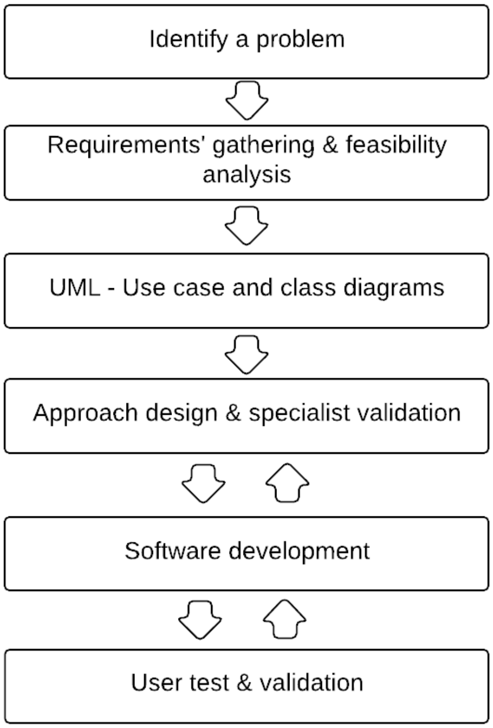

Figure 1.7: Flow diagram of the engineering approach used in the research project presented herein.

Along the descriptions of the sub-items of this methodology, some parts are described with more relevant context in the two published articles presented in Chapters 3 and 4.

1.5.1 Requirements' gathering and feasibility analysis

The requirements gathering for the project is based on X pillars. Initially, a review of literature to analyze the existing technologies and trends for GPR data visualization with GIS is performed. In a second stage, with an existing experience developed by the research team, a few difficulties were acknowledged. Once these difficulties were formed, an analysis with GPR users was carried out as a way of comparing if the difficulties found by the research team in previous experiences are applicable to GPR professionals in different sectors (industry, research, etc.). As a result, with a list of problems related to GPR surveys, users' needs are compared to what is currently offered by GPR manufacturers, 3rd party independent software producers, and open-source project, in order to evaluate the missing points. Therefrom, in further talks with GPR users, a list of requirements is defined along with proposed practices and software features as feasible solutions. Hence, this research project aims to actively pursue new solutions to supply the GPR community with new ideas and ways of joining aspects from both domains (geophysics and geomatics).

1.5.2 Use case and class data modelling

The first goal related to the software's conceptual design and data model's definition is to perform a data modelling using a UML taking into account a large literature review done on the best practices in GPR data acquisition, and interviews with GPR operators. UML is the widest utilized standardized modelling language, which consists of a set of diagrams types to specify, build, view, and document software. The guideline for acquisition planning is then translated to UML diagram type called use case diagrams, which stands as an illustration of the users, actions, and the interaction between them on the system. With a conceptual design capable of attending the highlighted hypothesis formulated, a database design, which integrates GPR data, survey-relevant data, and the semantically-rich standard 3D model of cities and urban utilities, is presented. This data model has to comply with existing standardized data models that integrate 3D objects from an urban environment such as pipes and cables as well as other objects that may be relevant during a survey.

1.5.3 Approach design and specialist validation

A GPR deployment approach defines a practical way of executing GPR surveys (following a guideline) and using at the same time the module developed herein as a supporting tool. The definition of this approach relates to when users prefer to use given features for targeting results. During the approach design, the main steps of a GPR survey are identified and, within each one, which tasks could be more suitably carried out by the GPR operators. This approach definition does not try to limit what GPR operators have to do in which of the steps, but rather to formalize a way of conducting a GPR survey with the developed WebGIS and how each one of the proposed features is planned to be used within the approach once they are conceived.

1.5.4 Software development

The software development methodology which will be used to approach this problem is the Extreme Programming method (XP method)[8], which is part of an umbrella term for software development named Agile Methodology[9]. Due to the high importance this project gives to user's experience and needs fulfillment, the XP method has been chosen by its elevated demand of interaction between the end-users of the project and the development team. The XP method is an alternative way for the traditional project management style, since it focuses on the unpredictability of client's needs and problems which the project may face by iteratively building and validating the product. This project methodology approach prioritizes the users' needs in stories and iteratively delivers them in predefined cycles for software usability testing. This method is a more aggressive

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[8] https://martinfowler.com/bliki/ExtremeProgramming.html

[9] https://www.infoworld.com/article/3237508/agile-development/what-is-agile-methodology-modern-software-development-explained.html

approach to solving complex problems of user necessities by requiring small teams to have excellent communication skills to understand users' issues.

The development is based on user stories, which are a short description of an action that users are able of taking in the software. It represents the action taken by a user who envisions to have a given result in the software. User stories are strongly correlated to the use case diagram, since may represent a direct translation of use cases (one user story being one use case), or they can be the breakdown of a use case, representing more feasible and detailed tasks for the developers (See next chapter). For this project, user stories are the direct translation of the use case diagrams. For example, a user story is "Visualize 2D GPR data" and it implies that a feature has to contain end-to-end functions for users to perform this action in the system.

Apart from the approach used by the software development itself, GVX-GPR is mostly based on the current technology which GVX was built with (See next chapter). Even though constraints have not been imposed, the future utilisation of the software within the platform would be extremely facilitated if the same tools and frameworks are used. Thus, the WebGIS has been inherited most of the existing tools and functionalities in GVX, at the same time that requirement-specific tools have been added as needed.

1.5.5 User test and validation

This phase validates user requirements for qualitative criteria such as usefulness and friendliness to newcomers in the GPR domain. At the same time, a measurable approach such as efficiency of time and resources and effectiveness (e.g. if the number improvements or the time saved while executing determined tasks such as preparation, execution, treatment, and delivery) has been developed according to the user perception. This distinction is a key and central concept in this research project. During the development of the tests, no quantifiable approach is conducted such as how many features have been or not found, but rather a quantifiable change on the perception of GPR user's (e.g. user A concludes that the impact of feature B decreases time of process X in approximately Y%). Due to time constraints, software development constraints, difference in complexity of different sites (for unbiased analysis), and elaborateness of survey planning, it is believed to be the most feasible approach for this research project. In order to do that, user feedback and the judgement of the research team are significant parts of the evaluation. This approach is very common in the technological entrepreneurship environment, where ideas need to be iteratively improved in order to rapidly acknowledge and respond to real users' needs.

Two study cases have been selected for this research project. Due to the complexity of interpreting geophysical data collected by GPR, the first set of GPR operators are non-specialists using the equipment with minimal or no training. Even though a professional locator knowing how to identify underground features, the use of a GPR does not seem to be obvious for the majority of those who operate it. In previous observations, the research team has witnessed professional land surveyors not able to set up the equipment properly, even using configurations not related directly to the geophysical properties of the surveyed site. Thus, such observations lead to conclude that non-specialists are one of the main targets of this research, taking into consideration that any facilitation offered during their handling of the equipment would be of great benefit.

Subsequently, the platform has been tested with professionals who have an in-depth knowledge of the technology and geophysical principles applied by a GPR. The purpose of this case study with professional users is to verify if the toilsome process of interpreting complex GPR data could be simplified and make the delivery process more efficient. The research team has access to two GPR instruments to perform experiments while Geovoxel Brazil possesses GPR instruments which have been used for the field tests. The two selected study sites are located in Canada and Brazil, with the view of expanding the reach of the research and exploring further variables that may affect the tests. It is believed that cross-continental tests could base the research project on more sound validation.

1.6 Expected results

The expected results of the research project can be summarized as five items. The first contribution can be seen as a map-based approach for GPR practitioners. This scientific project not only envisions to develop new tangible technologies but also a reproducible approach for newcomers, experts, and companies, to organize and understand the execution of a GPR survey. This approach suggests survey phases and sub-steps which are based for the integration between GPR instruments and map-based systems. Also considered as an expected result and tightly coupled with the approach's development are the user experiments. At the end of this research, a set of features is tested and validated with users, which tells whether the approach is contributes positively for GPR survey. Moreover, it shall be able to assert which geographical features are missing and what are their respective impacts on GPR surveys for these users.

Along with the approach, the development of a system to leverage map-based GPR approach is a concrete result of the project. This GPR-focused geographical information system contains a limited, yet important, set of features that enable GPR surveys to be executed and managed in a georeferenced environment. It provides a larger spectrum of possibilities to GPR users when testing the deployment of the geophysical method.

Thirdly, this research scientifically initiates discussion and raise awareness for a linger development of GPR technologies regarding geospatial features through extensive analysis and diversified user testing with two scientific papers presented in chapters 3 and 4. These papers formalize not only the approach but an initial analysis of user needs by proposing new visions towards the promising future of GPR.

The last and more specific category of expected results list are:

- A point-by-point analysis of GPR software and interfaces currently commercialized;
- A broad analysis of the current practices applied to GPR;
- An expansive outline of user needs;
- A representative number of market assessments regarding GPR services and products;

1.7 Manuscript structure

It is important to understand that this M.Sc. thesis is organized following the structure of a dissertation by articles' insertion as proposed by Université Laval's Faculté de foresterie, de géographie et de géomatique. Two main articles in Chapters 3 and 4 are the core scientific values added by this research project. Initially, a context is introduced along with the problematics, objectives, and methodology.

Chapter 2 - "Modelling and Software Design" presents the conceptual modelling of the WebGIS, starting by the requirements' gathering and user needs. Then, the UML diagrams (class and use case) are shown and explained. Finally, it concludes with a technology overview and architecture of the system.

In Chapters 3 and 4 which respectively correspond to papers 1 and 2, experiments performed with non-specialist and specialist GPR users respectively are presented and discussed. Both chapters count on forewords describing the publication details, context, and purpose of the publication (e.g. where it was published, why, the intent for that scientific community). These chapters have an introduction, problematics, methodology, results, conclusions, and discussions self-contained.

Chapter 5 - "Results and Discussions" expands on the results acquired on both publications for discussion purpose of not only formal questionnaires applied but informal talks recorded during the experiments, which could not be fully introduced in the articles due to size constraints.

Finally, in Chapter 6 - "Conclusions and Recommendations", the achievement of the global objectives, presented in first chapter’s, are discussed with the global comprehension and insights obtained during this research project, along with next steps and recommendations.

Chapter 2 - Modelling and Software Design

The current chapter, Modelling and Software Design, presents the requirements' gathering, the conceptual modelling, and the system architecture and organization. Section 2.1 cover the user's needs on which the approach and development is based. Section 2.2, introduces use case diagrams which depict all the high-level actions taken by users on the system, also featuring the actors involved during a GPR survey. The last section, 2.3, shows the main components and technologies of the WebGIS architecture of GVX-GPR in a high-level overview (due to open access due to confidentiality and copyright).

2.1 User Requirements

In order to address the issues and problematics previously discussed, user requirements are defined. This is dictated not only by what appears appealing in terms of technology, but taking into account the research team's own experience with handling GPR as well as the experience of GPR professionals. The requirements obtained are presented in the next items as user requirements for the WebGIS interface.

The core requirement observed during these users' requirement assessment can be highlighted as the need that GPR software has of geospatial features. Due to the mobility needs that GPR operators have when deploying GPR surveys, proposing a WebGIS interface, which counts on remote access to resources at the same time offering more handleability when operating another equipment, seems to be consistent. According to the way that a GPR survey has been perceived by the research team based on literature review and multiple user discussions, GPR practitioners shall be able to manipulate and access map resources before, after, and, exceptionally, during the execution of a survey. Accessing map resources not only mean being able to view open maps, at any given moment, but also to have in hand a unified view of the information belonging to the survey's area. These map resources can range from open mapping services, proprietary information (e.g. A CAD plan of a private building), cadastral databases (e.g. parcels), etc. This information may be already contained in the system (e.g. having OpenStreeMap road maps as a default layer) at the same time that GPR operators and Geophysicists must be able of uploading data of known formats by the industry. This requirement has a high impact on how the data modelling of this software has been designed. An example is that by having compliant databases, users can more readily plug in new resources and outer databases, increasing the amount of survey-relevant data during a data acquisition.

Apart from only visualizing information on the map, all types of actors (GPR practitioners, geophysicists, engineers, notaries) have the need to generate their own map resources. According to all the professionals from the GPR domain interviewed during the research project, most of what is registered during a survey end up to being free hand map sketches and pictures as reference points of the survey. Thus, users should have the ability of adding drawing, georeferencing objects, including GPR data, into the WebGIS interface.

Lastly, this approach is centered on unifying the two information resources in question, maps and GPR data. Thus, users shall be capable of handling GPR data in a geographic-coordinate-aware environment. After the survey and data processing, 'the software shall offer visualization of radargrams, 3D cubes (3D environment), and slices. Thus to the limitations and scope of this research, 3D cubes are acknowledged as part of user needs but not yet accounted as feature to be develop in this research project. Users shall therefore visualize radargrams and slices, and promptly connect them to the map, facilitating the spatial reference when looking at the information and assessing where the survey is located on the map.

2.2 Data Modelling

In order for data to be available for a larger community of users, usable across multiple platforms, and in well-known formats, this approach proposes the usage of a standard data model. The data is stored in a compliant database to a known standard, called CityGML (Kolbe et al., 2005). CityGML contemplates not only the data organization but the integration of available data provided by customers and/or open resources. Even though other standards exist (as of November 2018), at the moment of the research project scope's definition, CityGML has been judged to be a pertinent choice for the scope of the project due to multiple reasons. CityGML was selected due to not many standards propose a comprehensive and semantics-rich description of underground infrastructure as CityGML proposes. As an example, at the beginning of the research, when InfraGML was non-official but yet and ongoing proposition for OGC, two of the main existing and adopted standards were CityGML and INSPIRE. CityGML is an existing and well-accepted standard in order to explore existing data that would be compatible and can be aggregated to GVX-GPR. Furthermore, CityGML is a known standard and part of the application schema proposed by OGC and ISO TC211, which provides an interoperable representation of 3D cities models. It comprises multiple aspects of these models including topology, geometry, and semantics, and respective level of details for given models. As a result, CityGML offers a standardized representation and modelling of objects belonging to this urban environments which facilitate the exchange and storage of 3D city models' data between software, organizations, etc. It, at the same time, facilitates the addition of existing objects that could be relevant during the execution of surveys, thus, promoting the access to more information resources for GPR surveys. Further than that, the particular choice made for this research project is considered to be extremely relevant not only for the interchangeability of data but also to allow users to use existing data (from external data sources) to carry out their surveys. At the same time, enabling the production of reliable underground maps to the community or clients, as a standardized database, strengthens the interoperability of the acquired data.

In order to map infrastructures on the system, a class diagram of the proposed WebGIS interface has been produced to illustrate the schematics of the application. The core diagram of the application is divided into two separate parts. One consists of the CityGML-derived data standard, which role is to store UUN's and other city objects. The second portion is responsible for the management and storage of GPR data, which is not proposed by any standard to the date. These diagrams help the design and comprehension of the software by providing a high-level yet simple view of the main entities which such a system requires.

The data model inherited from CityGML Utility Network ADE (Becker et al., 2012) is presented in Figure 2.1. CityGML proposes an abstract entity called _CityObjects, which is a generic object belonging to a city model, but also a linkage to other CityGML datasets. For example, in the proposed model, a pipe is a specialization of a _CityObject, but in other CityGML datasets, it may be a house, a building, or a street. As mentioned, this ADE (Utility Network ADE) is centralized in a specialization of *_CityObjects* called *_NetworkFeature* (any composing element of UUN). This class is an abstract object to other four network object types that represent sub-types of components in underground utility networks:

- *Device* – Abstract class to represent the generalization of storage devices, measurement devices, controller devices, tech devices, and any other existing device (e.g. tank, switch, valve);
- *ComplexFunctionalElement* – Structures containing devices (e.g. stations, factories, treatment plants, pumping stations);
- *SimpleFunctionalElement* – Structures that do not contain devices (e.g. manhole, voltage regulator, inverted syphon);
- *DistributionElement* – Abstract class representing pipes, cables, and canals.

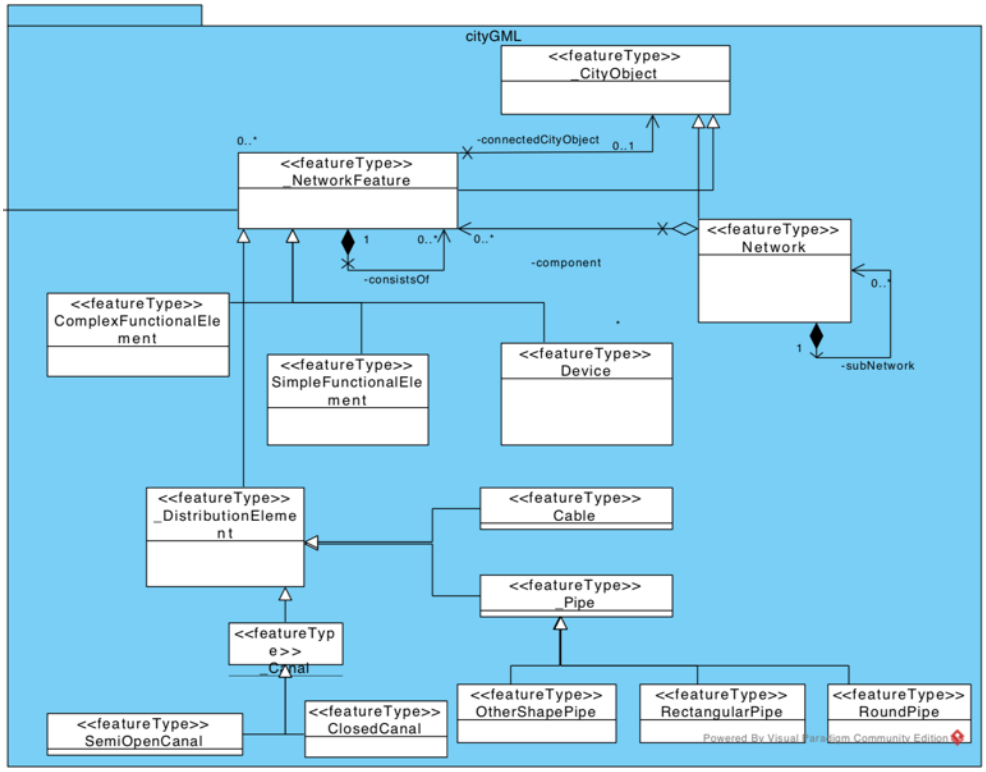

Figure 2.1: Inhereted data model from CityGML displaying the main features and their relations.

This CityGML UtilityNetwork ADE also contains a topological model which describes how the components of the networks are connected. Taking into consideration the proposition of this research, which is to validate the importance of map-based systems to carry out GPR surveys, having a topological model in place, as proposed by CityGML UtilityNetwork ADE, would disproportionally increase the complexity of the implementation and usage by the users, in relation to the scientific value added. It would only make sense to have topological models in the database if the software envisioned to be offered as a product for the management of underground infrastructures, which is out of the scope of this research project. As a consequence, due to GPR survey's characteristics, time constraints, and development complexity, the topology was not added to the developed tool. The complete version of the diagram can be found in CityGML Wiki[10].

The subsequent portion of the modelling (Figure 2.2) contains the new specific classes to handle GPR data as well as supporting classes with spatial data embedded. One of the central classes to a GPR survey is the 3D cube. 3D cubes of radar signal are 3D representations of the area of a GPR survey, represented by a polygon on the map (the top slice, or the area on a surface occupied by this cube), which are the interpolation of the GPR

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[10] http://www.citygmlwiki.org/index.php/CityGML_UtilityNetworkADE

survey lines covering the survey area with lanczos resampling. As seen in the diagram, ***gpr_3D_cube*** is composed by GPR survey lines (represented by ***gpr_survey_line)***. GPR survey lines are 2D point matrix with X, Y, and depth coordinates, and it is represented by a *MultiLineString* on a map. ***gpr_survey*_points** are the composing points of the GPR profile, which represent a GPR reading. GPR cubes belong to GPR surveys (***gpr_survey)*** which are, for the most part, represented by the same polygon as the GPR 3D cubes. In turn, one GPR survey can be composed of multiple GPR surveys through the self-relationship *-consistsOf*, by the fact that a GPR survey might have different areas on the same studied site. For example, a street having a GPR survey that covers that street, another that covers the sidewalk, and the two of them belonging to a survey "Street survey". The class ***gpr_survey_slice*** is a view from GPR horizontal slices extracted from a GPR 3D cube. The type of GPR used for a survey is also stored in GPR surveys since different GPR brands produce different file formats. And, finally, surveys also count on geo-annotations (***annotation***) and points of interest (***point_of_interest***), which store georeferenced data relevant to the interpretation later on. Geo-annotations may be 2D points, lines, and polygons (and may also contain pictures), and points of interest are exclusively 2D points. Lastly, these two diagrams are connected by an association of non-dependency called *-contains.* This relation connected the class ***point_of_interest*** (Figure 2.2) to the abstract class ***_NetworkFeature*** (Figure 2.1). It represents that points of reference (a hyperbola on a radargram) are likely/certainly an infrastructure on the map, which might have been surveyed previously (existing data) or a result of the interpretation process.

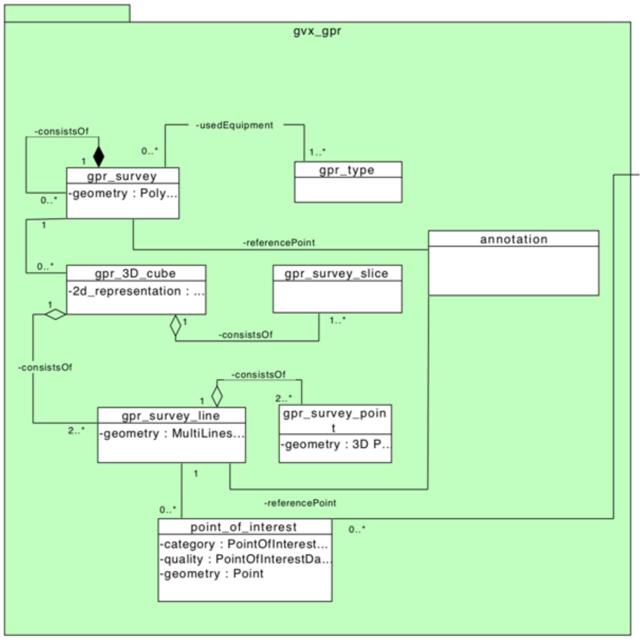


Figure 2.2: Class diagram developed to store and organize GPR data utilized by GVX-GPR.

2.3 Use Case Diagram

To illustrate the users and their interactions with the planned system (called GVX-GPR), a use case diagram has been designed (see figure 2.3). The goals of the application and the scope of the actions taken by these users are also described. Initially, three operators are foreseen based on the users' needs. They represent the types of operator that might use the system and visualize and handle data from different perspectives and ends. It does not necessarily mean that a GPR survey will be carried out by one of these three operators, but these operators represent the three levels of expertise and interest that operators using this system have. The operators and their specializations are presented below:

1. GPR Operator – This operator is responsible to carry out a GPR survey in the field, such as a land surveyor. This operator does not necessarily have to deduce all the information from the field, such as soil properties, grid distance, etc. But he has to take decisions even upon uninformed areas, not previously analyzed by a geophysicist or a geologist.
2. Geophysicist – This operator is in charge of not only analyzing the previous survey portion, such as setting GPR parameters with considerable level of competence (soil properties, antenna separation, time window, etc.), but also interpreting the data acquired by the GPR operator after the data acquisition has been completed. This operator holds enough knowledge of signal processing techniques, GPR principles, propagation of electromagnetic waves in different types of soil, etc.
3. End user – This generalization proposes an operator who uses the final interpretation drawn by the geophysicist once completed. In the main use case diagram, the end users are (1) engineers who use underground maps to plan a new civil engineering development, (2) field workers who use maps as a resource to avoid damage to existing underground utilities, and (3) notaries who use it as supporting documentation for ownership legal disputes. However, a much larger layer of operators can be considered to be potential users of this information such as households, businesses' owners, and anyone asking for UUN data.

In many of cases, "Geophysicist" and "GPR operator" might be functions performed by the same person. For example, during the requirements gathering for this research project, the two professional GPR users interviewed are (1) a GPR operator who is also in charge of the interpretation and (2) a geophysicist capable of handling GPR. For this reason, this research project describes GPR users as GPR specialist and non-specialists. A GPR specialist is, commonly, a professional with enough knowledge to carry out GPR surveys while having a deep knowledge in geophysical principles. A non-specialist, on the other hand, is a person with only enough knowledge to perform a survey, who does not have any technical background or specialization in the given domain (to perform complex geophysical analysis). In many cases, geophysicists are the ones to go out on the field and perform the data acquisition and interpretation, as a result, representing a GPR operator as well. The opposite is when a GPR operator (or a land surveyors, for instance) receives geophysics-related training in order to properly operate both the GPR settings and post-processing software. According to the research team's evaluation, the first case (Geophysicists that also perform the data acquisition) is still the most representative type of professional. However, with the diffusion of GPR best practices and better software, the second case (where land surveyors are capable of doing complex analysis) may prevail.

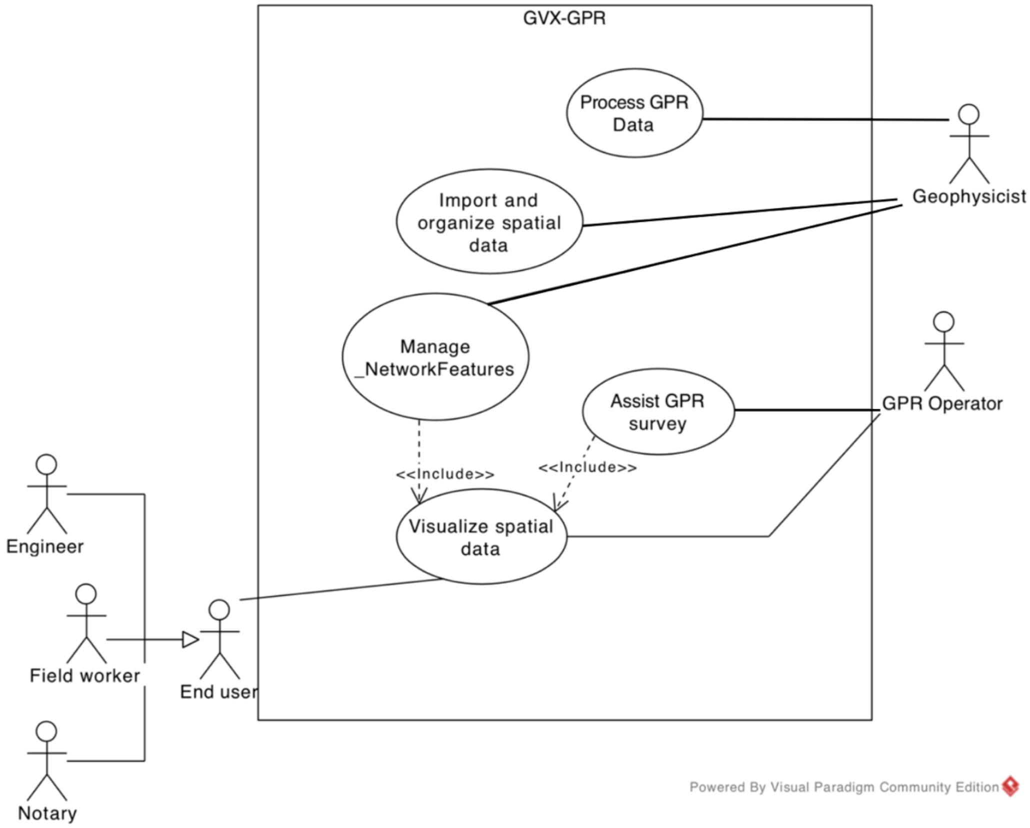


Figure 2.3: Use case diagram representing the main actors and main actions of GVX-GPR.

Following, sub-diagrams that explain the breakdown actions taken in each one of these macro use cases (Figure 2.3) as **Visualize spatial data, Import and Organize spatial data, Assist GPR Survey, Process GPR Data, and Manage_NetworkFeatures** are presented**.** End users are the ones interested in the final deliverable of a GPR survey and, as the focus of this research project mainly targets UUN, they would likely be ones to consume the information sources contained in **Visualize spatial data** (Figure 2.4). This diagram introduces a new generalized user named *System User*, which represents every possible user to make use of the tool (by visualizing data), since this use case is, in simple terms, the visualization of GIS layers (e.g. road maps, satellite imagery), infrastructures that have been recognized in the surveyed area (denoted as *_NetworkFeature),* and their metadata by selecting them on the map or on a menu. The classes prefixed by "_" (underscore) are abstract entities.

Show and Hide GIS layer allows users to toggle between activating or not a map overlay. *View GPR data* is divided between profiles and slices. Profiles are selected in the map and they geometry are shown in the map and, at the same time, the profiles appear in a gadget in the external regions of the system. For instance, GPR operators can visualize spatial data when conducting a survey, since they take advantage of the map resources (and others relevant to the survey) to identify the area of the survey, find cues on where infrastructures may be located (e.g. a manhole might be the termination of a watermain), whereas geophysicists may use map resources as basis for their analysis.

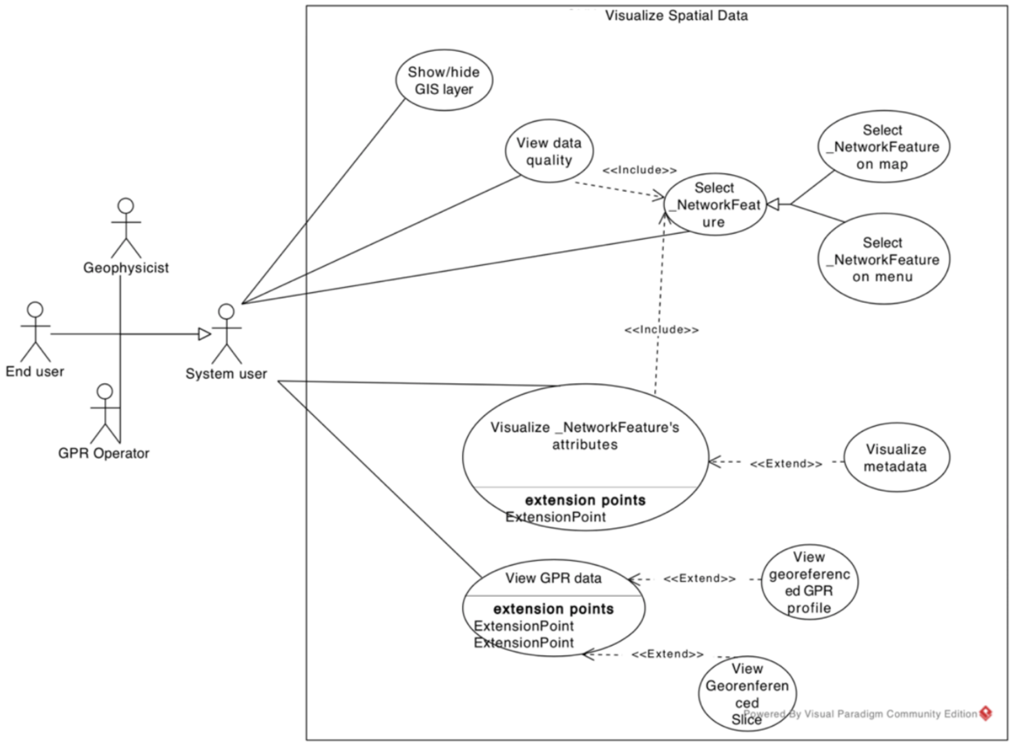


Figure 2.4: Sub-diagram representing actions for the action *Visualize Spatial Data*.

In order to visualize rich information, GPR operators are capable of **Import and Organize spatial data**. As shown in Figure 2.5, users can import different types of information, such as structured information (GeoJSON containing semantically rich infrastructures or further CityGML *_CityObjects*), semi-structured data (such as ESRI shapefiles) going directly into a geoserver and not into a relational database, and, finally, georeferenced images.

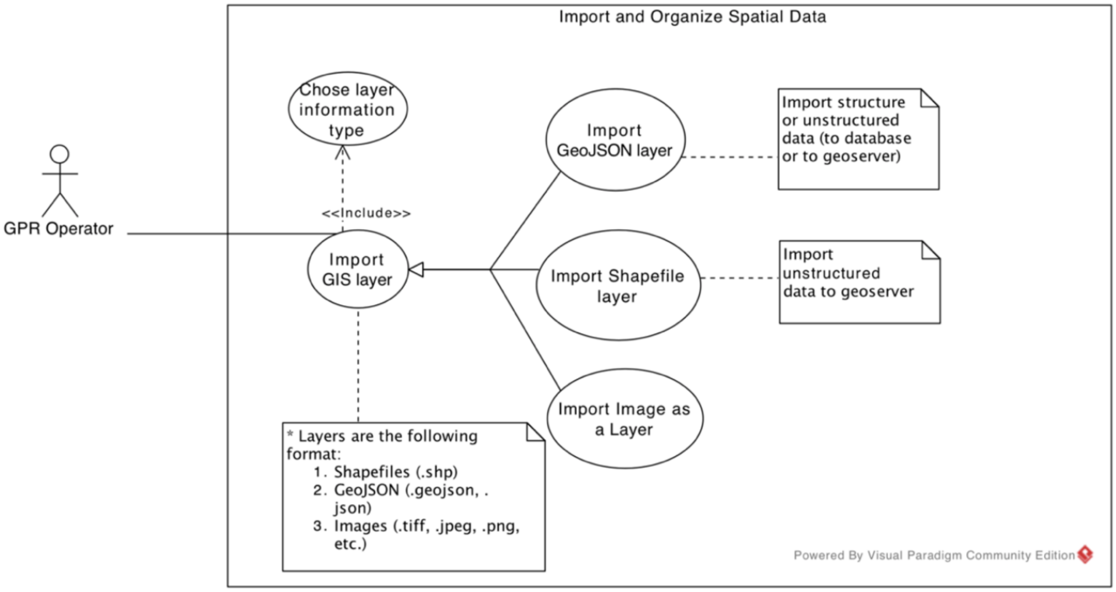


Figure 2.5: Use case diagram describing action *Import and Organize Spatial Data*.

The next features is **Assist GPR Survey** (Figure 2.6). GPR operators, in the field or during the interpretation, are capable of adding geo-annotations (and attach images to them) and points of interest to signalize likely targets. Surveys are composed of areas with boundaries and lines. *Draw survey lines* is tightly coupled with the use case *Georeference Radargarm* (Figure 2.7) in **Process GPR Data**. **Process GPR Data** (Figure 2.7) not only allow users to import raw GPR data to the system but to visualize generate slices from a 3D cube, which come from the interpolation of selected profiles on the map. Similarly, *Add points of interest* serves as a way to add geo-annotated comments and pictures (with color codes) for likely targets spotted during the GPR survey. These last two use cases (Generate georeferenced GPR slice and Add point of interest) are tasks that used to take place in the office but now are enable on site as part of the proposed approach.

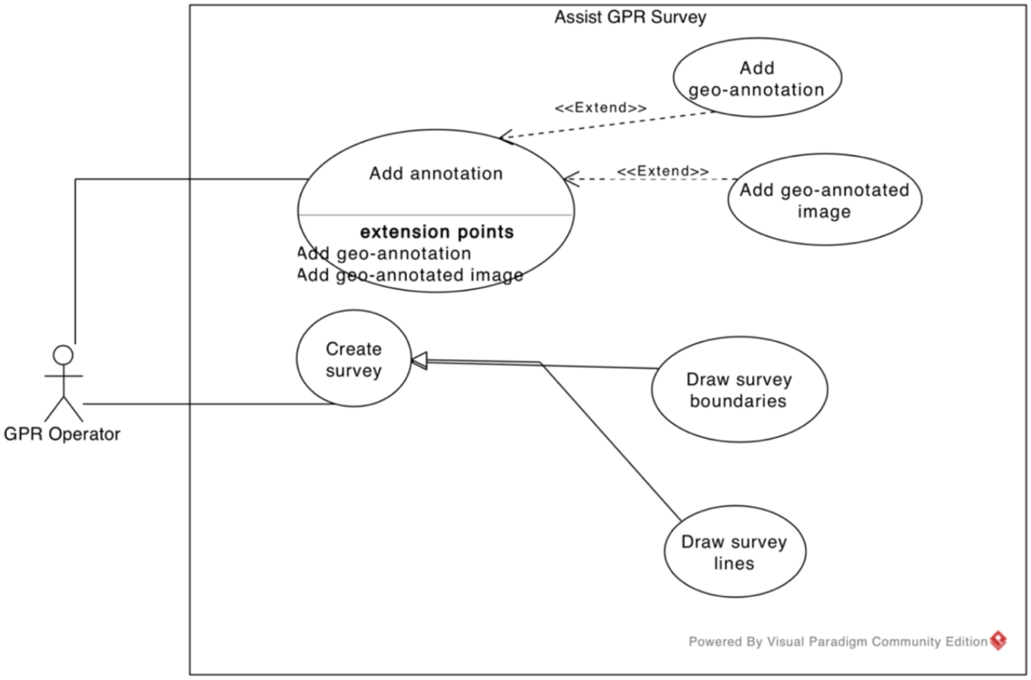


Figure 2.6: Use case diagram for *Assist GPR Survey*.

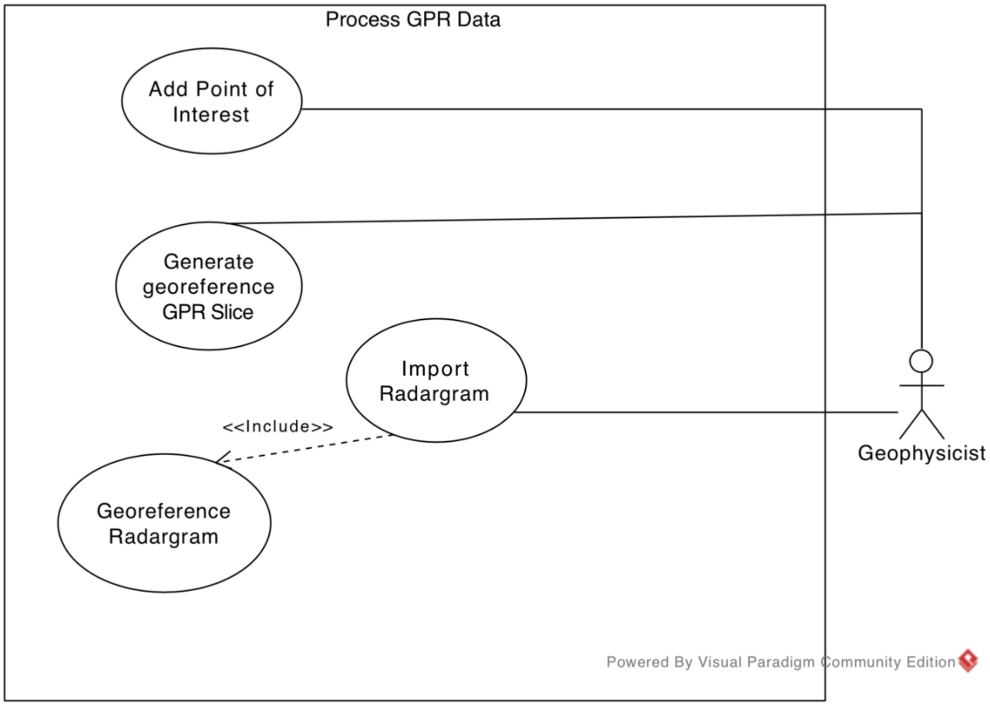


Figure 2.7: Use case diagram for *Process GPR Data*'.

To complete the GPR deployment, the interpretation of GPR survey becomes semantically rich data, which represents UUN and this is done through the next features as **Manage_NetworkFeatures** (Figure 2.8). Although this research project focuses on the data acquisition process, the formalization of data is just as crucial. To achieve thus formalization, geophysicists can Create, Read, Update, and Delete *_NetworkFeatures* (*CRUD _NetworkFeatures*). For every feature found, at least three properties are envisioned to be identified: 1) the type (is it a pipe or a cable?), 2) the depth, and 3) the sectional area. Further details are feature specific, which are integrated in *Define UUN-specific metadata* and, thus, added as the user is capable of gathering more details from it during the interpretation.

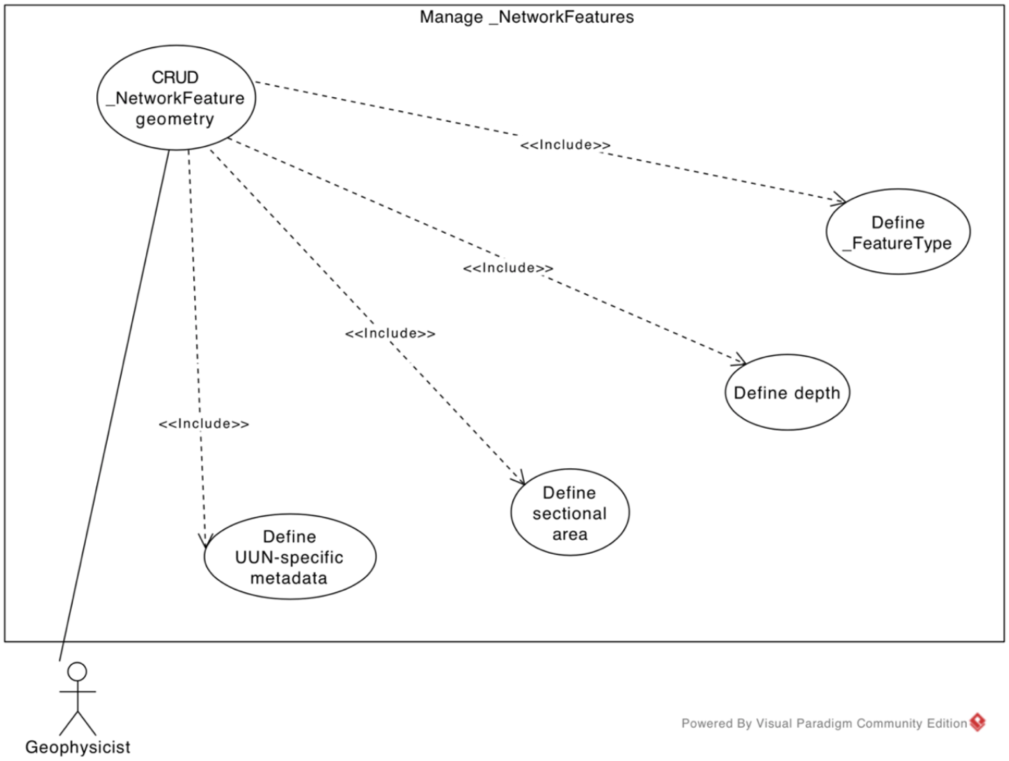
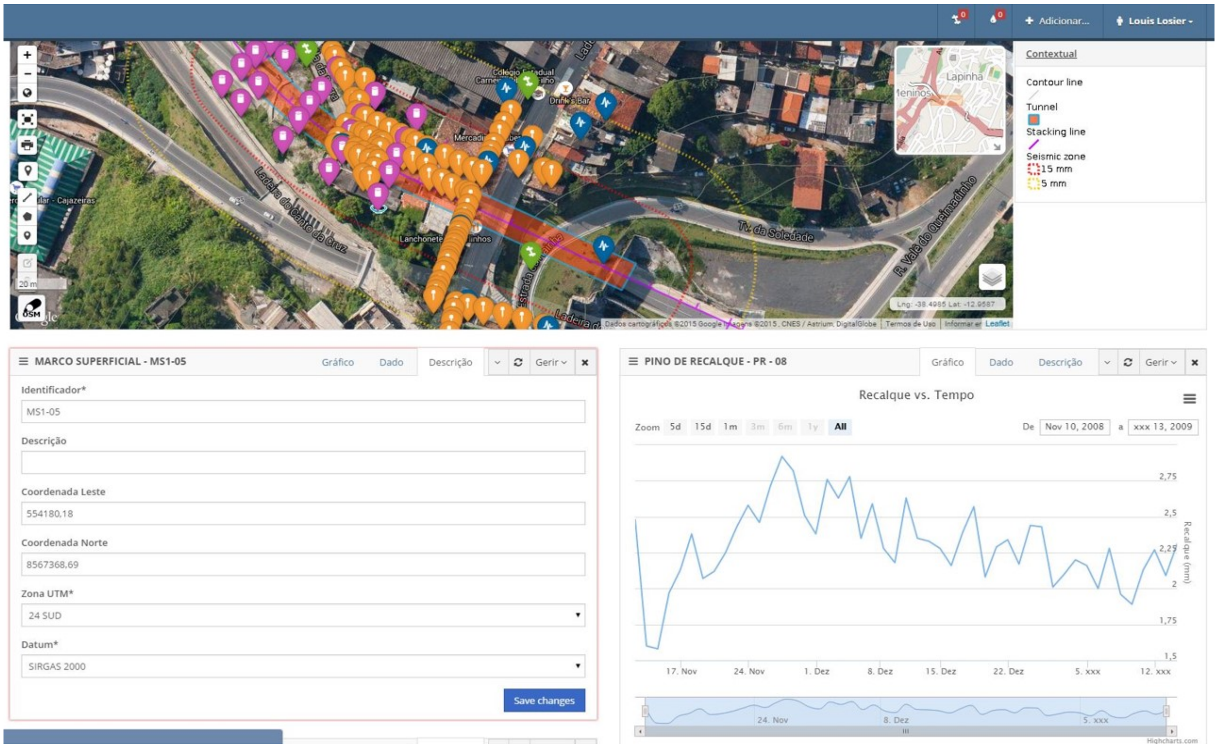


Figure 2.8: Use case diagram Manage_NetworkFeatures.

2.4 GVX-GPR: WebGIS Architecture

The development of the WebGIS interface is based on an existing tool provided by Geovoxel called GVX. The GVX platform-as-a-service (Figure 2.9) allows the integration of maps and geo-related data fed by sensors from different families and manufacturers and provides analytical tools such as personalized reports and graphics so that users can maintain proper risk management of their sites. The pins on the map represent geotechnical instruments acquiring data in real time while the table and chart below provide information of an instrument's settings and its readings.



Identificador*: MS1-05

Descrição:

Coordenada Leste: 554180,18

Coordenada Norte: 8567368,69

Zona UTM*: 24 SUD

Datum*: SIRGAS 2000

Save changes

De Nov 10, 2008 a xxx 13, 2009

Figure 2.9: GVX platform-as-a-service during the construction of a tunnel in Brazil (Losier et al., 2015).

GVX has been designed by Geovoxel. Geovoxel provides tools to help predict, respond to, and ultimately prevent accidents in locations more prone to natural disasters or during construction works (Losier et al., 2015). GVX is an innovative geospatial platform integrating multisource data (Figure 2.10) from soil movement sensors (geotechnical data), geophysical data, and climate information. The platform supports the decision-making process of stakeholders involved in risk management by presenting real-time web-based/mobile reports which contain all data pre-analyzed based on historical data and engineering assessments. The ones concerned with safety in those sites have therefore quick access to information and a fast synthesis with end-to-end data integrity. This state-of-the-art platform provides field engineers and risk managers with complete set of tools, allowing a proper risk measurement for a faster emergency response, thus saving lives and reducing economic losses.

Having involved in approximately 100 projects in Brazil from 2011 to 2017, Geovoxel supports governmental agencies and infrastructure companies in different activities by tracking several geo-related dynamic variables in the field and assuring a suitable risk management. Geovoxel solutions have a direct impact in saving lives and lessening the risk of unbudgeted monetary losses due to extreme events.

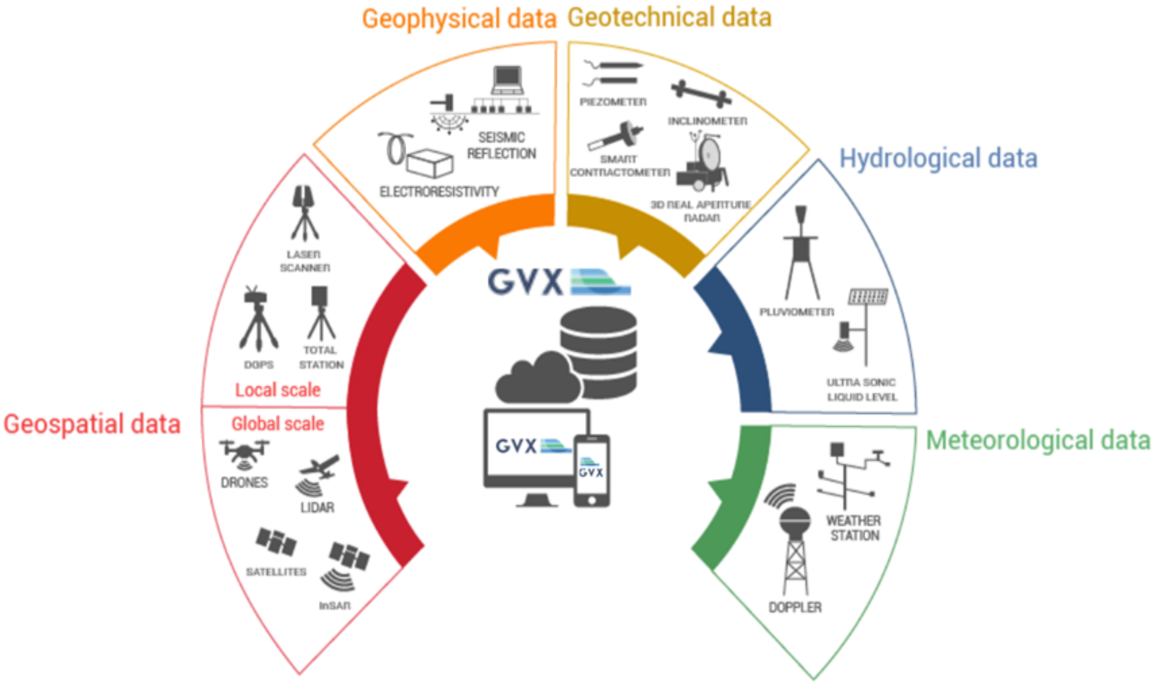


Figure 2.10: Multisource data integration on GVX represented by 5 main types of data.

2.4.1 Infrastructure overview

The development of the module GVX-GPR consisted of using the base of technologies which Geovoxel already uses for the platform GVX, with the view of simplifying the development by taking advantage of the existing infrastructure. A high-level diagram of the components used for the module are shown in Figure 2.11. In relation to the initial state of the GVX, the module adds a few components that were key for GPR support. The central box, named *Development stack*, contains the main software components and libraries composing the WebGIS interface. The system is mostly developed in Python language, but uses the framework Django[11] as its architectural pattern. Django offers a model-view-template (similar to a model-view-controller MVC). architecture

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[11] https://www.djangoproject.com

that allows users to more easily interface with databases and web/mobile clients by providing the scaffolds for an internet-enabled application.

The system can be accessed by mobile or computer through browsers, while the content of the application is always responsive to the user requesting the information. The user-side data manipulation is done with HTML5, CSS3, JavaScript and JQuery. The geospatial data visualization is handled on user side by a library called Leaflet, which is a widespread technology in the geospatial world. Leaflet was already the technology which GVX was based, thus, facilitating the building blocks of an application that was developed in an agile manner. Some other choices were brought into consideration during the project's architecture conception such as Cesium, Mapbox, and Google Maps. As presented in Pouliot et al. (2015), the preferred way to represent underground utility networks is by 2D features on flat maps. It is acknowledge that the scarcity of 3D data visualization (for instance provided by Cesium) and handling impacts user interaction and is a missing support for GPR data. However, only a specific set of features were developed for the MVP, which were essential to validate the objectives of the research.

Apart from that, two libraries were added to process and display GPR data, naming Matplotlib, a plotting library integrating numerical mathematics extensions such as NumPy which are used for the interpolations of geophysical data (to generate 3D cubes, for instance) and plotting of single radargrams, and D3. D3 is a JavaScript library based on Three.js which allows plotting of complex datasets, used to plot radargrams.

From an infrastructural point of view, data with semantics is stored in a Postgres relational database using PostGIS as its geospatial component. A single GPR profile is customarily composed on hundreds of thousands of points (if not million points). Due to the massive amount of resulting data, a point-by-point storage in a relational database would not be ideal. Therefore, a NoSQL (MongoDB) database node has been added to the GVX technology stack in order to store JSON-like objects containing these points. Yet, generating 3D cube every time a user queries for the interpolation of lines would be a misuse of processing services. The interpolation process is done with a scientific Python library named matplotlib which offers a pre-set of interpolation methods that can be used together with Pandas to enable the creation of 3D GPR cubes. In order to avoid the work intensive task of generating 3D cubes every time an area is queries, a fake cache server acts as an intermediary layer which calculates via hash whether or not that 3D cube has already been created, and if so, recurs to existing slices in a file server.

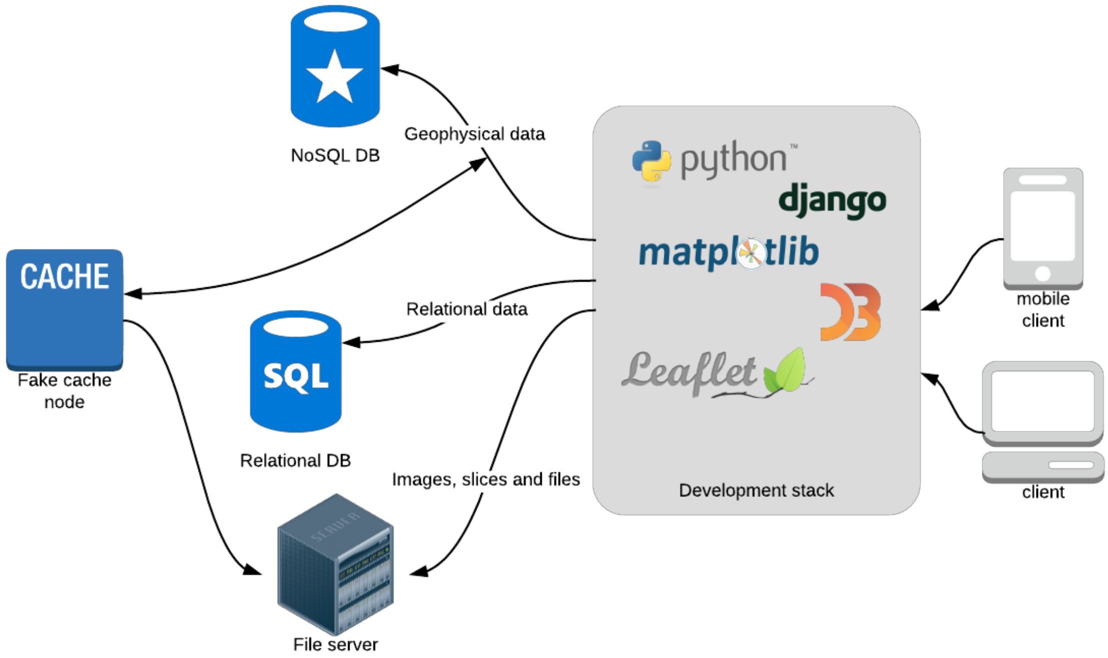

Figure 2.11: High-level view of the architecture and technology components used during the development of the WebGIS interface.

Chapter 3 - A WebGIS to Support GPR 3D Data Acquisition: A First Step for the Integration of Underground Utility Networks in 3D City Models

Résumé

Ce premier article présente une version préliminaire de l'approche développée dans le cadre de ce projet de maitrise. Cette approche consiste en l'intégration des sources de données géospatiales, l'utilisation d'un système SIG-Web et des fonctionnalités adaptées à l'acquisition de données GPR. Le SIG-Web est développé en tant qu'un module amélioré sur une plate-forme existante appelée GVX. Le module GVX-GPR fournit une visualisation interactive de plusieurs couches de données spatiales structurées et des données de levés de GPR. Ce module offre de nouvelles fonctionnalités par rapport aux enquêtes GPR traditionnelles telles que les points d'intérêt géo-annotés pour identifier des indices spatiaux dans les profils GPR, l'intégration de données contextuelles de villes, les images de drones et des images satellitaires à haute résolution. Cet article explique l'approche technique utilisée pour concevoir et développer ce système SIG-Web et une première version de l'outil GVX-GPR. Puis il présente une première expérimentation sur le site du campus de l'université Laval pour le levé d'une fibre optique enfouie. .

A WebGIS to Support GPR 3D Data Acquisition: A First Step for the Integration of Underground Utility Networks in 3D City Models

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Commission VI, WG VI/4

KEY WORDS: GIS, Underground Utility Networks, Ground Penetrating Radar, Subsurface Utility Engineering, 3D Data Acquisition

Abstract

For the planning and sustainable development of large cities, it is critical to accurately locate and map, in 3D, existing underground utility networks (UUN) such as pipelines, cables, ducts, and channels. An emerging non-invasive instrument for collecting underground data such as UUN is the ground-penetrating radar (GPR). Although its capabilities, handling GPR and extracting relevant information from its data are not trivial tasks. A literature review and field experiments indicate both GPR and its supporting software stack provide very few capabilities to co-visualize GPR collected data and other sources of spatial data such as orthophotography, DEM or road maps. Furthermore, the GPR interface lacks functionalities as adding annotation, editing geometric objects or querying attributes. A new Web-GIS based tool is proposed to support GPR data acquisition. The tool is developed as a new module in an existing platform called GVX. The GVX-GPR module provides an interactive visualization of multiple layers of structured spatial data, including GPR profiles. This module also provides the ability to geo-annotate points of interest for identifying spatial clues in the GPR profiles in order to perform a better deployment of the GPR field surveys. This paper presents the needs for this application as well as a preliminary view of a 3D GPR model placed along mapped UUN as 3D objects integrated in a city model.

3.1 INTRODUCTION

3.1.1 The lack of Underground Utility Data

In highly populated areas, a complex mesh of vital utilities such as gas pipelines, power and communication cables, drinking water and wastewater systems, is buried underground beyond sight (Figure 3.1). With the population growth and urban development, it is challenging not only to maintain an up-to-date spatial database of existing underground utility networks (UUN) but also to acquire spatial data of buried infrastructures in non-invasive ways (Jeong et al., 2004; Navigant Consulting, 2005; Pouliot and Girard 2016). For any development project requiring excavation and trenching, it has become more and more essential to acknowledge the necessity of having an available and reliable current database of UUN in order to avoid interruption of services and downtime costs due to damage (Costello et al., 2007; Lew and Anspach, 2000; Metje et al., 2007). For example, Info-Excavation reported 4.5 damages per day in 2015 for an approximate cost of $109 million CAN (Info-Excavation, 2015).

Ideally, UUN information should be made available to users such as city planners and excavation companies to design new city development and avoid service disruption during excavation. In reality, when this database exists, it is not compliant with well-known accepted standards for processing spatial date such as CityGML Utility Network ADE, INSPIRE network model, IFC utility model, and ESRI ArcGIS network model, leading to an inadequate representation of these structures (Becker et al., 2013). Only a few places around the world like Switzerland, Norway, the United States, India, Malaysia, and some others have shown enough interest in developing structured 3D data of their UUN (Cornette and Galley, 2011; Choon, 2013; Ghawana et al., 2013; Valstad, 2006).

Figure 3.1: Example of underground utility networks, central London. Image courtesy of Hitachi (Source: Bentley Intelligent 3D Models).

3.1.2 3D Data acquisition with Ground Penetrating Radar

Among the most accepted non-invasive underground 3D acquisition methods, the Ground Penetrating Radar stands up from many others for its capability of covering large areas (Daniels, 2004). An example of a GPR (GSSI) used to survey UUN's by Geovoxel in the city of Rio de Janeiro, Brazil, before excavating a rail trench is shown in Figure 3.2. The GPR uses electromagnetic emitter and receiver to identify the location and the depth of subsurface utilities (Daniels, 2004). It may provide line scan, 2D or 3D images (cube) of time travel that maybe converted in depth information.

Figure 3.2: Ground-penetrating radar survey in progress.

Although GPR has many supporters, its handling is not trivial, even for experts (Annan, 2009; Jol, 2009; Rahman and Zayed, 2016). First, it is noticeable the lack of specialized tools to help the data acquisition pipeline, from getting contextual data prepared before going in the field to the visualization of GPR data within the project's context (Dallaire and Garneau, 2008; Pouliot et al., 2016; Li et al., 2015; Themistocleousa, et al., 2015; Talmaki et al., 2013; Tischler 2003; Zheng et al., 2004). These steps require an integration of resources which varies in format, date, and details. Among the non-specialized tools found in the literature, it counts even less the ones that provide offline support, such as ESRI ArcGIS, for remote areas in which the data acquisition is often performed (Sandweiss et al., 2017; Proulx-McInnis et al., 2013). Subsequently, during the data acquisition, as shown in Figure 3.3, most of GPR embedded software integrates a real-time display and in-site interpretation tools as signal data processing, but the geographic interaction level remains limited, if simply inexistent. Scarcely any GPR producer has a fast-moving reaction to these technological needs except a few like the EKKO_Project (Sensors & Software, 2017).

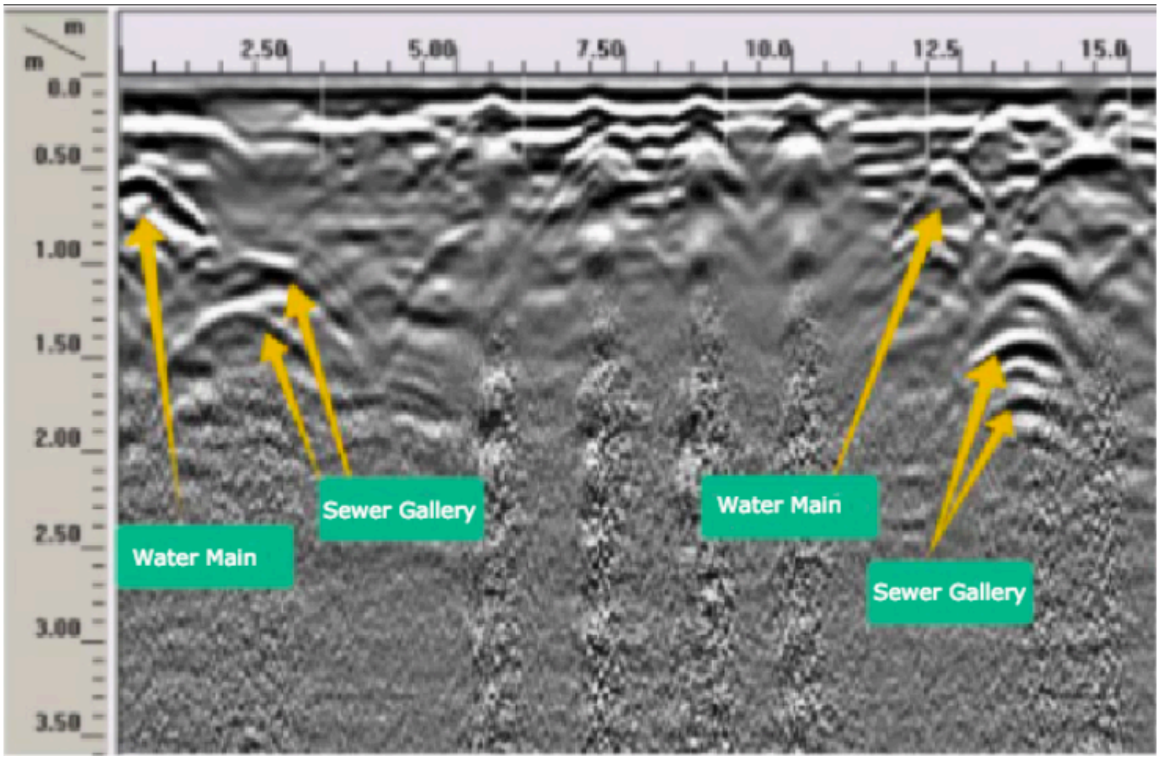

Figure 3.3: GPR profile showing hyperbolic diffractions indicating possible UUN's. Image courtesy of Geovoxel.

3.1.3 Research project objectives

To conduct a more precise and reliable GPR data survey, it is hypothesized that basic features such as adding annotation, viewing photos, querying attributes or metadata, and drawing while being on-site would be of great benefit to the GPR operators. Furthermore, offering comprehensive approach for covering preprocessing, acquisition, and visualization of relevant existing data for on-site consultation contributes to the effectiveness of identifying underground elements in the field. Many manuals and standards provide guideline for collection and mapping of underground infrastructure (ASCE, 2002; CCGA, 2014; Chen and Cohn, 2010; CSA, 2016; Metje et al., 2007). However, these standards do not seem to be known (or sometimes disregarded) by many GPR practitioners.

Based on experiments (Pouliot et al., 2016) and the previous literature, a better visualization of multiple layers of existing data in parallel to real-time acquired GPR data is perceived as valuable to facilitate the identification of UUN. The main objective of our project, started in Fall 2017, is to demonstrate the value of adding to GPR deployment in the field GIS capabilities and geo-standards as proposed by OGC. To achieve this objective, a new Web-based GIS platform is proposed. The following sections present its design and development, and its further application for specific GPR investigation of UUN as 3D objects, part of a larger group of city objects integrated in a 3D city model.

3.2 GVX-GPR – An integrated approach

3.2.1 The GIS system - GVX GPR module

To support GPR deployment in the field and thus improve 3D data collection of UUN, Web and GIS capabilities is proposed on portable devices via a Platform-as-a-Service tool called GVX; a marketplace for WebGIS, designed by Geovoxel (http://geovoxel.com/). Geovoxel is currently performing GPR surveys and it has been noticed that the GVX platform has the potential to be a suitable tool in improving the execution time and quality of delivered GPR data by assisting this 3D data pipeline.

The GVX platform integrates spatial data collected by remote sensors such as geotechnical instruments for mitigating, on-the-fly, the hazards such as landslides, water floods, dam cracks, and infrastructure collapsing. The GVX also has an innovative dashboard (Figure 3.4) to support the decision-making process, being a multifunctional GIS which integrates multiple specialized modules in different areas of civil/construction.

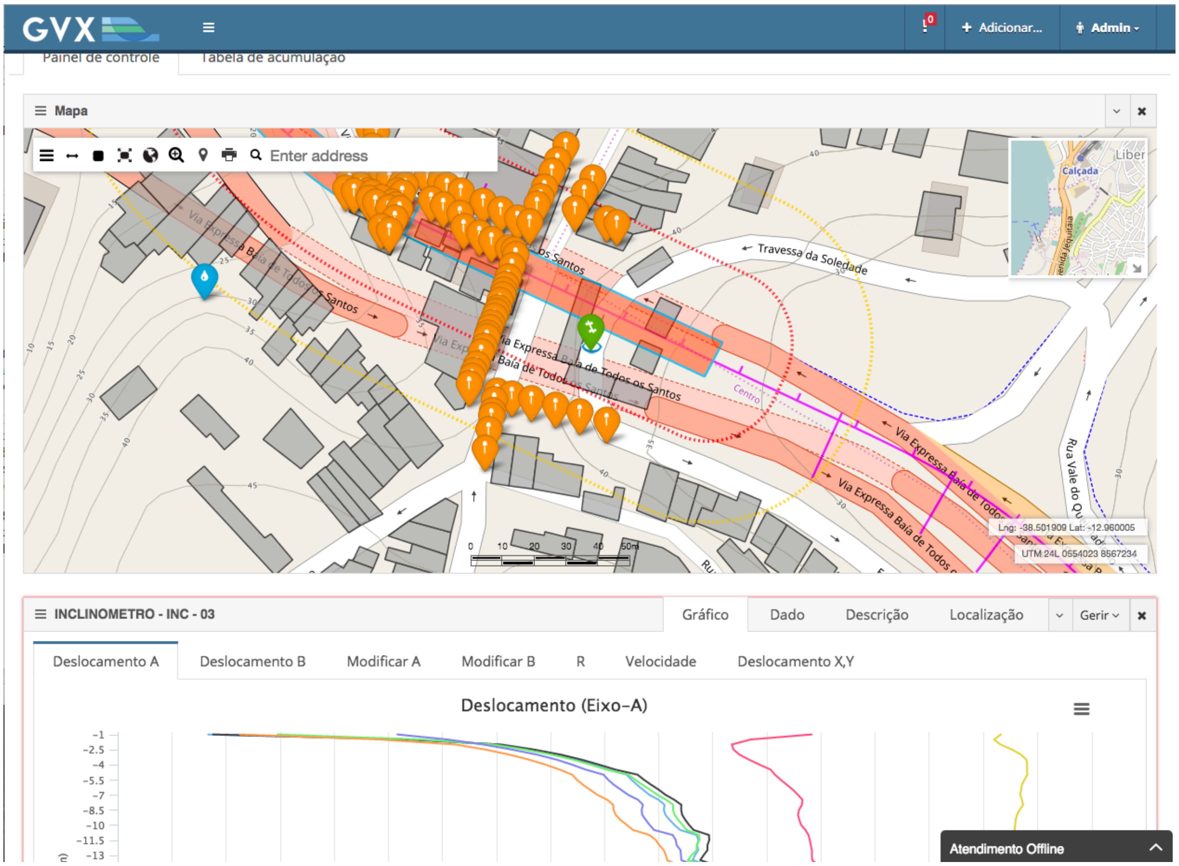

Figure 3.4: Current GVX's dashboard.

Whilst Geovoxel has the expertise to manage GPR data, the GVX platform still needs improvements for the identification of UUN. The new GVX-GPR module aims to help GPR operators to:

- Conduct a more complete GPR investigation;
- Increase efficiency of post processing by reducing uncertainties of collected data;
- Perform smoother and faster production of integrated and versatile maps of GPR investigation to support decision making process for field survey as well as industry-fashioned documentation;
- Propose more reliable underground infrastructure 3D models, available to a larger community of users.

3.2.2 Preliminary Results

The results of this project can be classified into two groups. First, the design of the new GVX-GPR module is required and, second, field experiments with GPR operators is performed in order to test the usability and feasibility of the GVX-GPR module. The first phase related to the design of the GVX-GPR is almost complete, while the second phase of field experiments is just starting and will be ended within months.

Regarding the design of the new GVX-GPR module, the overall use case settled for the GPR operators is given in Figure 3.5. It proposes capabilities to handle GPR data, to integrate various categories of spatial data, visualize, and export data. Next, in Figure 3.6, the class diagram designed to store the spatial data is presented. The data model has its basis found in the CityGML NetworkUtility ADE model (Becker et al., 2013 detracted by the topological component due to the territorial scope of a GPR survey.

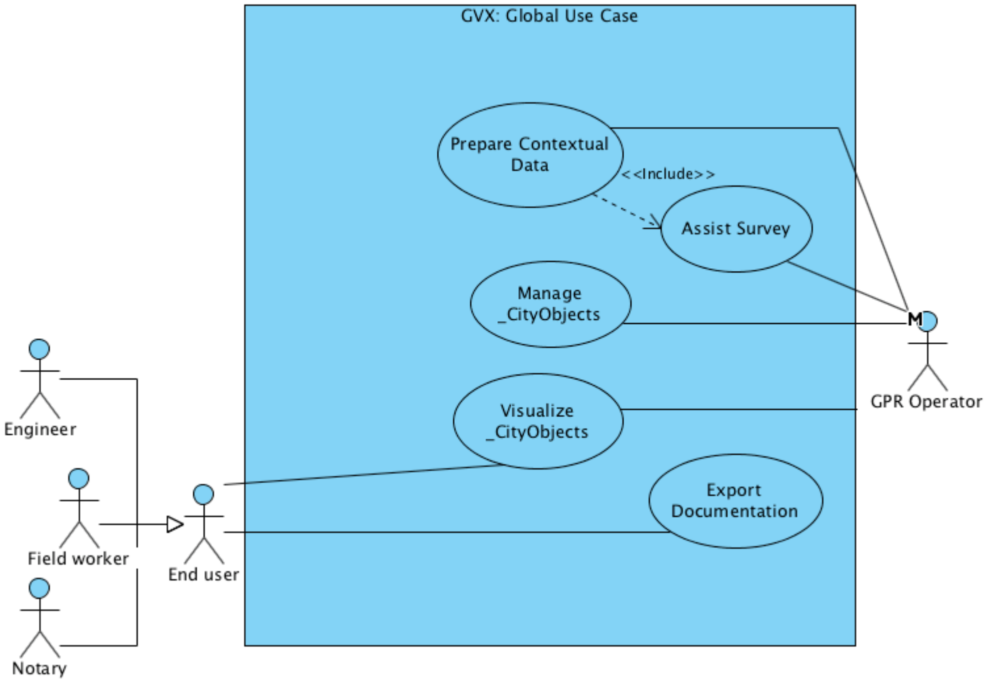

Figure 3.5: Use case of the new GVX-GPR module.

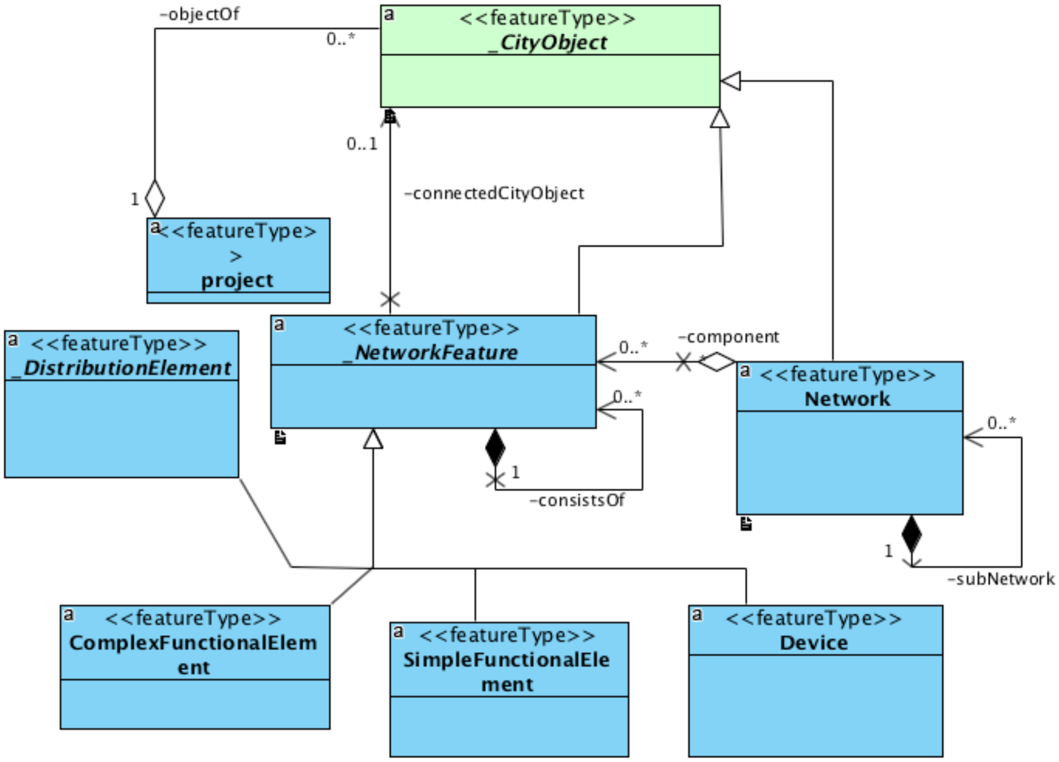

Figure 3.6: Class diagram of the new GVX-GPR module.

Examples of the proposed GVX-GPR interface are provide in the following figures. In Figure 3.7, a GVX-GPR's mock-up available on portable device as tablet, allowing the overlapping of exist spatial data as road, footprint of buildings, and UUN, is shown. Even though the collected data has 3D information as Z coordinates or depth, the current interface is preliminarily 2D. Based on experiments (Pouliot et al., 2016) and the time constraints to improve GVX that currently offer 2D viewing interface, map and vertical profiles (or cross-sections) were estimated more convenient to interact for the target audience. The integration of a horizontal slice of a 3D GPR cube and existing spatial data is given in Figure 3.8. Finally, a multi-map interface which facilitates the planning of the survey by allowing GPR users to identify, previously going to the site, obstacles posing challenges to the process is displayed in Figure 3.9. Moreover, improving the capacity of finding cues and identifying points of interest after the acquisition has finished, accelerating the post processing time, and increasing data quality are other needed improvements.

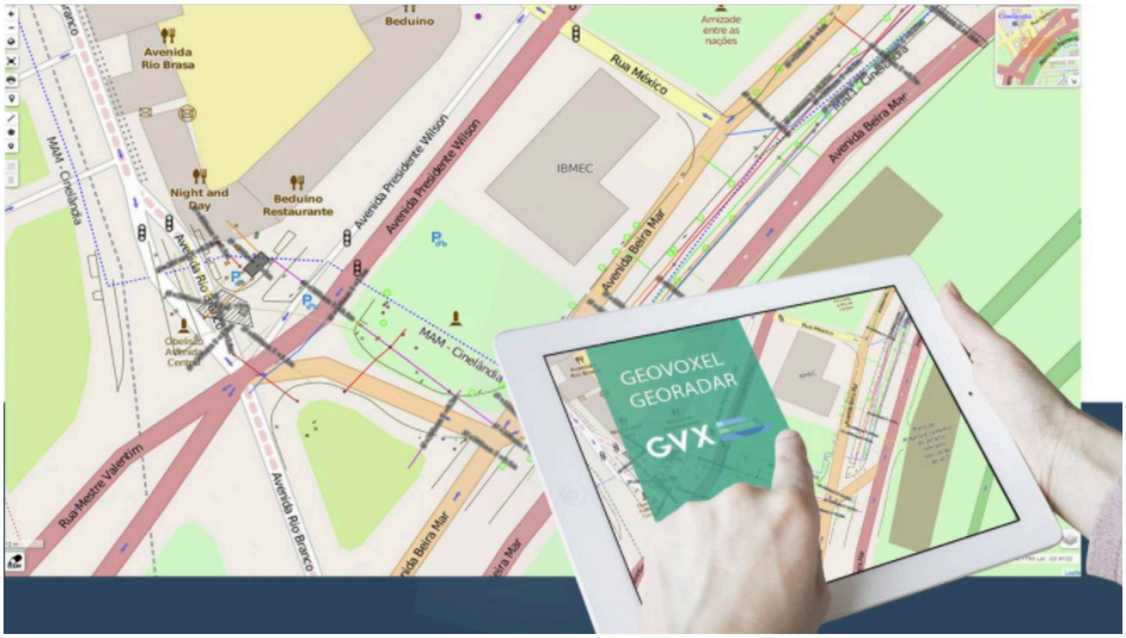

Figure 3.7: GVX-GPR mock-up interface.

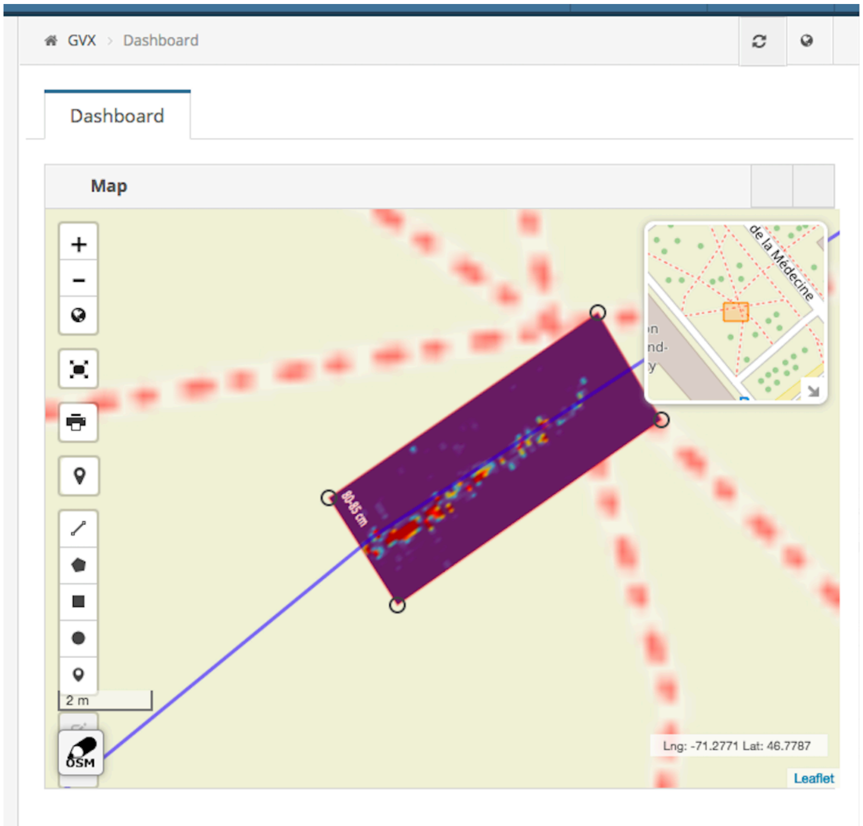

Figure 3.8: A georeferenced horizontal slice of a 3D GPR cube (purple rectangle) overlapped with the existing information (road in red and pre-surveyed UUN in blue).

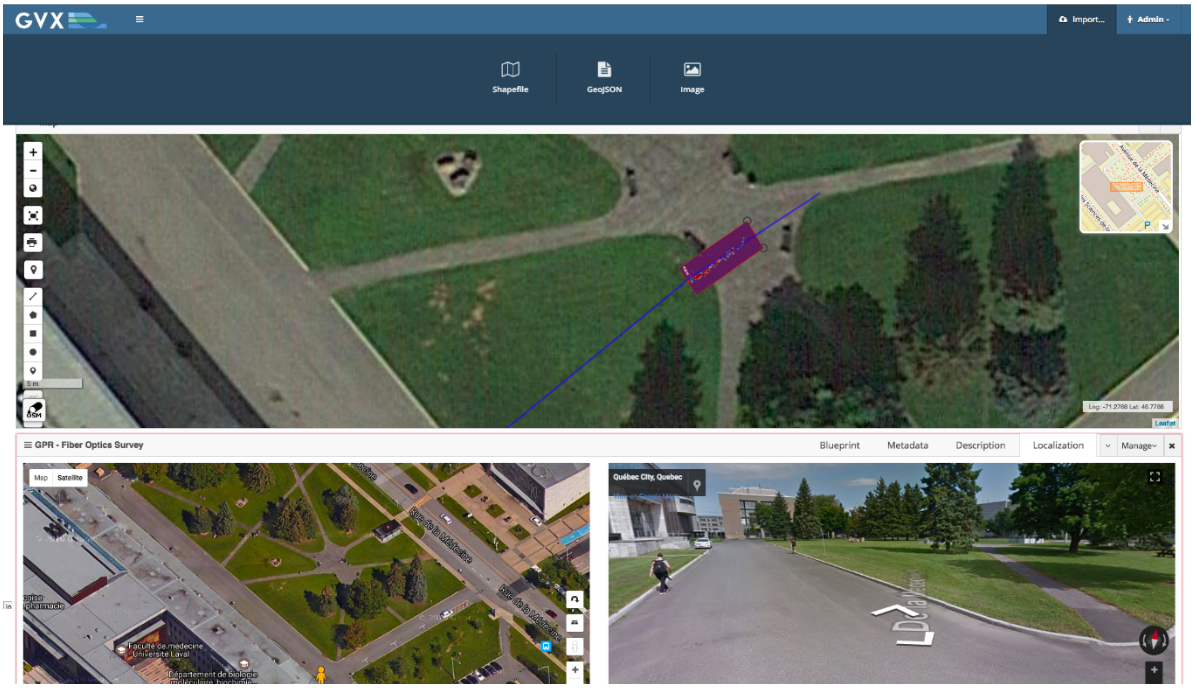

Figure 3.9: A multi-angle view of the studied site.

3.3 CONCLUSION

This project proposes the development of a new Web-GIS based tool to improve GPR field surveys. Having Web and GIS functionalities integrated to GPR instrument and software appears to us as an innovative improvement to GPR operators since it may significantly increase the completeness of surveys and, thus, increasing efficiency of post-processing data, higher levels of data reliability, hence, reducing costs and accidents related to UUN's damage. End-users as industries of construction or land planner authorities would benefit from the solution by having access to more precise x, y and z location of underground infrastructures. Furthermore, applying a standardised data modelling that consent 3D data management as CityGML to GPR data acquisition and processing, will allow us to demonstrate the importance of having integrated the underground network in the 3D city model environment.

As indicated, the project is still ongoing and, whereas the design phase is almost completed and approved, the next step is to perform field experiments with GPR operators to complete the second validation phase related to usefulness and value added. Currently, two user categories (GPR specialist and non-specialist) and experiments are planned. GPR specialists will allow us to validate our initial hypothesis and objectives while the second group of testers (not GPR specialist) will initiate discussion on how GPR-GIS instruments/software can be suitably exploited in mapping UUN as part of 3D land information system.

Chapter 4 - Detection of buried infrastructures using ground penetrating radar: The validation of a map-based approach for GPR users

Résumé

Dans ce deuxième article, l'approche développée dans ce projet de maitrise et une version améliorée de l'outil GVX-GPS sont expliqués avec plus de détail. En particulier, quatre fonctionnalités sont développées et expliquées, soit (1) l'intégration cartographique, (2) les géo-annotations et les points d'intérêt, (3) le géoréférencement de radargrammes et, finalement, (4) la visualisation géoréférencée des profils de GPR. Cette approche a été testée auprès de deux catégories d'utilisateurs; soit des praticiens experts et non experts en géophysique. Selon ces utilisateurs, l'approche proposée peut considérablement améliorer le déploiement de levés de GPR. À l'aide de cette approche, les utilisateurs peuvent découvrir des objets souterrains non cartographiés préalablement, délimiter la zone d'étude et à interpréter des ensembles complexes de données de GPR. Cette approche optimise le temps et facilite l'interaction entre les profils de GPR avec les ressources cartographiques afin de produire des cartes fiables et conformes aux normes géospatiales telles que CityGML.

Detection of buried infrastructures using ground penetrating radar: An integrated approach enabled by GIS and Web technologies

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Abstract

This paper proposes an approach to improve the deployment of ground penetrating radar (GPR) to detect and locate urban infrastructures. It consists of exploiting geographic data layers, database management systems, and a WebGIS, allowing users to handle GPR data within a georeferenced environment. A new module, based on the platform GVX, is developed that provides users with four features, being (1) map integration, (2) geo-annotations and points of interest interaction, (3) radargram georeferencing, and (4) georeferenced slice visualization. Experiments with two categories of users, expert and non-expert GPR practitioners, have been performed. Based on the users' evaluation, the approach is valuable and can significantly improve GPR deployment. It helps users when discovering unmapped underground objects, delimiting the survey area, and interpreting GPR complex datasets. Overall, the approach optimizes time survey and facilitates the interaction between GPR profiles and 3D meshes with map resources, allowing users to produce reliable maps, conforming to geospatial standards (CityGML).

Keywords: Ground Penetrating Radar, GPR, GIS, Underground Utility Networks, Spatial Data Integration, UUN, Spatial Database, 3D Data Acquisition, Geospatial, Geophysics

4.1 INTRODUCTION

4.1.1 Underground Utility Networks' Detection and Damage Prevention

With the increasing number of services offered to the population such as telecom, electricity, sewerage, water, the agglomeration of infrastructures supplying these services is proportionally ascendant, creating a complex and invisible-to-human-eyes mesh of vital underground utility networks (UUN) (Jeong et al., 2004; Navigant Consulting, 2005). In Figure 4.1 an example of such a situation in the city of Rio de Janeiro is shown. In complex construction sites and large infrastructures, the lack of information on the subsoil may lead to damage of buried infrastructures during excavation and interruption of crucial services, inducing high repair costs and delaying constructions (Costello et al., 2007; Lew and Anspach, 2000; Metje et al., 2007). For instance, in 2017, Info-Excavation reported over five damages per business day in the province of Québec, Canada, implying an increase of 11% in the number of damages relative to 2016, which already represented CAD$123 million in social-economic-related, direct and indirect, costs (Info-Excavation, 2017). Countrywide, the social-related costs were estimated at almost one billion CAD per year (CCGA, 2016). In an assessment study of US/UK-based companies, contractors, and clients, as presented by Metje et al. (2007), seven companies have had 4017 utility-related incidents over a four-year period from 2010 to 2014.

Figure 4.1: Example of underground utility networks, Rio de Janeiro (Courtesy of Geovoxel).

With the social, economic, and health danger taken into consideration, private and public institutions have been uniting their efforts to properly locate and map underground utility networks (U.S. Department of Transportation, 2014; Pouliot et al., 2015; Pouliot and Girard, 2016). With this goal in mind, stakeholders should know beforehand taking decisions about new urban developments or interventions how structures are laid in the ground to avoid costs and inconveniences to the population and environment. This emerging field of locating and mapping underground infrastructures has gained visibility and became a new domain of expertise called subsurface utility engineering (SUE). In an assessment of Leuderalbert (1999), for every dollar spent on SUE, a value of $4.62 is saved.

4.1.2 Problem statement

Underground infrastructure's data still relies on a seemly complex set of constraints regarding its efficient acquisition, interpretation, sharing, modelling, and visualization. These issues rise when the installation of underground infrastructures is made with an improper level of accuracy and/or documentation, promoting deficient map resources.

Even though standards formalize best practices (ASCE, 2002; BSI, 2014; CCGA, 2014; CSA, 2016), the vast majority of underground infrastructures have been built years, sometimes decades, ago when standards and best practices were not yet in place. This led practitioners to develop ways of detecting these buried objects destructively, via boreholes, for instance, and later on, non-destructively, using geophysical methods. One of the most accepted and emerging non-destructive techniques to gather subsurface data, to detect and locate buried infrastructures and more, is the Ground-Penetrating Radar (GPR) (Benedetto and Pajewski, 2015; Jaw and Hashim, 2013; Metwaly, 2017). By using a GPR system with antennas capable of transmitting and receiving electromagnetic pulses, users can assess not only the stratigraphy of the ground but also identify subsurface utilities and their location (Daniels, 2004).

Although the use of GPR is growing in popularity, its manipulation and parametrization are not trivial and the interpretation of GPR profiles is still challenging even for experts, depending on the complexity of underground facilities, depth of burial, and soil characteristics. (Benedetto and Pajewski, 2015; Cassidy, 2009; Jol, 2008; Rahman and Zayed, 2016; Li et al, 2016). The interpretation of GPR data is the most time-consuming part of a survey and may take longer than its realization itself in the field (Jol, 2008; Rodrigues, 2016). It is generally done with highly specialized software, in a stage called post-processing phase (Benedetto and Pajewski, 2015). Compared to LiDAR (Light detection and ranging) sensor which propose similar scanning systems as GPR surveys, GPR data does not present interpreted data (distance between the instruments and a known target).

The processing of GPR data and interpretation of radargram requires specific skills and knowledge, similar to the ones of setting up the parameters of GPR instruments critical to the GPR survey quality.

In an assessment carried out in the frame of the study presented herein, where three companies in North America and one in Brazil were interviewed, due to time constraints or *seemly* low complexity of the targets (an often deceptive assumption), most surveys do not undergo interpretation in the office and even more do not comply with SUE standards. According to the company in South America, only advanced civil engineering works require SUE, and the high costs associated with SUE tend to make the practice unfeasible to contractors. Likewise, even though land surveying companies are looking into expanding their professional's capabilities, the majority of GPR operators are not capable of adequately interpreting GPR scans. In a talk with an American GPR training company, its founder has stated: "Maybe more than half of GPR operators can handle the equipment properly, but less far can process data adequately".

According to Leica[1], a GPR manufacturer, "Using a user-friendly post-processing software reduces the time needed for converting radar data to digital maps by up to 80 percent". There are only a limited number of GPR applications which offer enough features for geospatial data visualization and overlaying GPR data with other sources of data (Dallaire and Garneau, 2008; Li et al., 2015; Tabarro et al., 2017; Themistocleousa et al., 2015; Tischler, 2003; Zheng et al., 2004). Although most GPR's embedded software (e.g. GSSi, Sensors & Software, IDS & Leica, and MALA) propose a real-time display and tools (e.g. signal data processing and hyperbola fitting), the geographic interaction level as adding map annotations, attribute or metadata, drawing line and box or querying spatial data is nearly inexistent. Moreover, GPR data acquired without GPS rarely ends up georeferenced in an official coordinate system, which limits its capability to be interpreted within a map context with multiple sources of valuable geographic data. Compared to the long-existing geospatial technology's interoperability, features, and user interaction, there is room for improving the geographic interface of GPR software.

4.1.3 Objectives

By providing interoperable Web and GIS (Geographic Information system) capabilities to GPR users, it is hypothesized in this study that GPR data acquisition can be significantly less burdensome to experienced and new professionals. More specifically, in terms of data handling and interpretation, it can improve data completeness and quality, at the same time decreasing complexity and time.

With the goal of validating the usability and impact that GIS may have to GPR deployment in the field, an integrated approach, consisting of exploiting geographic data layers, a database management system, and a Web-based information system, is proposed. In this paper, this approach is referred to as a WebGIS-based approach, in relation to its capabilities of providing users with a geographic-coordinate-aware system available at any stage of a survey. In this approach, users can handle GPR data within a georeferenced environment, in which data is always available, from all locations. This new WebGIS-based approach aims to help GPR practitioners to:

- Conduct GPR surveys that bring resources into more effective actions and results;
- Perform more efficient production of subsurface maps, which support the decision-making process during fieldwork;
- Deliver more reliable underground infrastructure data, available to a larger community of users; and
- Reduce the delays and, possibly, the number of returns to the study site, consequently making GPR surveys more efficient.

Based on a literature review here presented and interviews with GPR companies and practitioners, this WebGIS-based approach can be useful and may suggest new practices for surveying UUN. The innovation part of this approach is having user interaction with not only GPR raw data but also integrated map layers directly in the field. Which shall spatially enable GPR operators to have new outlooks when producing GPR profiles and depth varying slices., suitable to refine their understanding of the subsurface area. In addition, being able to geo-annotate and interact with points of interest (POI) observed both on GPR profiles and maps. These capabilities of the proposed approach are singular and they may help to provide interpretation clues related to underground targets and thus initiate, in the field, the challenging process of GPR data interpretation. After the survey, the proposed approach allows the users to integrate GPR raw data, GPR profiles and/or depth slices and geo-annotated POI into a database consistent with open standardized data model and format of 3D cities such as CityGML.

Consequently, the main outcome of the proposed proposal is to serve the needs of not only GPR operators, GPR industry and manufacturers, but also official authorities who are more and more demanding precise and updated information about the location and the depth of underground infrastructures. In having a more precise location of underground infrastructures, the impact for the society may be noticeable by possibly reducing the number of damages during excavation, increasing the security for heavy equipment operators and citizens, and proposing the more efficient use of land. Thus, the decrease in unanticipated costs for repairing utilities and/or lessening risks of services' interruption due to trenching hazards is another major outcome. Finally, this approach may encourage the creation of a new market for the geospatial technology industry, since this segment currently lacks businesses involving GPR handling and data processing.

4.1.4 Methodology

The methodology is based on an engineering approach that aims to identify a problem, design a solution (a WebGIS-based approach), develop a minimally viable software tool with an essential feature to support the approach's deployment, and finally to test the approach by validating it with users. During tests, four features that are currently missing in most of former GPR software were assessed. Users' comments about the proposed approach were collected during and after the experiment via forms and discussions. Since GPR practitioners may have various profiles (as being or not aware of GPR technology and data interpretation, specialist or not in geosciences), the WebGIS-based approach was tested during two field experiments. According to Nielsen and Landauer (1993), finding usability problems has its best cost/benefit ratio when tested with four users, and testing with two users being a minimalistic yet optimized way of assessing the proposition. The first experiment consisted of a GPR operator who is considered skilled enough to handle the data acquisition and draw obvious conclusions, but inexpert in further analyzing and tuning the data to obtain conclusive information upon dubious situations. This experiment mostly aimed at validating the usefulness of the approach instead of its specifics. This is also meant to decide whether the proposed approach could help beginners to reach more effective detection and location of underground infrastructures. For the second experiment, a survey was carried out with a proficient GPR operator, who has an in-depth knowledge of geophysical data interpretation and principles. During this experiment, this user evaluated the impact of the approach features in surveys' results and, if relevant, fine adjustments could be applied to the WebGIS-based approach.

The preliminary development of the tools developed in this approach was presented in Tabarro et al. (2017). In this paper, the complete system along with two field experiments are presented. The pros and cons of the proposed WebGIS approach are discussed from the users' perspective. In addition, a more complete literature review on the integration of GIS and GPR instruments is also given.

4.2 Ground Penetrating Radar

Even though this paper does not intend to be a reference in GPR theories and practices, to appreciate the results presented herein, some GPR principles relative to the techniques, device interface, and data processing and integration are briefly introduced.

4.2.1 Principles and Devices

The Ground-Penetrating Radar technique has its first appearances in 1929 (Stern, 1930) and later in the 1960's (Benedetto and Pajewski 2015). GPR systems, regarded preliminary as too complex, have been evolving over the decades not only to improve quality of the acquired data but the handling of the equipment, which required an extremely high level of expertise (Annan, 2009; Rahman and Zayed, 2016; Jol, 2008). Daniels (2004) is a good reference for the GPR techniques. In summary, GPR systems, as highlighted in Figure 4.2, involve the use of control units composed of antennas for transmitting and receiving the radar signal and a display unit. The receiver component usually allows signal sampling and processing and recording options. One example of a GPR device mounted on wheels, which is small and mobile enough to survey local area in an urban environment, is given in Figure 4.3.

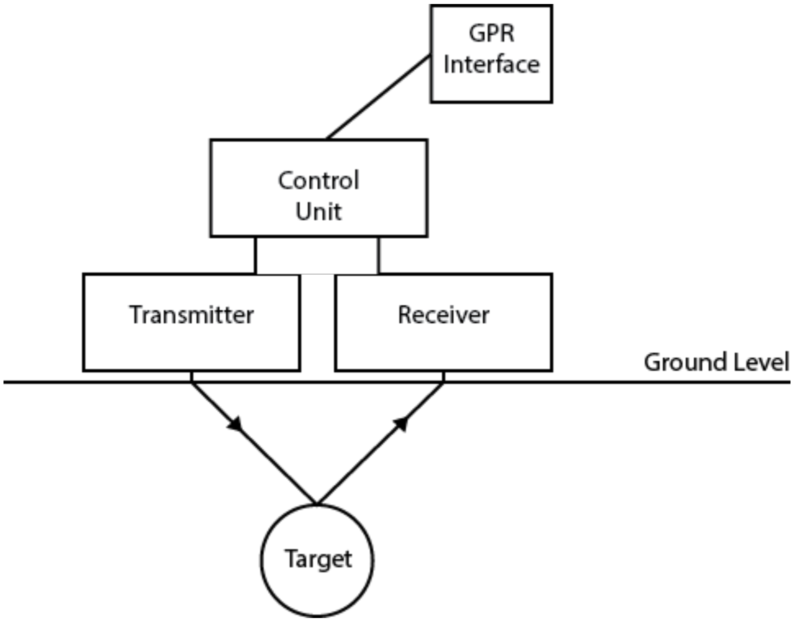

Figure 4.2: Block diagram representing the components of a GPR.

Figure 4.3 : MALA X3M in action at Université Laval – Québec.

GPR devices use the electromagnetic signal in the microwave band frequency, which usually ranges from 30 MHz to 3GHz. However, commercial GPR's tend to have frequencies from 50 MHz to 1GHz (Benedetto and Pajewski 2015). As a rule of thumb, the smaller the buried features being searched, the higher the frequency has to be but smaller depth of investigation in the ground is achieved than for low frequency (Syntek Report, 1988). On the other hand, large features, such as water mains or even geological formations, would be better seen by low frequencies and possibly at large depths.

The identification of features on GPR profiles happens through the difference of the dielectric properties of materials. As shown in Figure 4.4a, GPR profiles contain hyperbolas that are the results of the dielectric constants' difference between the material of a buried object and the surrounding soil. This difference dictates if the hyperbolas are well formed and visible with minimal effort or if they will need processing in order to clarify the interpretation. For instance, an ideal scenario for a day-to-day GPR interpretation would be a metallic pipe buried in very dry sand, since their dielectric constants are almost completely apart in the spectrum. On the other hand, GPR users would have difficulties to find the very same pipe in very wet soil, due to a smaller relative permittivity (ε_r) of the surrounding soil. This is especially important for GPR users to acknowledge, since it can be a limiting factor for the depth of investigation in the ground and noise or poor definition of radargrams, due to the high signal attenuation.

Based on the characteristics of the buried features to detect and the ground, GPR users have to select the proper center frequency depending on the antennas used, time window, time sampling interval, station spacing, antenna spacing, antenna orientation, and survey lines orientation and separation spacing to carry out a GPR profile (Annan, 2009). The acquisition of GPR subsoil images can be achieved through multiple survey lines, some in parallel and some perpendicular, and close to each other, which are combined to create an equally-spaced 3D mesh (Figure 4.4b). After the GPR data collection, data processing and enhancing is required as editing, rubber-banding, dewow, time zero correction, filtering, convolution, elevation correction, depth conversion, etc. (Sensors & Software, 1999; Syntek Report, 1988).

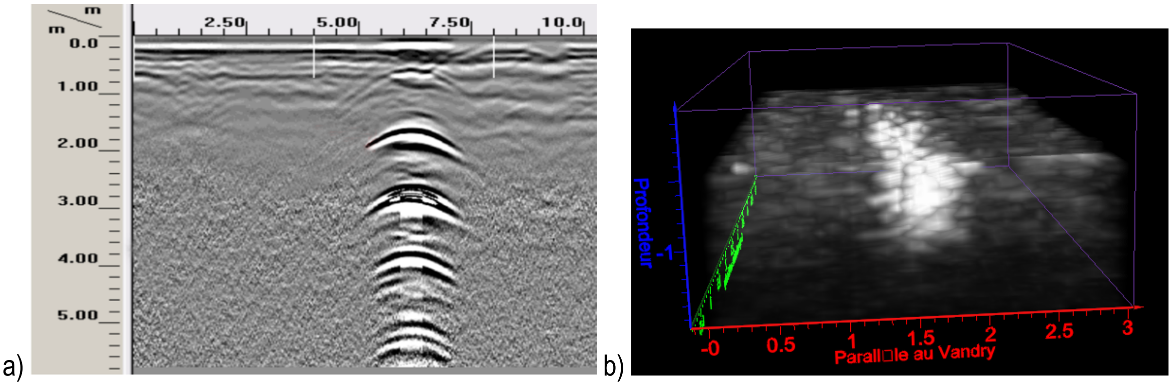

Figure 4.4: GPR data: a) Radargram showing a clear target, being the X-axis the distance and Y the depth of investigation (courtesy of Geovoxel), b) 3D cube of a buried cable produced using Voxler, the blue axis indicates the depth while the red and green axis are the X and Y distances (source Pouliot et al., 2016).

4.2.2 Technology and map-based systems for GPR

GPR technology has been evolving for the past years, and apart from GPR manufacturers, third-party companies and open software initiatives have shown interest to develop tools for GPR data acquisition such as GPRSIM[12] and gprMax[13] for the simulation of GPR data and ReflexW[14], RGPR[15], and GPRSlice[16] for its visualization and handling.

Despite their efforts, only GPRSlice provides users with a geographic interface, allowing users to visualize GPR data on top of a map, in a 3D environment, during post-processing. Among GPR manufacturers, Sensors & Software and IDS have also shown interest in the development of map-based interfaces. Based on GPR software technical documentation, literature review, and interviews with representatives of GPR manufacturers,

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[12] https://www.gpr-survey.com/gprsim.html
[13] http://www.gprmax.com/
[14] http://www.sandmeier-geo.de/reflexw.html
[15] https://github.com/emanuelhuber/RGPR
[16] https://www.gpr-survey.com/

a synthesis of features that refer to data visualization and user interaction is given in Table 4.1. This synthesis is not exhaustive, but rather the result of a brief investigation to identify missing features of the current GPR software. As it can be seen, most GPR manufacturers propose user interfaces with minimal options for interacting with the data (as zoom, pointers). Almost no system is offering functionalities to georeference the radargram or integrate geospatial data and information.

Moreover, as a part of the existing technology and domain assessment done by Geovoxel in South America, among 13 companies offering GPR survey as a service, none of them offered georeferenced data as a final deliverable. All of them propose reports (text manuscript and figures) and CAD (Computer Aided Design) plans as deliverables and may, upon request, provide Esri-Shapefiles containing the survey's results. Other studies also support the findings of this assessment (Jeong et al., 2004).

Table 4.1: Review of GPR options for displaying and interacting with data (yes = feature observed, no = feature not observed, partially = feature is there but not fully operating).

Features	GSSI - Utility Scan PRO[17]	GSSI - Utility Scan[18]	GSSI - Utility Scan DF[19]	SENSOFT - LMX SERIES[20]	MALA - HDR Locator[21]	IDS - Opera Duo[22]
Natural User Interface (touchscreen)	No	Yes	Yes	Yes	No	Yes
WIMP*	Yes	Yes	Yes	Yes	Yes	Yes
Zoom	Yes	Yes	Yes	Yes	No	Yes
Radargram Geoferencing	No	No	No	Partially	No	Yes
Slicing	Yes	No	Yes	Yes	Yes	Yes
Georeferenced Slice Visualization	No	No	No	Partially	No	No
Map integration	No	No	No	Partially	No	Yes
Geo-annotations, Geo-annotated images, and Points of Interest	No	No	No	Partially	No	Partially

*WIMP = Windows, Icons, Menus, Pointer style of interaction of the user interface.

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[17] http://www.geophysical.com/utilityscanpro.htm
[18] https://www.geophysical.com/products/utilityscan
[19] https://www.geophysical.com/products/utilityscan-df
[20] https://www.sensoft.ca/products/lmx100/overview/
[21] http://www.malagpr.com.au/easylocator-hdr-locator.html
[22] https://idsgeoradar.com/products/ground-penetrating-radar/opera-duo

4.2.3 GPR and GIS Integration

The integration of GPR data with external spatial data has become more and more relevant (Buccella et al., 2009; Doan et al., 2012; Dong and Srivastava, 2015), and projects around the world have demonstrated how valuable this integration is since the early 2000's.

Klempe (2004) has demonstrated an application integrating 3D data, GIS, and GPR to identify quaternary subsurface glacial resources. For this application, GPR profiles were acquired, showing ground information along X and Z coordinates. GPR profiles were interpreted and features along the GPR profiles have been identified. These features have been then digitized and used along with drilling logs to create a more accurate mapping of the glacial beds. In India, a more complete approach (in terms of the amount of data) based on GPR, GIS, and remote sensing was undertaken to identify faults occasioned by the Indian tectonic plate (Bhosle et al., 2007). Other efforts have also been made in this direction, such as in Peru, where GIS and GPR were used to identify geoarchaeological monuments, layers, and volumes (Sandweiss et al., 2017). Ercoli et al. (2013) analyzed a tectonic basin in Italy through GPR profiles, using GIS, to assess the potential of GPR to image shallow geological faults. In Scotland, a similar approach was used to study palaeosols along the coastal line with GPR profiles (Chapman et al., 2009). Al-Ruzouq and Abueladas (2013) showed an example of GPR profiles along with 3D modelling, photogrammetry, digital elevation model, and orthophotos to generate 3D models of the upper ground and subsoil. GPR horizontal slices were created and superposed on a map interface to facilitate the interpretation via slicing, complementing the data with borehole logs as ground truth and calibration basis. In Slovenia, GPR and GIS were combined to estimate the geometry, volume, and characteristics of a major landslide area related to a likely breakdown of a rock mass (Verbovšek et al., 2017).

These are some examples which showcase the potential of GPR and GIS combined for the analysis of complex geological phenomena, demonstrating that the synergy between the two is long existing but only brought to attention in recent years.

4.2.4 Standards and Procedures

About the standards and procedures related to GPR survey, initiatives for properly formalizing practices and assess the quality of data for SUE have been emerging over the last decade. In the United States, the American Society of Civil Engineering (ACSE) has proposed the standard ASCE 38-02 which describe four levels of quality and their means of acquisition (ASCE, 2002). Both Canada (CCGA, 2014; CCGA, 2016) and Malaysia (National Mapping and Spatial Data Committee, 2006) have similarly followed the framework and implemented the respective standards CSA S250 and the Standard Guideline for Underground Utility Mapping. The American and Canadian standards not only propose methods but also standardize how data is represented.

In the UK, British Standards Institution has proposed, alongside clients and contractors, a thorough guide for data acquisition of the underground (BSI, 2014). PAS 128 of this guide establishes a framework for quality levels' requirements and the procedures recommended to achieve so. In a more detailed manner, varying from verification of the exposed infrastructure to simply accessing previously mapped data on location analytics solutions, British standard proposes that for a certain level of quality expected for the project, a certain density of survey lines is required, explicitly establishing the procedure which GPR users can follow.

As the single most important point of convergence between these standards, all of them propose as the best practice the mapping of UUN while they are still exposed, aiming to avoid costs and errors that are tightly correlated to other acquisition methods. The benefits of having well-defined standards and procedures are unquestionable, but they have to be strengthened as numbers still show a linear, if not growing, number of damages per day. If these procedures are followed accordingly, a sustainable development of the underground infrastructure would be achievable.

4.3 An Integrated WebGIS-based Approach

This review reveals that the coupling between GIS, Web, and GPR practices is currently loose-fitting. Consequently, a WebGIS-based approach is proposed herein that will allow GPR practitioners to handle, in the field, GPR data within an integrated and georeferenced environment. This WebGIS-based approach is divided into three major phases as Pre-survey, Survey, and Post-survey (Figure 4.5):

- **Pre-survey** consists of GPR users gathering and structuring, in the system, the available documentation from the area under investigation, based on what stakeholders require. Once the system contains enough contextual information (e.g. base maps, satellite imagery, annotations, etc.) users are able to analyze the area and identify possible obstructions or special requirements of the survey. In the pre-survey, users may follow their regional SUE standards which may recommend survey settings (e.g. mesh spacing), such as PAS 128 in the UK.
- In the following phase, the **survey** itself, users arrive on-site and undertake the data acquisition. Once the to-be-surveyed area is delimitated, users can carry out the GPR profiling and perform, at the same time, geo-annotations of relevant features of the investigated area.
- The final phase called **post-survey** occurs when users do on-site or off-site visualization of GPR data and geo-annotate them as likely underground infrastructures to be detected and located, also called

points of interest. Thus, deciding whether or not the information is enough to achieve the goal requested by stakeholders in charge of the project.

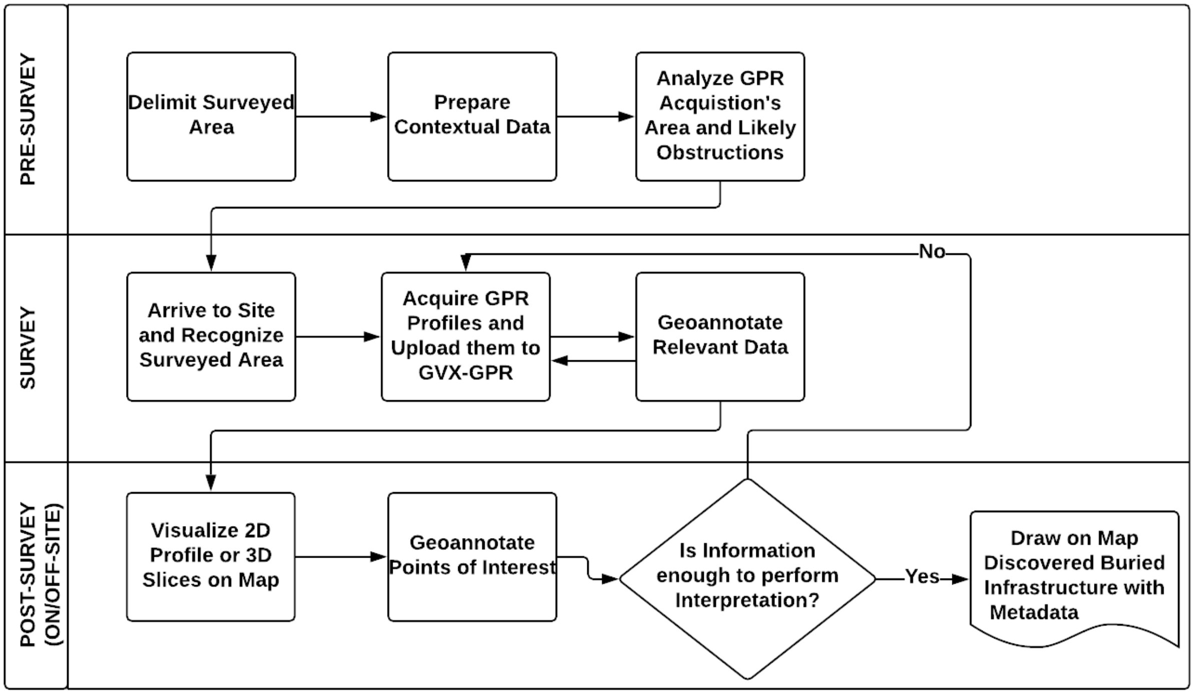


Figure 4.5: The WebGIS approach proposed to assist the deployment of GPR surveying.

Since the approach is based on database management system, it relies on a standard model widely used for 3D city models, CityGML, which contains an application domain extension for UUN, named Utility Network ADE model (Becker et al., 2013). CityGML, thank to this ADE extension, is the choice made in this preliminary design of GVX-GPR due to its potential to semantically describe underground utilities and the surrounding components (above and below ground level). Also, CityGML integrates other relevant *_CityObjects*, which can be a resourceful asset when performing surveys and management of 3D city models for a complete risk assessment. From an interoperability standpoint, having a database based on a widespread standard is a major advantage in the proposed approach, considering that collected data can be shared by a larger community and exported to other tools.

With the above guideline outlined, four features tightly coupled with the geospatial domain were selected by being estimated to be valuable and testable within the scope of this study. They are outlined and explained next.

Feature A – Map Integration

GPR surveys, at an industry level, rely on bare, if not missing, documentation. By providing users with a cartographical interface and access to various layers of structured spatial data, even as simple as road maps and VGI (volunteered geographical information), the boundaries and clues on where underground objects are located can be significantly more evident. With the ability to integrate non-proprietary map resources and images as layers for survey areas, the visual comprehension of the studied area is substantially increased. Moreover, by having access to a geodatabase, users should be able to connect to other map resources, taking advantage of the interoperability proposed by standards such as IFC and CityGML. Currently, the GPR community relies on general-purpose GIS's aside the GPR systems, which shifts away from the idea of an integrated approach.

Feature B – Geo-annotations, Geo-annotated images, and Points of Interest

During a GPR survey, users look for ways to tie visual cues to the acquired underground data, usually registered by photos and annotations in a field book. To improve this process, users should be able to more precisely pinpoint in a map where this visual sign is located and what it looks like. The lack of ability to correctly draw objects on a coordinate-aware system often leads to a dubious interpretation of data and/or demand further visits to the studied site. In the survey phase, most GPR's with geographical interfaces offer geo-tagging tools, but none of them let users draw geo-annotations (for instance, a polyline to represent a feature on the ground surface). By letting users to geo-annotate photos and draw on a map during the survey, and add points of interest during the on-site or off-site post-survey stage, ambiguous information can be considerably reduced. Moreover, despite data being offered by data providers, such as Google and OpenStreetMaps, it lacks exactitude due to new developments that may have happened in that area since the last data acquisition. Google Street View can be taken as an example; photos from the same area are taken within months of periodicity. For this reason, users should be able to generate new maps, which can be combined with other map layers to depict in details the surveyed area.

Feature C – Radargram Georeferencing

With an increasing number of GPR's with built-in GPS, the gathered geographical coordinates are a bridge between the GPR profiles and GIS. However, as seen in the GPR feature's evaluation (Table 4.1), most GPR systems do not count on such a geographical interface. As for GPR's that do not have built-in GPS and/or the survey takes place where GPR signal's strength is too weak, radargrams do not have a direct way of being attached to a coordinate system. The overlay of GPR radargrams within a map context proposes a way of drawing lines and polylines onto a map and binding them to profiles. For now, this process of georeferencing GPR profiles is manually done if no GPS is available.

Feature D – Georeferenced Slice Visualization

Whereas most GPR software are able to display slices of the 3D data acquired, the connection between a 3D GPR mesh and maps is inherent. If users manipulate 3D data in different coordinate systems rather than a geographical, they are required to perform a data translation. The superposition of horizontal slices gathered from a 3D GPR mesh should facilitate a more accurate translation process, reducing the gap between these different referencing systems as well as the interpretation error margin. Within a survey context, where multiple GPR profiles are collected to support underground features discovery, the user can select multiple 2D profiles, which are represented by polylines on the map, and generate 2D horizontal slices of a 3D mesh based on the profiles within a drawn bounding box. These 2D horizontal slices are overlaid with other selected layers to allow accurate location of underground features. The interpolated 3D data facilitates the process of identifying targets between lines, covering the gaps, thus giving more certitude to the survey's interpretation.

4.4 Experiments

The final step of the study presented herein is to test the approach and, in particular, examine the utility of the approach from the users' point-of-view. Finding GPR operators available for performing such test with the new system was not easy to achieve in the timeline. Two experiments were performed; each one testing a set of features with distinct users and study sites. The feedback from the users was recorded via a questionnaire and further discussion.

4.4.1 First Experiment

4.4.1.1 Case study

For the first experiment, a professional locator called the user in the following with a limited knowledge of geophysical principles and theory was selected. The goal of this experiment was to check if non-specialists in geophysics can achieve more effective detection and location of underground infrastructures when performing a GPR survey with the software-based approach. This experiment was performed with a GPR Mala X3M equipped with 200 MHz antennas and took place in the campus of Laval University, Québec, Canada. The user also had experience with equipment such as pipe locators and auscultation methods, and despite his capabilities of handling this GPR equipment, his main GPR uses related to find buried tanks since the interpretation tends to be complex and the resolution is too low for small targets. The survey area along with red markers for geo-annotated pictures, yellow markers as points of interest, and the red line for the location of the GPR survey line is shown in Figure 4.6. The test consisted of surveying a pre-selected area containing a buried power cable (25 kV) previously identified by a pipe locator and GPR surveys (Lavoie and Pouliot, 2016). It was also expected that the user validated if the CAD plan was reliable or not, according to industry standards.

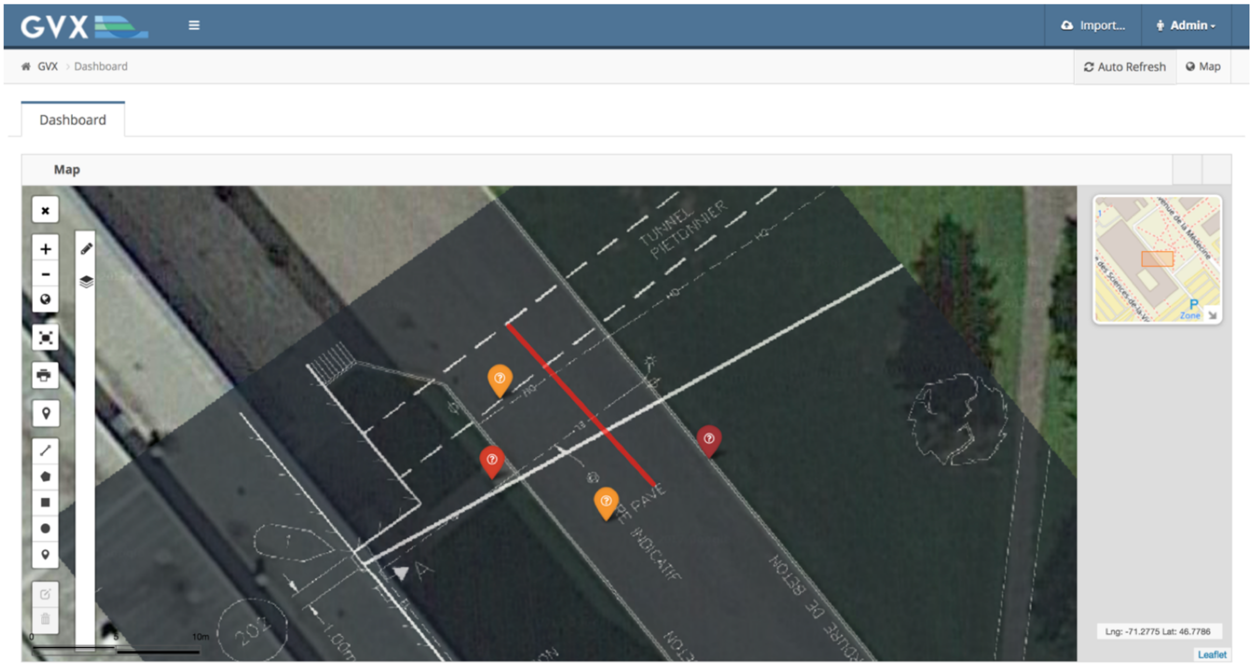


Figure 4.6: The surveyed area located in the Campus of Université Laval in Québec City, Québec, Canada, with one GPR survey line represented in red and points of interest in orange and red in the GVX-GPR user interface

4.4.1.2 GPR Survey

A brief explanatory introduction of the system was given to the user before being asked to follow the steps above mentioned. For this first experiment, the context data available for the project (CAD plan, orthophotography, points of interest, etc.) had already been integrated into GVX-GPR. With the help of the researchers who were present on site, the user identified the boundaries of the survey area based on the system. After being able to delimit the area, the user conducted the survey as usual, while geo-annotating GPR lines and images.

Once the survey was completed, the user considered all the available information to confront with what the CAD plan displayed. The user deploying the GPR and his on-site conclusion about the location of the buried infrastructure by co-visualizing the map, a CAD plan, and the surveyed radargram are shown in Figure 4.7.

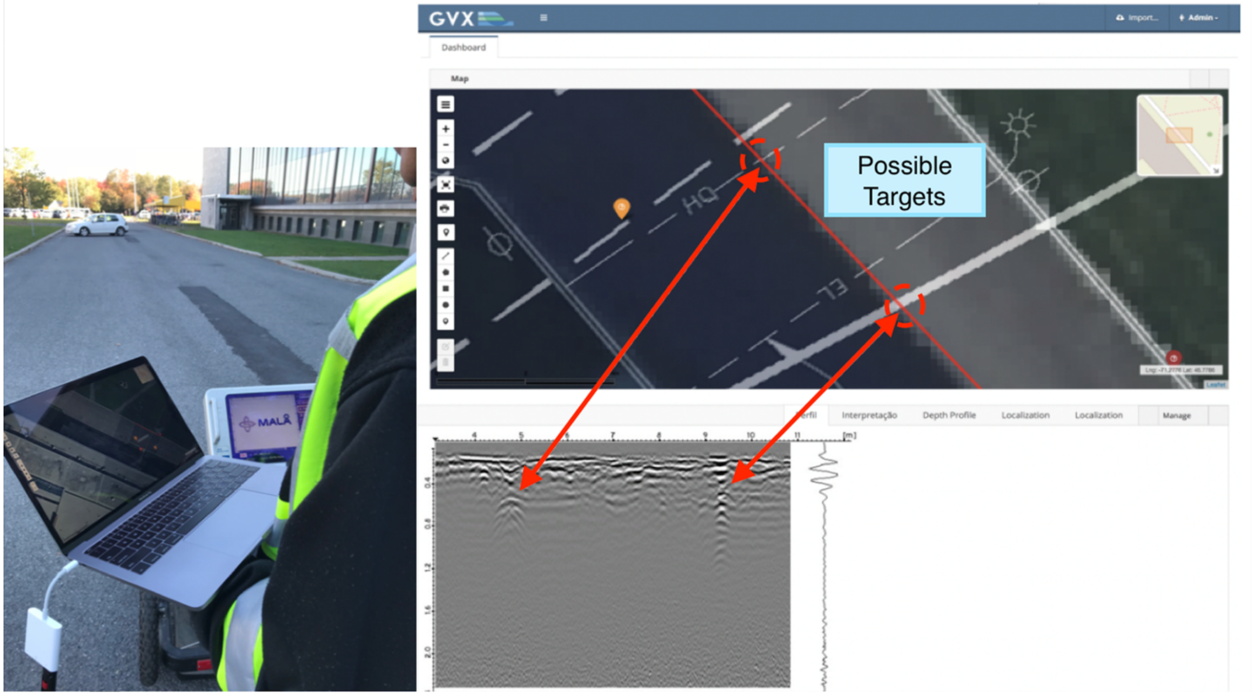


Figure 4.7: GVX-GPR in action - on left the selected non-specialist with the system - on right an example of the user interface with in red the GPR surveyed line and two possible targets located both on the 2D map and the radargram.

4.4.1.3 Results and discussion

After the experiment's conclusion, the user responded to a structured form with questions evolving from closed to open in order to assess the efficiency of the approach and its features (Table 4.2). In the first question, the user rated the approach as very useful. Moreover, most of the time, when he arrives at a given site, he does not know how the site looks like and if there are or not obstacles that may impact the survey. The user said "It happens often for us to receive a request for the location of a water main but we don't know if it is on one or the other side of the street. With more geospatial data, we would have more information to assume where it could be. The ability to have the CAD plan as an image layer, for example, could make all the difference, but it is seldom the case.". He added that the ability to have a prior notion of the study site would allow him to take more conclusive actions when on site, such as seeing poles, manholes, and other exposed cues (on satellite images and street cameras), which would expedite the execution of the survey due to a finer planning.

Table 4.2: Structured form filled out by for the user (non-GPR specialist) of GVX-GPR module after the first experiment in the campus of Laval University, Québec, Canada.

Question	Answer
How would you rate the usefulness of having access to the GVX-GPR module during the survey?	Very Useful
Did the GVX-GPR module help your spatial notion in doing any of the following actions? If yes which one?	Discovering underground targets - YES Decrease the execution time of a survey - YES Save time on finding survey limits - YES Annotating points of interest - YES Storing images related to the field - YES
Did the GVX-GPR module help you to meet your goals?	Apparently helped substantially but a longer period of testing would be required for a conclusive analysis

Even with an overall positive response from the user towards the approach, it was noticeable his unfamiliarity with WebGIS technologies. Although the user appreciated the tool, a longer period of testing and adaptation would provide the user with further freedom dealing with the tool. This first experiment reveals that even with the aim of simplifying surveys, there would always be a potential initial rejection by users. The general impression and usage have been positive, but further testing would allow a more in-depth validation. This owes to the fact that the users rarely performs post-processing. According to him, most of his GPR surveys are very punctual and, most of the time, involve identifying similar objects.

Additionally, from the user's point of view, the most valuable feature of the GVX-GPR module relies on having geospatial data provided by clients or open data sources, which could be added to the system. For instance, he pointed out that even though maps like Google and OSM make a difference, the most difference was having a CAD plan as a layer, which greatly facilitates the deployment of the GPR survey. The hypothesis that geospatial data integration may facilitate the interpretation process can be considered to be partially true, is that day-to-day surveys do not always count on as many sources of information as the test did. Nonetheless, the ability for a user to aggregate more information adds an extra window of opportunity for him to take advantage of existing information.

4.4.2 Second Experiment

4.4.2.1 Case study

The second experiment was performed with an experienced geophysicist also called the user in the following with more than years of experience in surveying methods for underground networks and undersea oil exploitation. The survey area, a street located at Federal University of Rio de Janeiro (Brazil), was selected due to several underground utilities buried underneath, which were already surveyed years back by the user. The equipment used was a GSSi Sir 3000 equipped with 100 MHz antennas. The survey area on which a fictive survey grid is superimposed is shown in Figure 4.8.

Figure 4.8: GPR survey in progress using a GSSi 3000 (100 MHz antennas) along a street located at the Federal University of Rio de Janeiro (Brazil). A fictive survey mesh is overlaid on the photograph to illustrate the survey strategy.

4.4.2.2 GPR Survey

The pre-survey began in the office when the user evaluated the area based on the available layers in the application. A satellite layer and Google Street View were used to help the user to identify possible barriers that could be encountered during the survey. Once this analysis was completed, the user went to the study area and the survey began with the user evaluating the area to geo-annotate items which were of his interest, such as cracks on the asphalt pavement, poles, and objects to be tied with the beginning and end of survey lines (Figure 4.9).

After carrying out the GPR profiles, the user continued by drawing the survey lines on the map and uploading profiles to GVX-GPR. With all the profiles collected and accordingly organized in the software, the user judged that the amount of data collected was sufficient to meet his interpretation requirements. He continued by visualizing the radargrams and generating 3D slices of interpolated profiles. A horizontal slice from the 3D GPR mesh along the extension of the surveyed area and a 2D radargram previously selected by the user are shown in Figure 4.9.

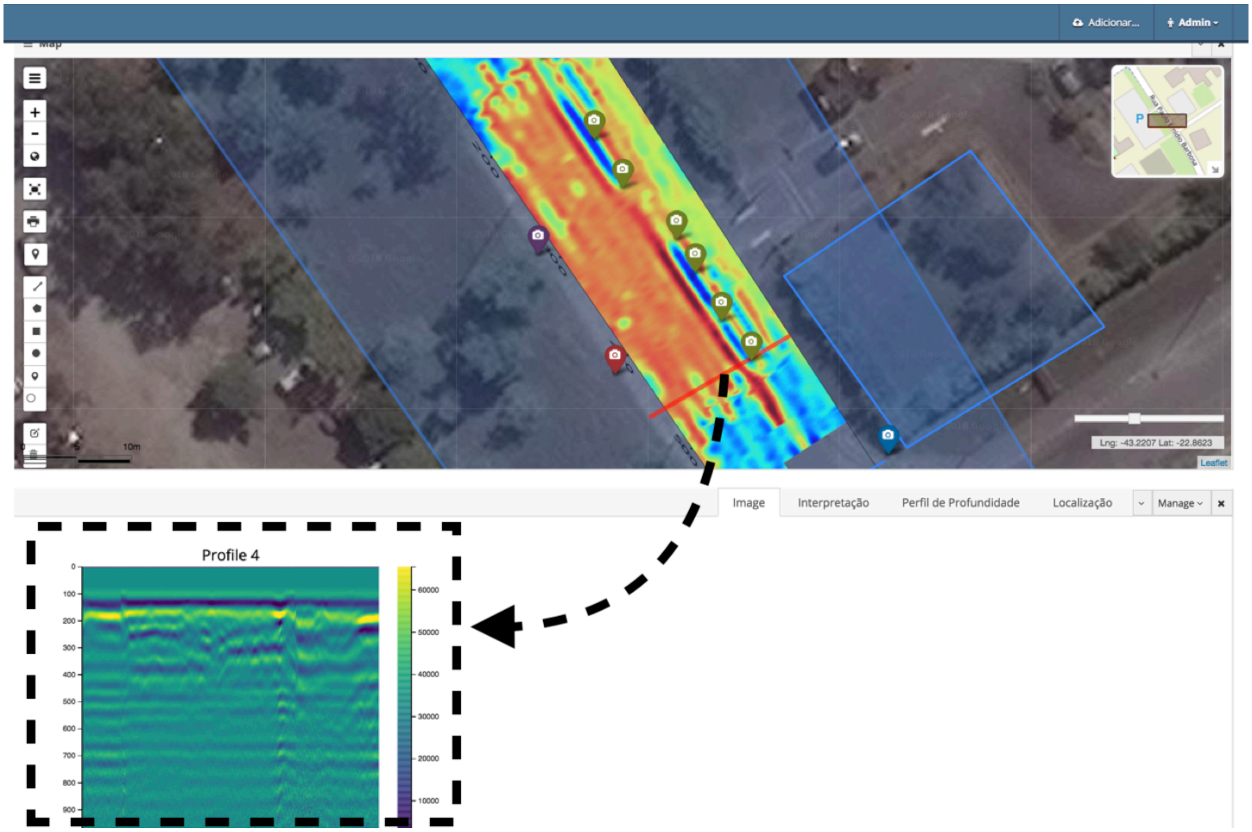


Figure 4.9 : Lower plot: Radargram selected on the map represented by the red line, connected to its respective radargram by the black dashed line with an arrow. Upper plot: horizontal slice from a 3D GPR mesh along the street located at the Federal University of Rio de Janeiro (Brazil) overlapping a Google satellite layer in the GPR-GVX module.

4.4.2.3 Results and discussion

As shown in Table 4.3, a similar questionnaire was used for the second experiment but containing specific sections to evaluate the user's opinion on the time required, data accuracy (X, Z, and Y), data completeness, and usability related to each of the proposed features. The new questions were introduced in a timely matter, succeeding the implementation of features in the tool, at the same time that trying to validate more specific aspects and questions that are relevant to highly proficient GPR users.

For the first part of the questionnaire, the answers given by the specialist were positive, stating that the usefulness of the approach is noticeable, allowing him to discover new targets and avoid losing time searching for the survey area and to generate more documentation through geo-annotations, images, and points of interest. The user mentioned that the system has a potential to help users find the GPR parameters but it is not yet capable. In the last questions, the user stated that even with this different approach (map-based), the ability to add targets on the GPR profile is an extremely helpful feature that standard GPR software solutions offer. He added that the ability to add targets to a GPR profile and see them geoferenced on the map would be a significant improvement containing the best of the two approaches. This could cause an enormous impact in data accuracy when geoferencing network features.

On the other side, the user demonstrated a partial frustration with missing features such as data filtering and equalization in the third question. However, this approach was based on a minimum viable product that held enough capabilities to validate the hypothesis that GPR software are missing map integration, not necessarily taking into account data processing at the moment.

According to the user's comments, he had an overall very positive perception of the new four features proposed by GVX-GPR regarding their impact in time, accuracy, completeness, and usability. The user remarks that adding contextual data is particularly interesting since they document visible clues (for instance manholes and poles) through pictures that are most of the time impossible to confirm with open maps (Google, OSM). According to the user, the first and last lines of the survey are usually tied to specific points, such as sidewalks, crosswalks, and poles, which are very important for the success of the interpretation.

Table 4.3: Structured form filled out by the user (GPR specialist) of GVX-GPR module after the second experiment at the Federal University of Rio de Janeiro (Brazil).

Question	Answer
How would you rate the usefulness of having access to the GVX-GPR module during the survey?	Very Useful
Did the GVX-GPR module help your spatial notion in doing any of the following actions? If yes, which one?	Discovering underground targets - YES Avoid losing time in searching where to start and end the GPR survey - YES Help in finding the right parameters for setting up the GPR - NO Help in delimiting the area to survey - YES Annotating points of interest - YES Storing images related to the field - YES
Did the GVX-GPR module help you to meet your goals?	Helped substantially
What are the most frequent tasks you do using your usual GPR software stack?	Data filtering, equalization, positioning, error suppressions, 3D image generation.
When you are using the GVX-GPR module, do you find anything frustrating that you wish easier/different?	3D image manipulation and target positioning

4.5 Conclusion

A new WebGIS-based approach is proposed herein for carrying out GPR surveys to identify and locate underground utility networks. In this approach, a map interface, integrated with four main features which are map integration, geo-annotations, georeferenced radargrams and slicing GPR data, was designed and tested. Using Web and GIS functionalities integrated to GPR instruments and software are a notable improvement to GPR operators since it may significantly increase the completeness of surveys and, thus, the efficiency of post-processing data. Based on the comments of two users, a non-GPR specialist, and a GPR specialist, who tested the GVX-GPR module, the WebGIS-based approach is perceived as valuable and significantly improve the GPR deployment in the field. It helps the user to delimit the survey area, and, ultimately, identify and accurately locate underground infrastructures. Overall, the proposed approach optimizes the survey time and allows noteworthy visual interaction between GPR profiles, 3D meshes, and others sources of information. With this approach, users can more easily deploy survey and post-processing on site, not avoiding returns to the site due to the mistrust clients have (of the survey result) in comparison to existing documentation (e.g. blueprint). It implies in a facilitation of the use of SUE practices at the same time that processing delays could be reduced.

After conducting the experiments with two different users of different levels of practice with GPR, the proposed approach introduces another perspective on how data interpretation and collection can be done. Even if two user tests do not fully represent a totality of GPR users, these tests give a solid proof of concept to continue the approach development with more users. Letting users to work in georeferenced environments and to interact with GPR data anywhere, opens a number of new possibilities. Even though the GPR industry has started to show some evolution in this direction, more awareness on user interaction clearly seems to urge for improvement, since the combination of geomatics and geophysics is axiomatic. With improved techniques, the GPR community would be able to grow substantially at the same time that end-users, like construction or land planner authorities, would benefit from having access to more precise XYZ location of underground infrastructures.

Furthermore, applying a standardized data modeling as CityGML to GPR data acquisition and management appears as a first (and important) step towards reliable and integrated underground to city modeling. Having integrated the underground network into a 3D city model environment is perceived as a major improvement in the context of multiple domains applications for leveraging the sustainable development of underground infrastructure.

The current version of GVX-GPR module served as a proof of concept but still requires improvements to be fully operational. Further developments are for instance required for onsite data processing, performing multi-sensor data integration, and visualizing in augmented reality environment.

Acknowledgements

This project is co-funded by CRSNG RGPIN-2015-05514, Mitacs (http://mitacs.ca/en), and Geovoxel. We would like to thank Geovoxel Brazil and Promark-Telecon for not only providing the GPR equipment but also acting as users of our experiments, as well as the Université Laval for the equipment and area provided.

Chapter 5 - Results and Discussions

For a more complete overview and interpretation of the tests as well as the results obtained during the two experiments, unreleased material in the publications is provided in this chapter. Due to constraints imposed by the editors, further details on how the tests have been organized, the results, and the findings and limitations observed during the testing phases are given and discussed herein. This chapter is divided into two sub-sections on the first and second experiments, respectively, offering a synthetized, unified, and more exhaustive version of the results.

5.1 User Testing #1

More results and details about User Testing #1 are presented in theses sub-sections along discussions about the reasoning behind some of the choices made for the test such as place, number of targets, etc.

5.1.1 Study Site and Equipment

The selected area is located at Université Laval's campus, located in Québec City (Canada), partially covering Pavillon Ferdinant-Vandry's front yard. The covered area to be mapped by the survey was approximately 154 m^2 (11x14m), in a mix of grass and pavement. The average orthometric altitude of the surveyed area is 92.2m. Following the selection, the UUN's are known based on a CAD plan, provided by the university. Thus, all the information available to the user was added to make the survey scenario as ideal as possible. Alongside the CAD plan, previous survey's maps were also added as contextual data (Lavoie & Pouliot, 2016) to help the research team to compare the work being conducted with previous results. Finally, control points have been collected to help the research team to identify the existing objects, as part of the third and final step for the pre-survey phase. Figure 5.1 shows CAD plan overlayered on GVX-GPR showing the location of the underground objects. The details of the underground objects to be and located are presented below.

- Fiber optic cable (previously located with a pipe locator)
    - Depth: 0.78 cm
    - Diameter: 10 cm
    - Represented in magenta in Figure 5.1
- 25kV Power Cable
    - Depth: ~ 1m
    - Diameter: 12 to 25 cm
    - Represented in yellow in Figure 5.1
- Underground tunnel (walkway)

  - Depth: > 8m
  - Width: Approx. 4 m
  - Represented in white in Figure 5.1

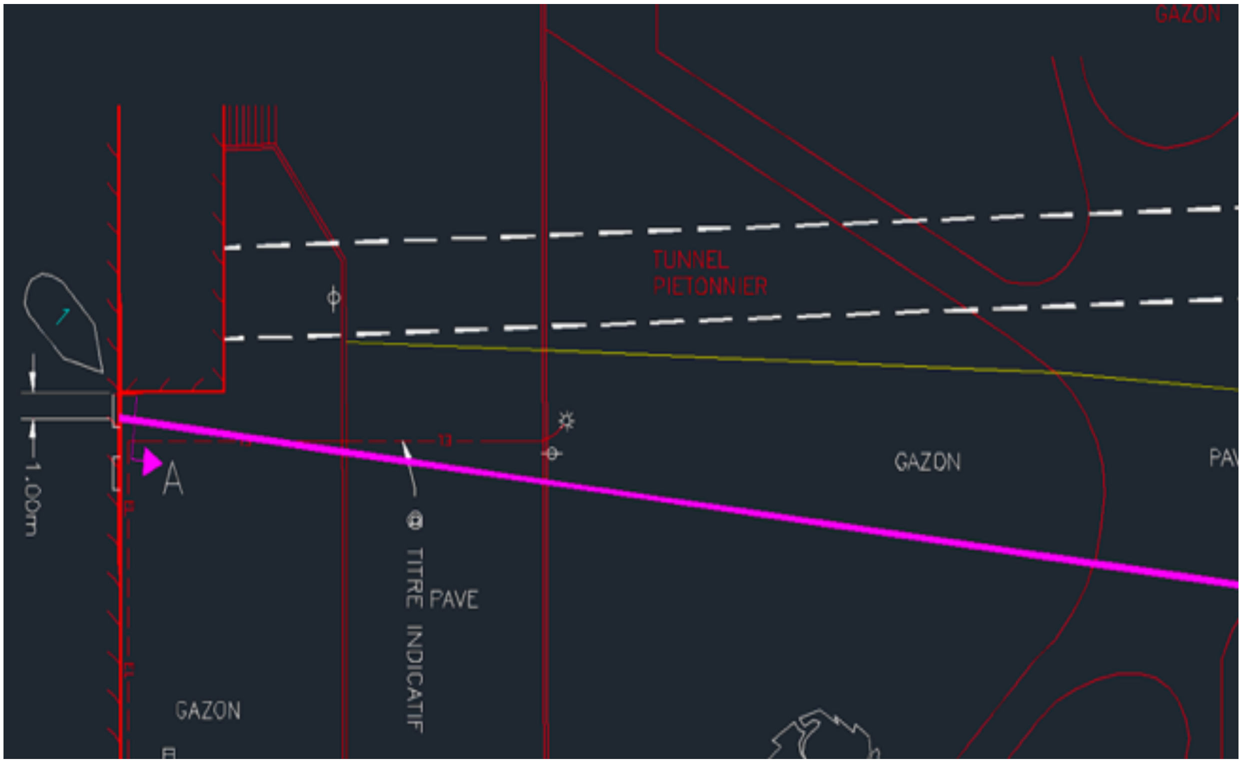


Figure 5.1: CAD showing the underground infrastructures on the UL Campus site (magenta line is the power cable, yellow line isthe fiber optics cable, white dashed lines is the underground tunnel).

The experiment counted on a GPR MALA X3M was provided by Promark-Telecom. Promark-Telecon is an underground surveying company present in Québec City with decades of experience in a wide range surveying methods. Follow are the equipment's technical specifications.

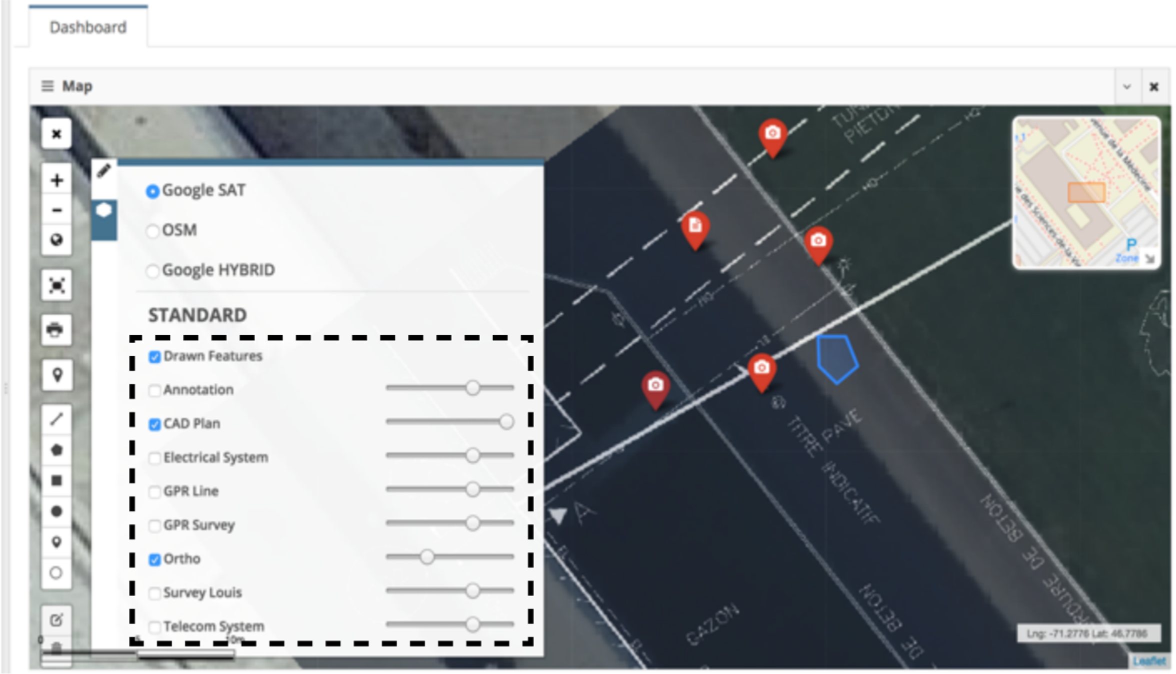
- GPR - Mala X3M
- Operates with MALÅ shielded antennas (100, 250, 500 and 800 MHz)
  - Antennas used: 500 MHz
- High speed communications (Ethernet) with XV Monitor/notebook PC
- Compact, lightweight, portable and field rugged design IP67
- Auto stacking for highest data quality and optimized speed performance
- Power Supply: Mala Standard Li-ion battery pack 12V
- Low power consumption for extended operation. > 6 h with standard battery pack
- Operating Temperature: -20° to +50°C/ 0° to 120 °F

- Dimensions: 310 x 180 x 30 mm/ 12.2 x 7 x 1.2 in

5.1.2 Survey Setup and Execution

Before the survey begin, all of the available information was integrated into GVX-GPR. A view of the interface with some of the information layers visible (CAD plan, base map, geo-annotated points) is shown in Figure 5.2. The layers available to the user during the survey are:

- CAD plan overlay;
- Layer containing previous survey's interpretation;
- OpenStreetMap base map;
- Google satellite imagery;
- Survey area delimitations; and
- Sample geo-annotated points of interest with pictures.



● Google SAT
○ OSM
○ Google HYBRID

STANDARD

☑ Drawn Features
☐ Annotation
☑ CAD Plan
☐ Electrical System
☐ GPR Line
☐ GPR Survey
☑ Ortho
☐ Survey Louis
☐ Telecom System

Figure 5.2: GVX-GPR's layer selector open (black dashed square) displaying to the user the available layers for the survey, along with red markers meaning geo-annotated images and/or comments about the survey site.

In the year of 2016, the research group performed a first user test with GPR and Promark-Telecon, in which two participants aided the research group. During this experiment, the two professional land surveyors provided the equipment and the expertise to (1) discover the location of underground objects as the ground truth with a (2) survey a fiber optics cable. For the current user test (described in this chapter and performed in 2017) one of the users who aided the research team became the subject of the test for the GPR approach. In order to facilitate the differentiation between the survey carried out in 2016 and the other one in 2017, within this section, they will be referenced to as Survey A and Survey B. For survey A, the land surveyor assisted the student to perform a data acquisition in a sub-section of Pavillion Ferdinan Vandry's front yard, represented by the blue polygon in Figure 5.3. For the Survey B, the same professional undertook the area within the red polygon (Figure 5.2) to a GPR survey. This is a strategy was partially on purpose since it helped the researchers to reduce this user bias towards a target that the GPR practitioner already knew, at the same time introducing new objectives. For Survey A, the user counted on the GPR to locate the a fiber optics cable (a very small target, represented by the orange line), that also crossed the area selected by the research team for Survey B, giving the user a notion of continuity, thus facilitating the interpretation of that target by comparatively equal characteristics. During Survey B, the user could also see on the map that there were, at least, two extra objects in that area that were not present during Survey A: (1) a 25kv cable and (2) an underground tunnel. This time, he was asked whether or not he could find buried objects given the information provided with the system (post-survey phase).

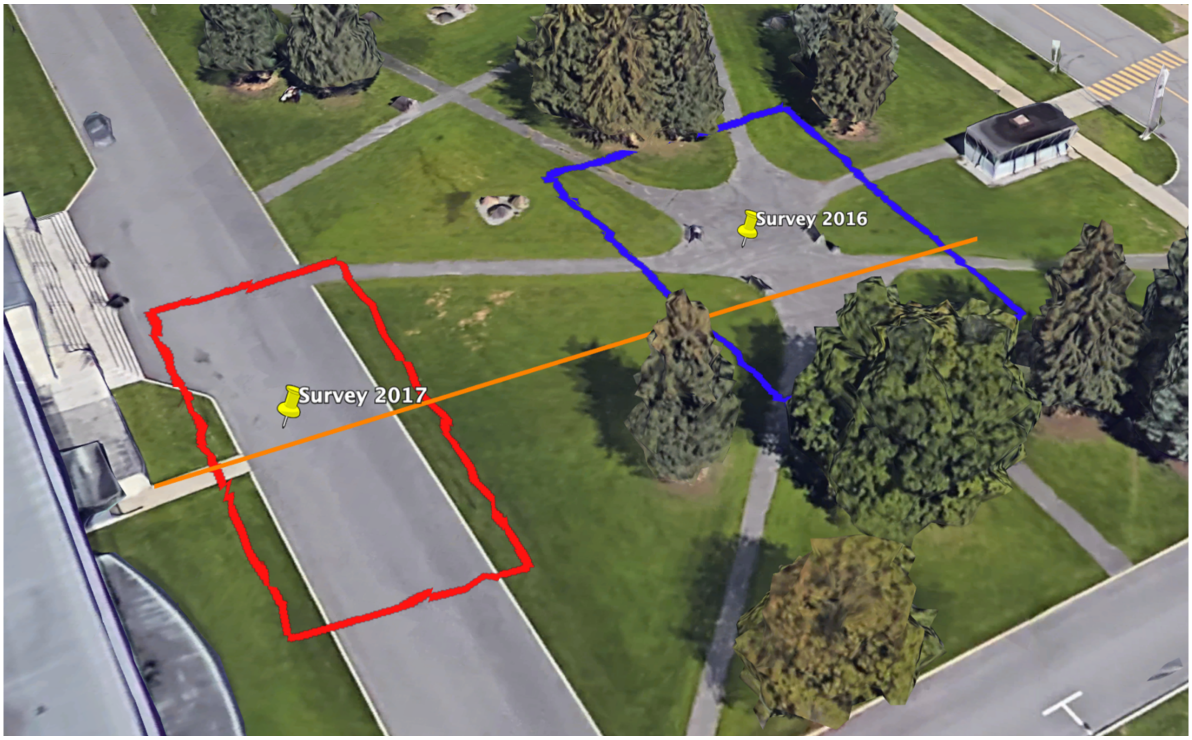


Figure 5.3: Area surveyed for survey 2016 (blue polygon) and area surveyed for survey 2017 (red polygon) and in orange, the buried fibre optic.

During the survey 2017, the user decided not to geo-annotate extra objects on the map due to the already-existing ones that already satisfied his needs to perform the interpretation. These annotations have been made by the research team previously the survey begin due to a series of facts. Firstly, the system itself, even though testable, was very immature in terms of testing and still contained multiple bugs for some of the use cases. To make the survey more fluid and happen naturally, likely having to deal with bugs (e.g. not being able to upload an image) would cause user frustration and disrupt test. Secondly, the user was not yet familiar with the system and could react negatively to having to learn how the technology worked while performing a survey. A more suitable way of introducing the user would be presenting him with a demo and providing him a longer period of adaptation to practice beforehand attempting to perform a real case. Finally, even though this survey's (survey 2017) site was a selected area with relatively controlled aspects, the access to the internet was not guaranteed everywhere within the surveyed area's bounds. Ideally, users would be able to have a tablet or smartphone with internet connection or a system that works in offline mode seamlessly. For this battery of tests, none of these were applicable. During the test, the system had not yet been deployed to a cloud provider, thus, not allowing the user to use other devices than a laptop provided by the research team (which ran the software locally). Due to this reason, being far from wireless routers (in other words, not counting on carrier's data access via a chip) could prevent the tests from happening. With all the information being provided locally to the running system, most of the internet access needed became nonessential and helped the survey fluidity.

5.1.3 User Discussion and Results

According to the user's standpoint, the user affirmed that his final interpretation most likely be to associate the hyperbola and the infrastructures shown on the CAD plan (Figure 4.7), as a result, confirming the existence of the two first objects (the fiber optics cable and the 25 kV power cable) when co-visualizing the radargram with the map resources. From the researcher's standpoint, the user relied a lot based on what the CAD plan told as the ground truth for the survey, instead of taking more advantage of annotations that had been previously made. For instance, both the CAD plan and a geo-annotation displayed a presence of a pole in that study site, which, according to the CAD, had a wire passing very near to where the fiber optics cable was present. Very likely, the user associated the fiber optics cable, which was an object he already knew, to what seemed to be a target on the GPR profile. However, two objects were believed to be the fiber optics and the 25kV electric power cable. Since this survey didn't have a confirmation for the location of an extra object such as this cable (only the CAD), this object may have been missed.

The user also concluded that according to his knowledge and based on the stairwell that gives access to the tunnel, this the third target (underground tunnel) was buried deeper than the depth of investigation of the GPR profile. A rough estimate of depth (8 meters) was donated by the user by analyzing the depth that the stairwells achieved in the underground. Depending on the type of excavation that was conducted in that area (open pit vs tunnel-boring drills), there could or could not be signs of soil disturbances cause by open pit. Usually, highly specialized GPR users are able to tell (by looking at GPR profiles) whether or not an open pit excavation was made, thus, confirming the existing of a tunnel. In this case, the user did not count on any signal processing tools and no clear sign was presented, leading him to the conclusion that this tunnel was deeper than the GPR reach.

For the experiment #1, it was possible to notice that tools that help users to configure GPR would be essential in this approach. In article number two, a GPR training company's owner commented that “the majority can handle GPR but not nearly half can interpret GPR”. During this survey, the research team configured the GPR in order to provide a functional test setup to the user. The user, on the other hand, already used this GPR on a daily basis as his own. The research team acquired data in known regions where cables had been located previously and noticed a discrepancy between the results the GPR gave compared to the ground truth. After some trying investigating the problem, the research team noticed that the GPR had the wrong wheel size configured, which could invalidate the survey completely. It was possible to notice that handling is, in fact, an achievable step for the majority of users, but properly configuring a GPR is a step just as essential as the interpretation process in order to produce good results. Based on this test and on evidence from interviews and scientific documentation, a new step in this approach, envisioning to help users to properly configure their equipment, would be very beneficial. For instance, the majority of cities have geomorphological map resources that could be integrated with weather map resources in order to know how the parameters of a GPR device would change in relation to the specificity of each soil type.

In a final talk with the user, he explained that even though there usually is not a lot of information available upon survey requests, he relies on a map-based system (provided by his company). This system, which is capable of showing approximately the area to be studied, also allows the user to draw where these infrastructures were located. This reveals that companies are using map-based interfaces to interface with field workers and clients, but there is still a gap between the data acquisition, interpretation, and the final result of a survey. As extensively mentioned in this research project, land surveyors are generating maps and documentation in a regular basis, and most of this information stands for nothing at the end of a survey, if not as a mean to arrive to the “final interpretation”. Based on this evidence, map-based system for the cadastral information of underground infrastructures should integrate new functions to allow users to produce geo-annotations on field. The user stated that occasionally (but not rarely) he is asked to re-survey a previously surveyed area. With this information available, he would be able to arrive to conclusive results more rapidly and precisely. Also, if GPR data is available for the surveyed area, the need of resurveying may even become dispensable.

5.2 User Testing #2

5.2.1 Study Site and Equipment

The second experiment (carried out within the scope of the project), took place at Universidade Federal do Rio de Janeiro (Rio de Janeiro's Federal University) on a street located in front of the university's rectory in February 2018. For this experiment, a rougher environment was envisioned but counting on the experience of the user, a geophysicist with more than 20 years of experience in the surveying industry. As part of the approach, the user selected a studied site of his preference, which he had already surveyed many years ago, in such a way that he could affirm the existence of underground networks in the survey area but he did not know how many they were or where they were located. This was a way of decreasing user bias towards a precise reinterpretation, letting the research group to regard improvements on the user experience and discovery of UUN to the approach more than to his previous knowledge of the survey area. The GPR provided by Geovoxel Brazil and used in this second experiment was a GSSi Sir 3000 with the following specifications:

- GPR Interface – GSSi Sir 3000
- Operates with multiple frequency antennas
    - Antennas used: 100 MHz
- Ethernet functionality disabled
- Data transfer via USB key
- AC Power 100-240V 47-63Hz

5.2.2 Survey Setup and Execution

The survey area, along with a GPR mesh in blue, reproduces the trajectory followed by the test subject for this experiment is shown in Figure 5.5. In total, 16 GPR profiles across the street and 5 others along the street were performed. Before going on site, the user evaluated the map resources in order to identify likely obstructions that could affect the survey's execution. Already on site, before starting the survey itself, the user was asked by the researcher to perform his annotations on paper as he stated to be his usual method. According to the user, he sketches the studied site along with pictures taken by his cellphone as a his field report, used later on to perform the interpretation (Figure 5.3).

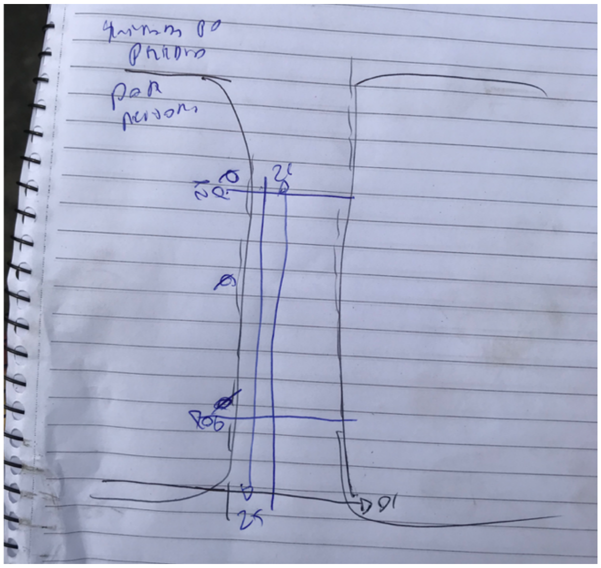


Figure 5.4: A handmade sketch of the surveyed side made by the GPR practitioner showing annotations representing the street, GPR lines, and points of interest.

After having finished sketching the surveyed site, the user executed the acquisition at the same time as he performed multiple geo-annotations (with and without image), on the system, of objects which could have a link with likely buried underground networks (such as a light pole and a buried electric cable), task which he used to do manually, on a piece of paper. As it is seen in Figure 5.5b, due to limitations of the interpolation method only GPR profiles across the street were uploaded to the system and used for the signal processing and interpretation. In order to simplify the data processing but still propose a viable solution to test slices of interpolated GPR radargrams, GPR profiles were organized in a data structure similar to a matrix (with indexes [Row,Column]), which considered that every parallel GPR radargram was equally spaced from each other, and the initial point of a radargram number N was placed in this matrix as (N,1), and the second (N,2), henceforth. In this way, introducing perpendicular lines to the existing ones would require a notion of geospatial correlation between these new points.

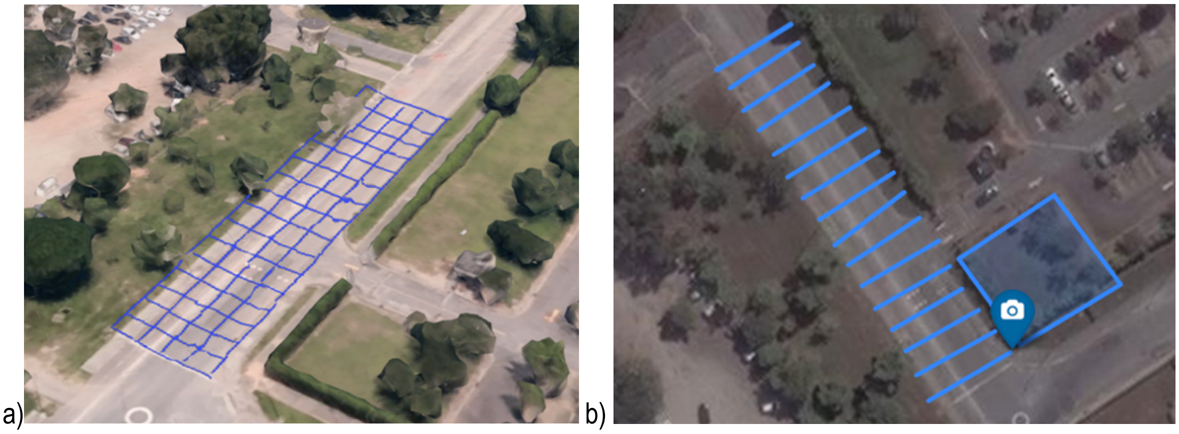


Figure 5.5: Planned GPR profiles of the survey area (5.4.a). Actual GPR profiles uploaded in GVX-GPR (5.4.b).

5.2.3 User Discussion and Results

To the user, the ability to geo-annotate objects was notable since the beginning. According to him and as observed by the researcher accompanying the user, in comparison to his traditional ways of carrying out GPR surveys is a significant improvement to the GPR practice. According to him, it is a common practice when surveys are conducted and have information sketched on paper through simple drawings of the surveyed area, beginning and end of survey lines, etc. Handmade map resources not only quantitatively lack information as it also represents a meager way of acquiring geospatial data in terms of precision. In comparison to what standards propose for mapping underground objects (which is the acquisition of the coordinates via proper measurements means such as GPS's), the time between carrying out a survey and starting the post-processing (which might be days), can very easily lead inexpert professionals to reproduce errors by associating semantics-poor objects (hand drawings) to survey elements.

The geophysicist verified the existence of a water main (presence of a manhole in the street view image as it can be seen in Figure 5.6). This water main could likely be, as shown in Figure 5.7, the strong reflectors underlined as blue lines in the GPR depth slice and identified by the white arrows, along the street direction.

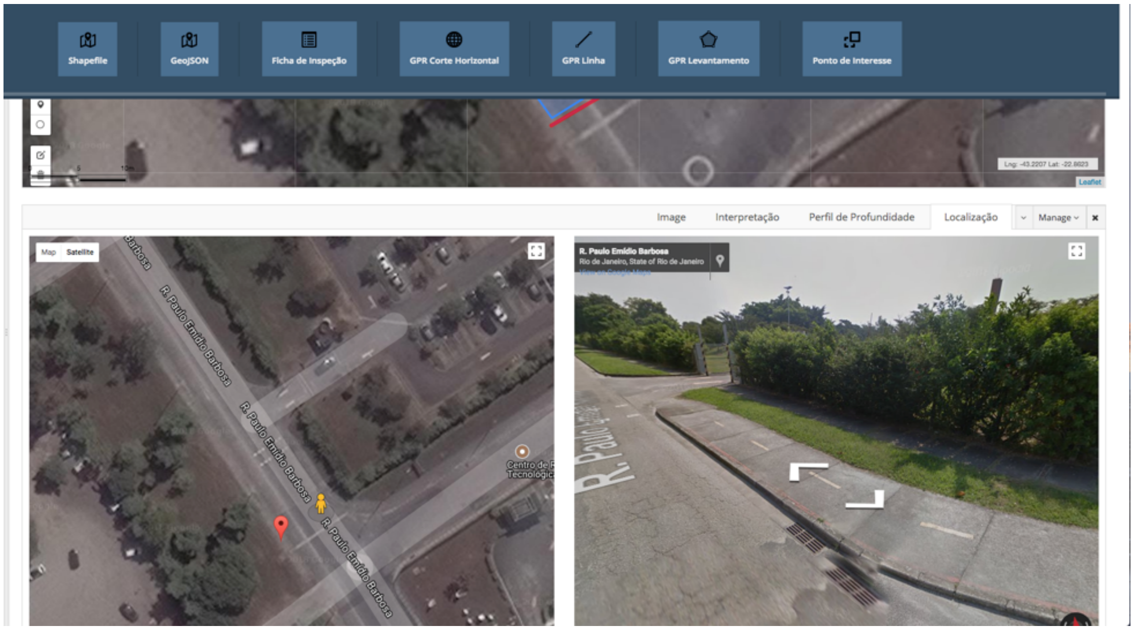


Figure 5.6: A multi-view perspective of a selected GPR profile, containing the selected feature (upper part, only partially displayed), a larger map view (bottom, left photograph), and the street view from Google Street View (bottom, right photograph).

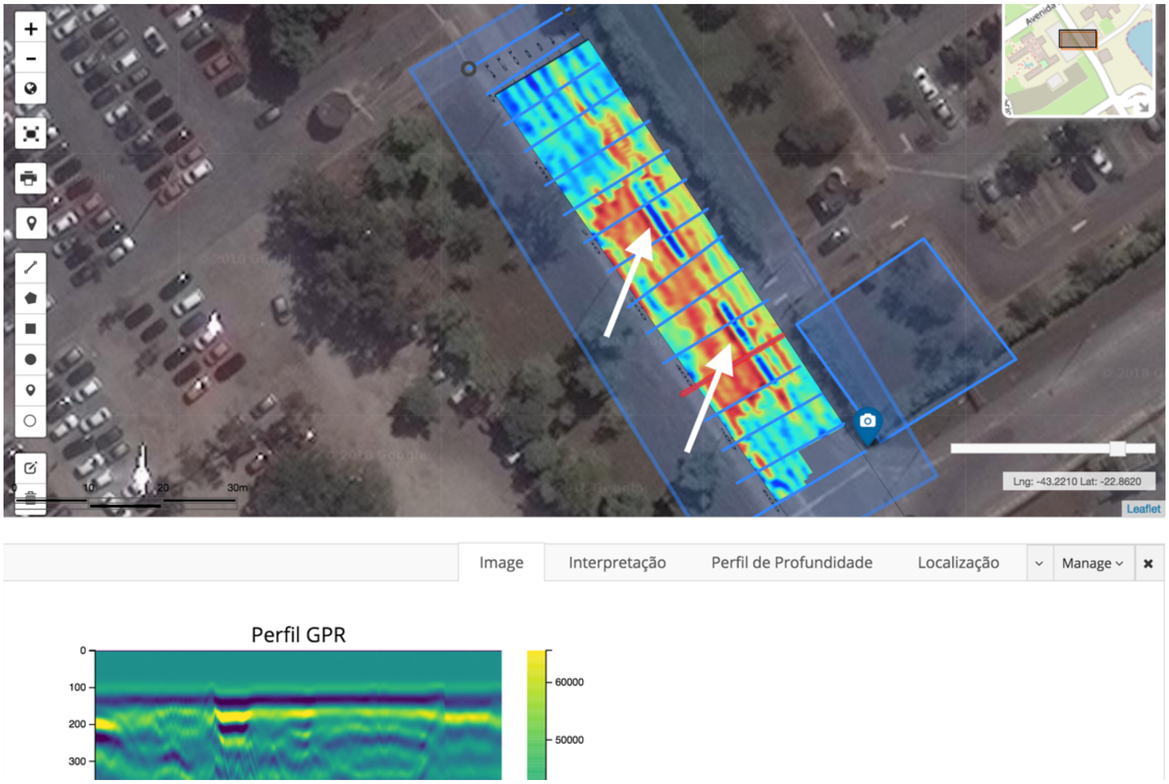


Figure 5.7: GPR depth slice (top figure) showing the likely existence of a water main (identified by white arrows) and radargram (bottom figure).

Subsequently, the user responded to the questionnaire (Appendix B). This questionnaire is an expanded version of the previous questionnaire used in the first experiment (Appendix A). More specific questions are found in this questionnaire relative to the influence that each feature has on each of the four next selected success criteria: (1) time, (2) x, y and z accuracy, (3) completeness, and (4) usability as shown on table 5.1.

For the first question, the user was inquired about the usefulness of the approach, with answers ranging from *not useful at all* to *very useful*. He mentioned that the approach helped him to find new targets, not to spent too long searching for the to-be-surveyed area, delimiting the survey area, annotating new points of interest, and stores survey-related images. If compared to how the user sketches survey areas, annotating points of interest seems a very appealing improvement to the way this user performs his acquisition. These annotations and proper drawing can substantially help the user to keep track of where the survey ends and begins, and how objects can relate. Even though the area to be surveyed was already known to the user, many obstacles could be spotted previously by seeing the map and the street view available for that area. This could substantially help the user to incisively arrive on site with some goals in mind. For instance, the manhole shown in Figure 5.6 is aligned with another manhole on the other side of the street, which was also visible from either the satellite image or the street view. Once spotted these two objects, the user could have made the connection, thus, looking for underground object more attentively in the area between. Once, the user commented about this relation between the two manholes. However, there is not enough evidence to say if the user was capable to notice them in the preparation phase or only when he was on site.

For this second experiment, a new statement was added to the second question: “Help in finding the right parameters for the setting of the GPR”. The explanation behind this answer is a conclusion drawn during the first experiment. Most newcomers or non-geophysicists often end up playing with GPR parameters to obtain more precise results. During the GPR setup of the first experiment (User Testing #1, Survey B), the results obtained during calibration of the GPR profile were discrepant from the ground truth. The GPR equipment was misconfigured and contained a setting for a larger wheel size, thus directly impacting the length of the survey’s lines, linear speed, and sampling frequency. Due to this reason, the research team aimed to validate if, by adding a geologic layer would help a proficient user to identify settings. However, due to difficulties encountered during this experiment, this map could not be provided, limiting this part of the analysis.

In the next question, when asked to fill a table correlating the indicators (time, [X,Y,Z] accuracy, completeness, and usability) to features on a scale from 0 (no impact) to 10 (great impact), the user answered as follows (Table 5.1).

Table 5.1: Score given by the user on the impact of the features on each success criteria (0 – no impact at all, 10 – great impact).

	Time	X,Y,Z Accuracy	Completeness	Usability
Add contextual data and georeferenced images	8	9	8	8
Add geo-annotations and points of interest (including pictures)	8	8	8	7
Co-visualize GPR profiles and map features representing position	7	7	7	7
Visualize 3D horizontal slices overlapping the map	8	7	7	7

When asked about which type of information was missing in the interface, he declares that even though the system integrates GPR profiles in an innovative manner, the existing GPR software lets users to mark likely targets direct on the profile, whereas the proposed approach lets users to add themselves directly on the map. This, presumably, causes an increase in the translation process of where the target is located in the radargram versus drawing it on the map. He added that it would be ideal if the GPR operators could add the annotations directly on the radargram, having points of interest directly added in the map, decreasing the human factor of adding a translation inexactitude from a linear metric dimension to a coordinate-aware space. As a matter of fact, the ability to annotate radargrams and have geo-annotations produced automatically on the map had been previously acknowledge as a point of improvement by the approach in past meetings by the research team. With users being capable of draw a point of interest directly on a GPR profile, the human error caused by "approximately guessing" where that target is located along a line on a map could be drastically diminished. Furthermore, this seems as one of the main points of improvements that the GPR industry and embedded software have shown interest to develop such as the previously mentioned IDS's Opera Duo (Figure 1.5).

When asked about common tasks he is used to do with GPR and which are things he found frustrated in the system, the user stresses that the approach presents an innovative way of conducting surveys, most GPR operators still strongly rely on signal processing tools. He also reported that "data filtering, data equalization, data positioning, error suppression, and 3D image generation are my default actions after a survey. I see the potential offered by a map-based tool like so, but it would still lack functions that us (GPR operators) are used to". This concern presented by the user was acknowledged by the research team as a missing point of the approach but an inviable development considering the objectives aimed with this approach. Even though users strongly rely on these filtering techniques, for example, they are not part of the validation process of this project.

At the same, an ideal scenario for a comparative analysis as such would require that the compared objects (approach vs approach or existing software vs GVX-GPR) had the same basic features as basis for the comparison. It is clear that these missing features pose challenges to GPR users in order to carry out an end-to-end survey, but it would be a more suited addition once the validation of the map-based approach was done.

3D cube slices are a significant improvement, but he would not dispose of having the ability of handling a 3D cube and/or slicing it in different ways than just depth slices. The same partial frustration is shared in the eighth question. He pointed out that, with the current GPR software, targets are mostly interpreted/positioned directly on the radargram, and when a 3D cube is generated, all these annotations are connected and may be judged to belong to the same infrastructure, such as in GSSi's RADAN (Figure 1.6). The user commented, once again, that the ability of adding target position in radargrams and to have them directly becoming points of interest on the map would be disruptive and unquestionably simplifying. Evidently, the elimination of a translation from a cartesian coordinate system to a geographic coordinate system mitigates the margin caused by human errors during the interpretation.

Finally, in a more informal talk to the user, based on his experience in the industry, he judged the value which the approach adds. According to him, many companies do not count on a comprehensive and thorough data management tool for GPR surveys and other underground surveying methods as well, which refers to the hypothesis that end users are able to explore this information in different ways, in a more detailed manner. He indicates "we are used to carry out GPR surveys at airports to analyse deformations on the runways. This often shows to facilities' stakeholders and civil engineers in charge, that the current situation is or is not good. Once they know that, they have a reactive measure in order to solve the problem at that moment, and it often costs a lot of money … with a more comprehensive approach like this helping this management, recurrent surveys would feed a database and allow them to do spatio-temporal analysis. In this case, they would be able to take proactive measures, evaluating what degrades more the runways, and planning budget in a more intelligent manner". This, at the same time, shows that companies are still unaware of the benefits added by SUE, and are still willing to pay higher prices due to damage or outwear of an infrastructure. According to industry cases witnessed by the researches, most companies in South America still strongly lean towards short-term less-expensive solutions, like performing a GPR survey to identify the current state of the object, instead of implementing long-term solutions such as a data management system. This may not be a worldwide problem, but it is easily affirmable that based on the fact that this industry lacks software for acquisition and processing leads us to believe that there are many possibilities for new technologies proposing underground data management.

The GPR user adds that most of his clients still rely on CAD plans with annotations as a database system that keeps that most recent changes and updates done to a project. This fact is a strong indication that companies need to improve their processes and the way that they organize data, not only for their civil engineering developments (e.g. what is the current situation of a cable) but also for the management of data acquired from the underground. It is plausible to say that if these companies do not maintain a proper record of their infrastructures, they eminently do not keep track of the underground data acquired by GPR, thus, limiting the analysis of the evolution of the project (such as trends for soil displacement, maintenance record of UUN's).

Chapter 6 - Conclusions and Recommendations

This last chapter first proposes a section that return on the objectives and discuss the achievements. Second, a summary of the contributions is outlined. Finally, a last section proposes a discussion on the limitations of the proposed approach and future works.

Return on the Objectives

At the beginning of this project, we proposed an overall objective that comprehended the deployment of GPR investigation by supplying to users WebGIS capabilities available on a portable device in the field. As a response, a new WebGIS-based approach was designed and developed as a tool named GVX-GPR, that can be used on the field during a GPR survey. Additionally, specific objectives were targeted in order to challenge the overall objective. The following objectives were verified in having two field experiments with two categories of users (expert and non expert in geophysics). Here are the objectives and an associated discussion (mainly based on user's comments):

Conduct GPR surveys that bring resources into more effective actions and results, increasing users' comprehension of the survey site and the interpreted data:
With the approach, an integrated GPR-GIS system allowed both users to achieve a GPR interpretation within a georeferenced, in a seamlessly facilitated process. This is particularly important for the objective of easing the GPR deployment process. With the approach, users are capable of understanding how GPR data belongs to the location they are surveying. Mainly in experiment #1, even a single GPR profile could show to newcomers that a likely discrepancy between the position of a target in a CAD plan and the one acquired were due to likely bad settings in the GPR. Newcomers to GPR can significantly take advantage of this facilitation of in interpretation process. This also enforces and leads us to conclude that with more data being acquired and less complexity, less technical effort would be needed for conclusive results.

Ease the GPR deployment for not only experienced professionals but also newcomers, increasing the usage of this geophysical tool for UUN detection and location:
The proposed WebGIS-based approach demonstrates to be very useful and to bring multiple sources of information together to leverage GPR surveys, allowing users to have an enhanced perception of the spatial characteristics of object, affecting positively many aspects of a survey, from abstract criteria such as level of complexity to time and precision (more and more important to customers), which are current day-to-day constraints that GPR practitioners have to live with. It is possible to confirm that the approach seems as a successful and innovative way of combining geomatics and geophysics in a seamless and ordered way.

Achieve more complete interpretation with less technical effort, being as close as possible to identify and locate all UUN:

The first experiment, which took place at Université Laval in September 2017, was carried out by a non-specialist in geophysics but having many years in the market of surveying (with GPR and other equipment). As found from the discussion with the user, GPR operators count on minimal documentation and information resources about the survey area. The approach developed herein proved to be very useful for the user, even though the amount of information provided does not necessarily represent a daily basis scenario (according to the user, most of the time they are not even provided with minimal documentation).

Provide ample access to online information resources and tools, even though GPR practitioners may be outside the office:

As originally proposed, this research project has proved, through both users' testimonials, to make GPR survey more effective in terms of the comprehension that GPR users have of the survey site, the data, and the relation between them. In the current way GPR is practiced, the geospatial notion is far apart from the survey execution, since most of the information does not even get to be georeferenced.

Perform more efficient production of subsurface maps, which support decision-making process for field work:

With more information being collected through annotations and GPR data stored, it is reasonable to settle that more maps are generated in an efficient manner, especially if comparing the current handmade annotations with geo-annotated, semantics-rich information. In such a way, data is more reliable and more people may benefit from it, such as the GPR community, the geospatial community, citizens, companies, and government. The GPR community can take advantage of existing data to more rapidly draw conclusions about the underground but, just as well, base themselves on existing surveys that were previously performed. The geospatial community can extensively take advantage of more people generating new maps, from the under and the upper ground. Citizens, companies, and government are provided with reliable information, that followed procedures and have its bases on widely accepted standards proposed and maintained by a community of experts.

Deliver more reliable underground infrastructure data, available to a larger community of users:

In this research project, a new software-based approach is proposed to facilitate the execution of GPR surveys by the means of adding long-existing geo-features in other areas such as topographical survey and UUN surveying with pipe locators. As seen and verified through exhaustive documentation and research, the use of surveying technologies can be very helpful for the market of SUE.

The user in experiment #1 stated that not only the module helps in the discovery process of buried objects but it allows professionals to organize their information for projects in a systemic way, which is useful during the execution of surveys in the same areas. This supports the idea that the approach supports GPR deployment for not experienced professionals and newcomers to the field. According to the results obtained, it is possible to affirm that the approach is useful for the efficient deployment of GPR surveys, thus, increasing efficiency when generating UUN maps. Particularly, this experiment firmly indicates that the approach can significantly help newcomers and non-specialists.

In the second experiment, the benefits of the 3D integration of GPR data, as well as the co-visualization of map resources overlapped with GPR data, were revealed. The main subject pointed out by the user is that GPR surveys at an industry-level of production do not favor the geolocation of points of reference or annotations by collecting GPS points. The process is usually much more expedite and hand annotations tend to be the one and only resources of information post-survey which specialists can count on in order to achieve an interpretation. As a result, the process of “tying lines and surveys” to visual cues is not endorsed but it is frequently executed. It makes clear that having the ability to geo-annotate items brings new precision and more reliability for surveys. The approach does not only positively affect the reliability of information generated but also substantially increase the amount of information added in structured databases. The assumptions that not only who hires a service would have more information regarding the project but also, with more data available, a larger community of users would benefit from its use.

Summary of the Contributions

The scientific contribution of this research project lays on the use of geospatial technologies in the GPR domain to improve the capabilities of UNN detection. Companies in the GPR manufacturing market and software development for geophysical surveying methods should integrate these geospatial technologies in their future advancements for GPR users. Ideally, GPR interfaces should propose these geo-features and consider this research as a call for action in geomatics and geophysics cross-domain ameliorations.

This research has also shown that the GPR community still lacks software resources, specially based on geospatial features. According to both users, geospatial features proposed by our approach can significantly ease the interpretation process done by GPR in multiple ways (geo-annotating objects, integrating new maps, or visualizing GPR data in multi-map interfaces), allowing more professionals to come in this domain and expand their utility. This is a clear results of our work, and an important step in the opening of new tool and instrument market for underground object survey, i.e. geo GPR..

As mentioned in the beginning, this project had the ambition to expand the knowledge base in both geomatics and geophysics. We do believe that in having used open source solutions for the development of GVX-GPR, a standard for encoding the database (CityGML), and disseminated the results in broad scientific community (two papers) and practitioners' communities (two experiments and lots of direct discussions), we meet this allege.

Some other points can also be considered to be contributions or reflections presented by this research project. This research project presents a detailed analysis of GPR software and interfaces currently available in the market, as well as the features (geographic or not) present in each one. Along with this analysis, GPR practices were also reviewed. Not only GPR software were analyzed, but also many companies gave their testimony on how they are using GIS technologies in their daily basis when deploying GPR. After analyzing the documentation, standards, and scientific resources, the research team has detected even more details about practices, in different levels and applications of GPR, with information from user interviews. These interviews not only depicted which practices these GPR user were using, but it allowed us to propose an extensive list of user needs of geographical features missing in GPR.

Limitations of the Approach and Future Works

After this step taken towards the analysis on how georeferenced information can be merged with GPR data to offer more precise map resources to GPR operators, it is important to recognize that the current GPR community counts on multiple data processing techniques. A map-based proof of concept has been proposed and tested, showing a branch to be explored in this cross-domain task, but, GPR still relies on more data processing tools and little on integration with georeferenced information on maps. Not only the interaction level of GPR interfaces with maps have to be improved, but also how users interact with and manipulate the available data on UUN in order to acquire the most precise and veracious interpretation out of the collected data to identify and locate UUN.

Regarding the results obtained by the tests, it is important to say that all the problem's analysis, development, tests, and validation were conducted in a Master's project. Despite of the 2 years invested in this project, not only the development of the system had to be very limited and scope-focused but the tests and scenarios were just enough to validate the premises which the research team identified. Each experiment required a time invested in order to properly plan and execute it. Despite of the research team's willingness to further analyze the interaction that users have with the map-based interface and the measured quantitative results (how much feature X impacts on precision), time posed a big objection. In order to collect more meaningful quantitative results for this approach, as previously mentioned, it would be ideal to have a system which already counts on most of the signal processing tools that GPR's have built-in. In order to achieve this, time would play an important role for their development and validation.

The limited number of experiments is a clear drawback in our methodology and result's analysis. The limited number of experiments performed can be attributed to the availability of professionals and equipment to carry out the tests. Each test requires prior communication with land surveying companies in order to have an access to skilled professionals as the one that undertook the tests. The tests somehow interrupt their works and require permit to survey such area. Those aspects were an important limitation in the selection and the setup of the study sites.

With regard to technology, even though users are often dealing with 3D data, they do not interface or handle with 3D itself at any point. The 3D slices are automatically generated and placed on the map, and users are not able to tell specifically how many slices and at which depth they are located. In a real-world application, this would pose obstacles for GPR users since each object being surveyed may be in completely different depths. For proposed validation, the research team pre-set slices at given fixed intervals and depth since the location of most underground objects was known or estimate. Whereas, an ideal technology would let users to slice the cubes in multiple directors and in diverse intervals.

Finally, this research work proposed an approach that can effectively improve GPR deployment through geospatial features and data integration. Nonetheless, missing points were not only early observed by the research team but also pointed out during the experiments are:

- ***Combining signal processing techniques with geospatial features and data integration***

As often mentioned by the users, the proposed approach is appealing but GPR processing still requires a great deal of signal processing. All GPR embedded software, nowadays, heavily relies on these techniques such as band-pass filters, dewow, noise reduction, etc. It is reasonable that users would miss these features in the proposed approach. Thus, for the next step, adding these techniques would be a priority in order to properly evaluate the impacts and value of this geophysical and geomatics combination.

- ***Adding 3D data manipulation and visualization***

Along signal processing techniques, complimentary GPR software (processing tools used in the office) let users to manipulate 3D GPR data cubes. By manipulating 3D cubes, it is meant to let users to slice cubes in multiple directions (currently, GVX-GPR only support top automatic slices of a 3D cube in pre-defined intervals) as well as to permit changes in the coloring, filtering, etc. directly in the cube.

A likely future development would be to have a 3D data cube to be handled by users at the same time that any changes done on the cube are automatically reflected on map features. For isntance, a change in color would alter the layer showing the GPR survey slices, or a lateral slice would display a line on the map to help users to link the coordinate system where the cube is with the geography-aware coordinate system.

- ***Quantitatively comparative tests***

Once the WebGIS approach has matched capabilities with current GPR software, combined with geospatial features, thorough and precise assessment of these capabilities to improve GPR deployment and detection of UUN can be achieved. Even with a great effort envisioning realistic test case scenarios, users would still require third part tools (signal processing, etc.) to finalize an industry-level interpretation. With the goal of quantitatively measuring, for example, time and quality, it would be ideal to have a system and approach able to entirely replace what is already used. As previously mentioned, this research was a first step into validating this approach, but ampler testing and validation would bring more completion to the analysis.

- ***Automated displacement and hyperbola recognition***

As a long shot for the technological development of GPR, we can take as example the agricultural domain which has an acute development of geospatial technologies such as tractors that are capable of determining trajectories and self-executing harvesting and/or doing plantation. Added to this process, it would be at least interest to count on machine learning techniques for a precise pre-treatment of GPR data and classification of GPR radargrams based on similar characteristics from previously surveyed areas. This also enforces the importance to have GPR historic data stored, organized, and (as a step further) classified.

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Appendix A – Questionnaire User Testing #1

1. How would you rate the usefulness of having GVX_GPR during a survey's execution? (1 not useful at all – 2 slightly useful – 3 very useful)

   ☐ ☐ ☐

   1 2 3

2. Did/Would GVX-GPR help your spatial notion in doing any of the following, if yes which one.

   - Discovering underground targets Y / N
   - Decrease the duration of the GPR survey Y / N
   - Avoid losing time in searching where to start and to end the GPR survey Y / N
   - Help in finding the right parameters for the setting of the GPR Y / N
   - Help in delimiting the area to survey Y / N
   - Annotating points of interest Y / N
   - Storing images related to the field Y / N

3. Did/Would GVX GPR help you to meet your goals? (1 didn't help at all – 2 marginally helped – 3 slightly helped – 4 helped substantially – 5 helped a lot)

   ☐ ☐ ☐ ☐ ☐

   1 2 3 4 5

4. Which other type of information could be useful during the execution of a GPR survey:

5. What are the the most frequent tasks you do using product GVX-GPR? Explain and ideally show how you do these tasks (step by step).

6. When you are using GVX-GPR, do you find anything frustrating that you wish was easier/different?

7. Is there anything that you wish GVX-GPR allowed you to do that it doesn't allow now?

Appendix B – Questionnaire User Testing #2

1. How would you rate the usefulness of having GVX_GPR during a survey's execution? (1 not useful at all – 2 slightly useful – 3 very useful)

   ☐ ☐ ☐

   1 2 3

2. Did/Would GVX-GPR help your spatial notion in doing any of the following, if yes which one.

   - Discovering underground targets Y / N
   - Avoid losing time in searching where to start and to end the GPR survey Y / N
   - Help in finding the right parameters for the setting of the GPR Y / N
   - Help in delimiting the area to survey Y / N
   - Annotating points of interest Y / N
   - Storing images related to the field Y / N

3. Did/Would GVX GPR help you to meet your goals? (1 didn't help at all – 2 slightly helped – 3 helped substantially)

   ☐ ☐ ☐

   1 2 3

4. Ranging from 0 (very unsatisfied) to 10 (very satisfied), categorize how much you imagine each feature impacted time, accuracy, survey completeness, and usability (of a GPR).

	Time	X,Y,Z Accuracy	Completeness	Usability
Feature A				
Feature B				
Feature C				
Feature D				

5. Which other type of information could be useful during the execution of a GPR survey:

6. What are the the most frequent tasks you do using your usual GPR software stack? Explain and ideally show how you do these tasks (step by step if possible).

7. When you are using GVX-GPR, do you find anything frustrating that you wish was easier/different?

8. Is there anything that you wish GVX-GPR allowed you to do that it doesn't allow now?