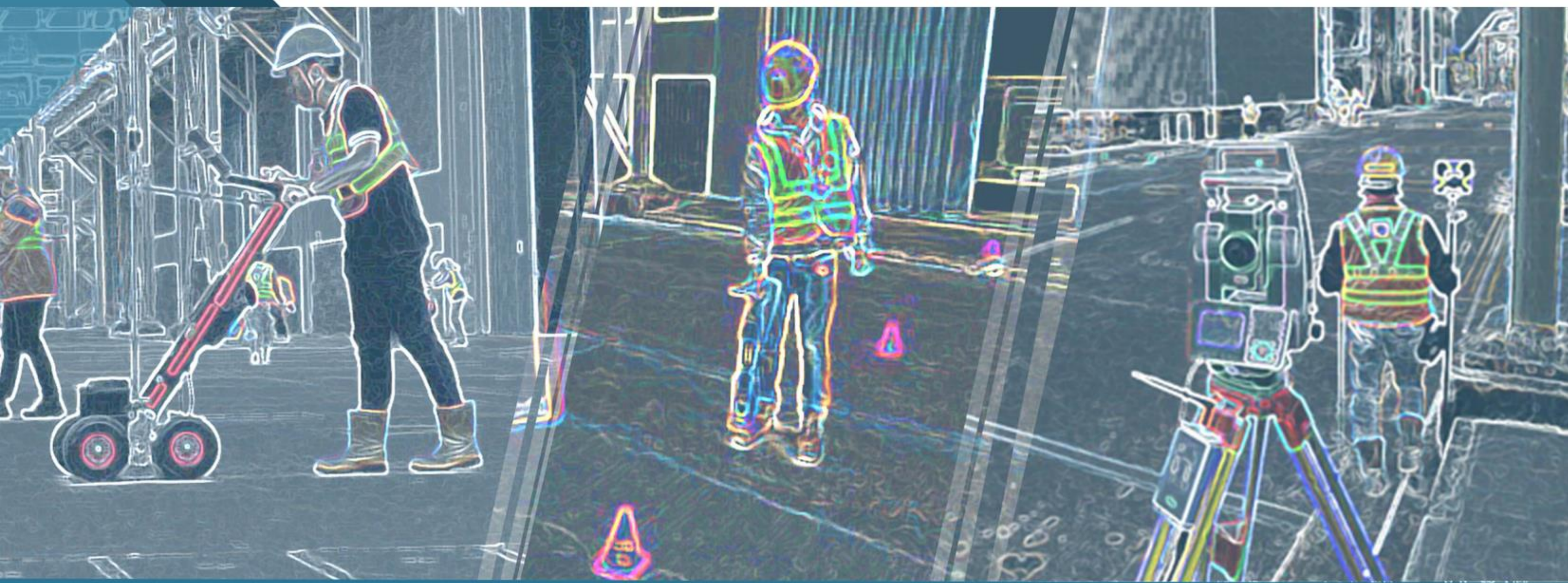
# SPECIFICATIONS FOR NONDESTRUCTIVE TESTING, SURVEYING, IMAGING AND DIAGNOSIS FOR UNDERGROUND UTILITIES

## 1,2 GROUND PENETRATING RADAR (VERSION.1)

# [ NDTSID-UU-1,2 ]




THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

DEPARTMENT OF
LAND SURVEYING AND GEO-INFORMATICS
土地測量及地理資訊學系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SPECIFICATIONS FOR NONDESTRUCTIVE TESTING, SURVEYING, IMAGING AND DIAGNOSIS FOR UNDERGROUND UTILITIES

Prepared by Wallace W.L. LAI and team of researchers,
Department of Land Surveying and Geo-informatics (LSGI), The Hong Kong Polytechnic University



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E-mail: uus.specification@polyu.edu.hk

## Foreword

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# GROUND PENETRATING RADAR (GPR)

## Table of Contents

## A – Acknowledgements to Steering, Technical Workgroup 1,2

This document (1,2) is one of the specifications prepared for accrediting laboratories/survey companies conducting underground utility survey. This document was prepared after three consultation meetings held from September 2018 to February 2019, as well as incorporating comments provided by various Government departments. It will be reviewed and updated when necessary. The project team expresses the greatest appreciation and gratitude to the following parties for providing support during the drafting and implementation of this specification.

- ***Local steering committee members:***

Chan Pak-Keung (Adjunct Professor, University of Hong Kong)
Lau Wai, Tony (Technical Director, Black & Veatch Ltd.)
Lo King-Yin, Victor (Chairman, Civil Discipline Advisory Panel and Past Chairman of Civil Division of HKIE)
Wong Kin-Yan, Samson (Former Senior Accreditation Officer of Hong Kong Accreditation Services)

- ***Workgroup 1,2 members***

Chan Yuen-Lok (The Hong Kong and China Gas Company Limited (Towngas))
Chiu Sing-Kit (Hong Kong Telecommunication (HKT) Ltd.)
Fung Yuk-Lun, George (MTR Corporation Ltd.)
Ho Shun-Yat, Sam (Sum Kee Construction Ltd.)
Kung Hiu-Leung, Daniel (Hong Kong Institute of Utility Specialists)
Lee Tsz-Ki, Pinky (Castco Testing Centre Ltd)
Mong Seng-Ming (Geotechnics & Concrete Engineering (Hong Kong) Ltd.
Pak Chun-Wai, Kenneth (Vocational Training Council)
Siu Ka-Lai, Peter (Viewbond Hong Kong Limited)
Wong King (Hong Kong Institute of Utility Specialists)
Yan Kwok-Keung (China HK Society for Trenchless Technology, Waterland Detection Engineering Ltd.)

- ***International advisory committee members:***

Nicole Metje (University of Birmingham, UK)
Tom Iseley (Trenchless Technology Center, USA)
George Tuckwell (RSK Environment Ltd., UK)

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- ***Project team:***

Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University (LSGI, PolyU):
Chairman: Lai Wai-Lok, Wallace;
Members: Chang Kwong-Wai, Ray, Cheung Wei-Yat, Bella, Chiu Sin-Yau, Lydia, Luo Xiang-Huan, Tess, and Sham Fung-Chu, Janet

# B – Background

## B1 – History of GPR

The history of ground penetrating radar developed from the discovery of electromagnetism by Michael Faraday, mathematical formulation by James Clerk Maxwell, advances in radar sounding in air during the Second World War, and the subsequent application of air-borne radar to ground-based radar during the post-war era. A brief history of the development of GPR, modified from a number of references from Sensors & Software (2019), is as follows:

| Year | History |
|---|---|
| 1831 | Michael Faraday presented a paper about the characteristics of electromagnetism to the Royal Institution in London. |
| 1860s | James Clerk Maxwell published the four ‘Maxwell’s equations’ describing the physical rules of electromagnetic waves moving in free spaces. Heinrich Hertz proved the existence of electromagnetic waves in his doctoral thesis. |
| 1904 | Christian Hülsmeyer filed the first patent on a radar application for measuring distant objects with radio waves, which formed the basis for the detection of aircraft during the Second World War, for example over the battlefields of the English Channel and Pacific Ocean in the early 1940s. |
| 1950 - 1960 | The first real field trials of 1-10 MHz radio signals were used to detect the water table. Early use of radar altimeters over the Greenland ice sheet resulted in accidents, because it was not appreciated that radio waves could penetrate the ice, thus giving false altimeter readings (Waite, A.H., & Schmidt, 1961). A radar altimeter was later converted to estimate ice sheet thickness in Greenland. These two events are regarded as the trigger for the real birth of GPR. |
| 1960 - 1970 | Ice sounding continued in research groups at The University of Wisconsin, USA and the Scott Polar Research Institute at Cambridge, UK. Non-ice uses were also initiated by Unterberger in salt mines and Cook in coal mines . The Apollo lunar science program started to study the Moon’s surface electrical properties (SEP) during the Apollo 17 mission. The Apollo program gathered a team including GPR innovators such as Annan, Olhoeft, Redman, England, Watts, Rossiter, Jiracek, and Phillips. |
| 1970 - 1975 | The dispersal of scientists in the Apollo team led to the transference of lunar research knowledge to institutions such as the Geological Survey of Canada, US Geological Survey (USGS) and universities, and resulted in the commercial development of hardware by Annan, Davis and Morey, who produced the first commercial GPR products. |
| 1975 - 1980 | Many GPR developments occurred worldwide, such as Annan and Davis with the Geological Survey of Canada, Olheoft in USGS, Arcone in Cold Regions Research and Engineering Laboratory, Unterberger at Texas A&M and BGR in Germany. Application areas included permafrost, ice sounding, bathymetry, soil moisture for agriculture, potash mine hazards, nuclear waste disposal site assessment, measurement of concrete properties, rock quality determination, hydrogeology and many others. The largest barrier to technological advancement was the availability of suitable instrumentation. |

| | |
|---|---|
| 1980 - 2000 | Field trials and commercial surveys of many subsurface scientific and engineering applications were started, nurturing a continuous evolution of technology and practical field solutions. A wide range of commercial products or prototypes become commercially available and the first international GPR conference was conducted in 1986 in Georgia, USA. The American Society for Testing and Materials (ASTM) published the first user guideline (D6432) for GPR for subsurface investigation. |

## B2 – Significance, Applications and Scope of Specification

### B2,1 Significance and applications

Underground utilities are the veins of any city. Lack of power, water, drainage, sewerage, lighting or communications paralyzes a community. It is not surprising that this paralysis often happens when utilities are not correctly located before groundworks occur, or when pipe seepage, leakage or bursting causes subsurface washout and void formation (Lai et al. 2018a). Information provided by GPR is therefore essential to the provision of useful underground 3D maps before digging occurs (TRB, 2009; TRB, 2012). Spiking a power cable or breaking a water-carrying utility can lead to suspension of services, and in many cases, causes causalities. Locating and mapping utilities with geo-referenced positioning, and testing and diagnosing the underground conditions (e.g. voids and seepage or leaks) (Cheung and Lai, 2019) helps to reduce the extent of damage, as it is well-known that design and as-built drawings, as well as visual inspection from the ground, do not provide reliable and accurate information.

The **geo-referenced underground utilities and diagnostic drawing/map** is the major deliverable of ground penetrating radar (GPR) surveys, but how these maps are produced based on proper test/survey/diagnostic procedures that vary significantly between companies and individuals. Erroneous or incomplete information about the utilities map can mislead the user, causing unnecessary damage and exposing the public and workers to danger. Experience and knowledge of the subject area greatly enhance the credibility of the map and, most importantly, help clarify when the test/survey/diagnostic results are uncertain due to site, materials and equipment limitations rather than the Signatory/Survey Operators' abilities. The successful management of the above factors can be summarized in a **4M1E** framework, namely **M**an/woman, **M**achine, **M**aterials, **M**ethods and **E**nvironment, which can be applied within an accreditation framework following 'ISO/IEC 17025: 2017: General requirements for the competence of testing and calibration laboratories'. In view of the above needs, this document provides a unified specification and standard for GPR's use based on 4M1E, which aims to help utility companies, service providers/laboratories, developers, estate managers, contractors and consultants to maintain consistent quality of service of GPR surveying, imaging and diagnosis.

### B2,2 Scope

1. This specification covers the history, theories/principles, personnel, instrumentation, field procedures, suggested quality levels and accuracies used with non-destructive and near-surface GPR systems. GPR makes use of high-frequency electromagnetic (EM) radio waves (from 10 to 3000 MHz) to acquire information about the underground situation. Changes in the EM properties (dielectric permittivity, conductivity, and magnetic permeability) of materials are detected, and are a function of variables such as soil and rock types, water content, and bulk density. Data are normally acquired using ground-based or borehole dipole antennas. The transmitting antenna is designed to radiate EM waves that propagate into the underground environment and collect reflections from boundaries at which there are EM property contrasts, which forms the basis for utility detection and feature extraction relating to seepage/leakage or voids. The GPR receiving antenna is designed to register the reflected events (i.e. waveforms) over a selected time range. The cover depths of the reflecting interfaces are estimated by multiplying the two-way travel times in the GPR data and the estimated EM wave propagation velocity in the materials.

2. The approach suggested in this specification for using GPR is commonly used, widely accepted, and well proven. However, other approaches or variants of GPR that are technically sound may be substituted if technically verified, validated and documented.

3. This specification does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user to establish appropriate health and safety practices and determine the applicability of regulatory limitations prior to use.

## B3 – Glossary

The glossary in this specification is modified from Sheriff (1991) and ASTM D6432-11 (2011).

| | |
|---|---|
| 4M1E | Man/woman (Signatory and Survey Officer), machine, material, method, environment. |
| Antenna | Device used to couple electromagnetic energy into the underground. The most common dipole antenna is a linear polarization antenna consisting of two wires fed in the middle by a balanced excitation source (Balanis, 2016). |
| Attenuation | A reduction in signal amplitude caused by energy dissipation due to materials' conductivity ($\sigma$), dielectric relaxation associated with the imaginary component of the permittivity ($\varepsilon''$), and magnetic relaxation associated with the imaginary component of magnetic permeability, as well as scattering and geometrical spreading in the media. |
| Centre frequency | Middle of the frequency band defined by antenna's bandwidth. |
| Bandwidth | Operating frequency range over which an antenna transmits or detects signals above a specified amplitude or power. The GPR bandwidth is defined by the upper and lower frequencies radiated from a GPR transmitting antenna possessing power 3 dB below the antenna's peak power at its nominal centre frequency. In the general case of pulse antennas, the difference between the upper and lower 3-dB frequencies is used to describe an antenna's bandwidth. For example, if the 3-dB upper and lower frequency bounds of a 400 MHz antenna are 200 MHz and 600 MHz, respectively, then the bandwidth is also 400 MHz. |

| | |
|---|---|
| Bi-static | A survey method that utilizes one transmitting and one receiving antenna separated by a variable distance. It enables common mid-point, wide angle reflection and refraction, and enables a borehole radar's transillumination survey mode. |
| Common offset | A survey method that utilizes one transmitting and one receiving antenna separated by a fixed and small distance relative to the depth of interest. It is also known as mono-static mode, and is the most common type of GPR. |
| Conductivity | One of the three material properties related to GPR survey. It describes the movement of electrons or ions due to an applied electrical field. The units of conductivity are Siemens/metre (S/m). |
| Dielectric permittivity | One of the three material properties related to GPR survey. It describes the ability of a material to store electric energy by separating opposite charges in polarity. It determines how the electric displacement, D, responds to an incident electric field, E, through $D=\varepsilon E$. The units of dielectric permittivity, ε, are farads/metre (F/m). Relative dielectric permittivity (commonly called the dielectric constant) is the ratio of the permittivity of a material to that of free space, $8.854 \times 10^{-12}$ F/m. For material with a dielectric permittivity greater than that of free space, it will be lossy and ε is represented as complex number in real and imaginary parts. Both parts are frequency-dependent and are typically described by the Cole-Cole (Cole and Cole, 1941) relaxation distribution model. Nearly all dielectric relaxation processes are the result of the presence of water or clay minerals (Olhoeft, 1998). |
| Magnetic permeability | One of the three material properties related to GPR survey. It describes the ability of a material to store magnetic energy induced by re-alignment of electron spin and motion. It determines how magnetized polarization in the magnetic induction, B, responds to a magnetic field H, through $B=\mu H$. The units of magnetic permeability, μ, are Henry/metre. Relative magnetic permeability is the ratio of the permeability of a material to that of free space, $4\pi \times 10^{-7}$ H/m. It is commonly assumed that magnetic properties of materials in GPR survey are the same as those of free space. Nearly all magnetic properties are due to the presence of iron in a variety of mineralogical forms (Olhoeft, 1998). |
| Polarization | The orientation of the electromagnetic field vector's direction described by the polarization vector. Most GPR antennas are linearly polarized (Balanis, 2016). |
| A-Scan, scan, trace, wiggle trace or waveform | A representation of the underground situation by GPR signal strengths and polarities in time, which are convertible to depth with velocity information. The signals correspond to any scattering and reflection events from objects buried in a host material. Its time base is nano-seconds. |
| B-scan, or radargram | A 2D distance-depth representation of the subsurface created by stacking A-scans along GPR traverses, survey lines or transects. It can be represented by parallel and stacked wiggle traces and, most commonly, by colours indicative of different signal strengths and polarities within a pre-defined colour palette. |
| C-scan or slice scan | A 2D x-y plane representation of the underground situation at a particular depth range 'z' after collecting B-scans/radargrams in multiple GPR traverses and with different antenna polarizations. It is a reconstruction of the subsurface slice |

| | |
|---|---|
| | view, represented by colours indicative of different signal strengths and polarities within a pre-defined colour palette. |
| Resolution | The minimum separation distance between two objects distinguishable in GPR signals. |
| Scattering | A general term that describes the change in direction of GPR wave propagation over a short distance, where the incident GPR wavelength is comparable in size to that of a buried object. Scattering includes reflection (reverse in direction), refraction (forward change in direction), and diffraction (caused by rapid changes that are small compared to a wavelength). |
| Step size/A-scan resolution | User-selected distance between two A-scans. It is also known as station interval. |
| Signal processing | A series of essential steps used to modify GPR signals in order to image the underground situation. |
| Two-way travel time | The time required for the GPR wave signal to travel from the transmitting antenna to a reflector and return to the receiving antenna. It is measurable in A- and B-scans. |
| Geo-referencing | The action of tying in the coordinate system of a survey map with a ground system of local or global geographic coordinates. |

## B4 – Theories and Principles

### B4,1 GPR electromagnetic waves in materials

The electromagnetic waves transmitted by GPR are reflected, refracted, diffracted and attenuated in the form of three-dimensional vector fields. The orientation of the EM fields is governed by the vector direction or polarization of the respective electrical and magnetic fields. Change in the polarization of a linearly polarized electric dipole antenna causes maximum or minimum coupling to an underground utility when they are parallel, perpendicular or oblique to each other. For example, alignment of the electric field axis (the long axis of a dipole antenna) parallel to a pipe or wire provides the maximum response to a utility. On the contrary, a perpendicular alignment minimizes the response to a utility. Also, most GPR systems use pairs of transmitting and receiving antennas with the same orientation and polarization, and such systems provide the basis for this specification.

GPR makes use of radio wavelengths in the electromagnetic spectrum, with a scale of centimetres to metres. A transmitting antenna sends very short electromagnetic pulses (with a nanosecond time base) into the ground. The receiving antenna samples the reflected pulses as a plot of amplitude and polarity against two-way travel time (TTT) through an analogue to digital process. When changes to dielectric properties at a particular depth are more significant than the background noise level, the reflection can be interpreted as a signal relating to an underground feature. The transmission, reflection, refraction, scattering, absorption, dispersion and attenuation of GPR waves are dependent upon the different materials buried in the site (Daniels, 2004; Davis and Annan, 1989; Cassidy and Millington, 2009; ASTM D6432-11, 2011). For urban underground surveying and mapping, the nominal centre frequency typically falls within the 100-1000MHz range . In this range, the changes of velocity and attenuation are fairly small when compared with other frequency bandwidths unless the materials are highly conductive, which is known as the GPR plateau (Davis and Annan, 1989). The bandwidth at -3dB level and the centre frequency are normally of equal value. For example, for an antenna with a 400MHz centre frequency, the bandwidth is also 400MHz, as a rule of thumb.

There is a common misconception that GPR locates underground pipes, cables or objects buried in host media such as soil and concrete. In reality, it detects electromagnetic wave energy/reflections when an interface between two media with sufficient dielectric contrast exists and certain criteria concerning the GPR wave and the media are met. In GPR, the general rules of the four Maxwell equations in free space apply, while also taking into account the electromagnetic properties such as dielectric permittivity, conductivity and magnetic permeability of the materials involved. These three properties, as well as the system design, give rise to the five major limitations of GPR survey; namely, attenuation, resolution, scattering, near-field problems and uncertainties due to energy loss as a result of dielectric relaxation and magnetic relaxation. The relevant details are discussed in Section B4,2,3

## B4,2 Interactions between materials and GPR

### B4,2,1 Reflections and polarity

Reflections in GPR are represented in the form of A-scans, traces, or waveforms with a nanosecond time base. The A-scan manifests as a sinusoidal signal with strength and polarities plotted as a function of time convertible to depth with assumed or measured GPR wave velocity in materials in Section 4,2,2. The signals correspond to any scattering and reflection events caused by objects buried in a host material. The strength and polarity of a reflection is basically governed by the dielectric contrast between the two media at an interface, as follows:

$$\mathrm{R} = \frac{\sqrt{\varepsilon_1}-\sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1}+\sqrt{\varepsilon_2}} \quad \text{........ [1]}$$

where $R$ is the reflection coefficient, $\varepsilon_1$ and $\varepsilon_2$ are relative permittivity of media 1 and 2, respectively. Reference values can be found in Table 1. The magnitude of R determines the strength of reflection within the dynamic range of the radar system, and the +/- sign determines the phase changes.

**Table 1 Approximate Electromagnetic Properties of Various Materials (ASTM D6432-11, 2011)**

| Material | Relative Permittivity ε' | Wave velocities (m/ns) | Conductivity (mS/m) |
|---|---|---|---|
| **Air** | 1 | 0.3 | 0 |
| **Fresh water** | 81 | 0.033 | 0.10 – 30 |
| **Sea water** | 70 | 0.033 | 400 |
| **Sand (dry)** | 4-6 | 0.15-0.12 | 0.0001 – 1 |
| **Sand (saturated)** | 25 | 0.055 | 0.1 – 1 |
| **Silt (saturated)** | 10 | 0.095 | 1 – 10 |
| **Clay (saturated)** | 8-12 | 0.106-0.087 | 100 – 1000 |
| **Dry sandy coastal land** | 10 | 0.095 | 2 |
| **Fresh water ice** | 4 | 0.15 | 0.1 – 10 |
| **Permafrost** | 4-8 | 0.15-0.106 | 0.01 – 10 |
| **Granite (dry)** | 5 | 0.134 | 0.00001 |
| **Concrete** | 5-10 | 0.134-0.095 | |
| **Asphalt** | 3-5 | 0.173-0.134 | |
| **Sea ice** | 4-12 | 0.15-0.087 | |
| **PVC, epoxy, polyester vinyl, rubber** | 3 | 0.173 | |

### B4,2,2 Wave velocity in materials

There are three ways to estimate a representative wave velocity *'v'* in material in order to predict object depth *'d'* and material inhomogeneities, such as wetness of soil with the use of two-way travel time *'t'* through the equation $D = \frac{vt}{2}$. The three equations are as follows:

$$\mathrm{v} = \frac{2\mathrm{D_k}}{\mathrm{t_0}} \ldots\ldots[2]; \quad \mathrm{v} = \frac{2}{\mathrm{t_0}} \times \frac{\mathrm{x}\sin\theta}{\sqrt{(\frac{\mathrm{t_x}}{\mathrm{t_0}})^2 - 1}} \ldots\ldots[3]; \quad \mathrm{v} = \frac{c}{\sqrt{\varepsilon'}} \ldots\ldots[4]$$

where v = propagation velocity through the material; $D_k$ = known depth of a particular underground object, which might, for example, be determined through inspection of a drainage pipe connected to an accessible manhole; $\mathrm{t_x}$ = two-way travel time of the hyperbolic/parabolic reflection measured by a GPR device when it is directly on top of the object; $\mathrm{t_0}$ = two-way time of the hyperbolic/parabolic reflection measured by a GPR device when it is oblique to the object at a distance '$x$'; θ = angle between the GPR device and a linear object's alignment (Xie et al., 2018); $c$ = propagation velocity in free space ($3 \times 10^8$m/s); $\varepsilon'$ = real part of relative dielectric permittivity, relative permittivity or also conventionally known as the dielectric constant. Equations [2] and [3] are the preferred options for velocity estimation, while equation [4] shall be used as the last option and only if the parameters needed for the first two equations are unavailable. For equation [4], reference shall be made to the relative permittivities ($\varepsilon'$) and radar propagation velocities for various materials provided in ASTM D6432-11 (2011) and in Table 1, or as recommended by the GPR manufacturer.

### B4,2,3 Limitations

GPR is not a 'miracle tool' that allows invisible underground conditions to be automatically revealed. Instead, it is subject to a number of physical phenomena that limit its ability to 'see the unseen'. Table 2 lists five major limitations, which **ALL** have to be overcome and appreciated if a GPR survey is to be considered 'reliable'. A thorough study of this information can be used to explain how various limitations may have resulted in an unsuccessful GPR survey.

**Table 2 Limitations of GPR Survey**

<table>
<tr><th>Limitations</th><th colspan="2">Descriptions</th></tr>
<tr><td>Insufficient depth of penetration due to attenuation</td><td colspan="2">Theoretical depth of penetration = $\frac{\text{Dynamic range (dB)}}{\text{Attenuation rate (dB /m)}}$/2 …….[5]<br><br>where dynamic range is given by the manufacturer's specification, and attenuation rate in $\mathrm{dB\,/m} = -1640\,\frac{\sigma}{n}$, '$\sigma$' is conductivity and 'n' is refraction index $\sqrt{\varepsilon'\mu'}$ in which $\varepsilon'$ and $\mu'$ are real permittivity and real magnetic permeability respectively. (Annan, 2004)</td></tr>
<tr><td rowspan="2">Resolution limits</td><td colspan="2">Resolution is divided into two parts: horizontal and vertical resolution limits. Objects with spacing within these limits are said to be too close and reflections are unresolvable.</td></tr>
<tr><td>The limit of horizontal resolution is defined by the radius of the radar footprint as a function of depth, wave velocity and antenna frequency and is known as the First Fresnel Zone:</td><td>On safe side, vertical resolution limit is defined by a half wavelength, although a quarter wavelength may also be suggested(ASTM D6432-11, 2011), which is equal to:</td></tr>
</table>

| | | |
|---|---|---|
| | $r = \sqrt{\frac{v^2}{16f^2} + \frac{vd}{2f}}$.......[6]<br>where $f$ = antenna centre frequency, $c$= speed of light (0,2998 m/ns), $r$ = radius of radar footprint, v = wave velocity, $d$ is object depth | $\frac{Wavelength}{2} = \frac{v}{2f} = \frac{c}{2f\sqrt{\varepsilon\prime}}$....[7]<br>where f = antenna centre frequency, $c$ = speed of light (0,2998 m/ns), $\varepsilon'$= real permittivity |
| Rayleigh and Mie signal scattering | Three scattering regimes relating wavelength to object sizes are presented as follows:<br><br>Object dimension $'2\pi a'$ << λ. Rayleigh scattering (i.e. cannot see). When circumference ($2\pi a$) of an object with nominal radius 'a' is too small compared to the nominal wavelength (λ) of the GPR wave, scattering in Rayleigh region occurs and the object is said to be too small to be imaged.<br><br>Object dimension '2πa' → λ, Mie scattering (i.e. clutter). When circumference ($2\pi a$) of an object with nominal radius 'a' is of the same order and is similar in size to the nominal wavelength (λ) of the GPR wave, scattering in Mie region occurs and causes diffraction, which then blurs signals from objects of real interest.<br><br>Object dimension $'2\pi a'$ >> λ, Optical region (i.e. good reflection). When circumference ($2\pi a$) of an object with nominal radius 'a' is much larger than and the nominal wavelength (λ) of the GPR wave (e.g. λ is 10 times smaller than $2\pi a$), scattering in optical region occurs, giving a good reflection where the object is distinguishable from the background. | |
| Near-field problem | A near-field problem occurs when the cover depth of the object is too shallow (it is too close to the surface) to be accurately imaged by GPR. Near-field imaging can be assumed to exist within (≤ 2λ) (i.e. two times nominal wavelength from the material surface. Within that range, depth estimation is inaccurate because of EM induction. | |
| Uncertainty of reflector's depth | Uncertainty of reflector's depth shall be calculated according to JCGM (2008): Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Combined uncertainties ($\Delta d$) of depth shall be estimated and reported before and refined after the GPR survey based on the errors of velocity using equation [4] as well as [3], respectively. Uncertainties are in general larger in deeper than shallower objects. | |

## B4,3 Image reconstruction

A-, B- and C-scans are the most commonly used representations in GPR imaging. Definitions of these scans are described in the glossary. The reproduction of these images requires a series of standardised data processing steps. The processing of GPR data is based on the well-established methods used in seismic geophysics. Its emphasis is on signal quality enhancement and how this enhancement maps the objects of interest, such as underground utilities, voids, the position of artefacts, the water table, and steel bars in concrete. This process reconstructs signals by modifying the raw signals according to few fundamental physical principles (e.g. wave attenuation with increasing depth) and is somewhat reliant upon human perception (Lai et al. 2018b) in the mapping and imaging stage (e.g. thresholding frequency range in bandpass filtering).

The representation of GPR signals can be summarized as A-scans, B-scans and C-scans. Stacked A-scans form a B-scan in two ways. The stacking can be done by alignment of multiple B-scans collected in various perpendicular and parallel traverses, or allocation of A-scans at specific coordinates measured by total station or global navigation satellite system (GNSS). B-scans are then processed with 2D and 3D processing steps as described in Section F. Finally, the output is an intensity map in 3D space from which a user can select to retrieve a horizontal C-scan at any particular depth. Spatial stacking of GPR signals into these three representations provides positions, coordinates, orientations and conditions of underground objects of interest that have significant dielectric contrasts with the host material.

B4,4 Horizontal Location Accuracy

The horizontal location accuracy levels (absolute or relative to depth, whichever is greater) stated in BSI:PAS 128 (2014) shall be the benchmark of test/survey accuracy in reliable survey. Table 3 further divides the horizontal location survey accuracy in three quality levels: reliable, survey unreliable (SU), and survey not successful (SNS). Vertical accuracy shall be subject to the results of uncertainty measurement suggested in Table 2, and estimated according to JCGM (2008).

**Table 3 Recommended quality levels and accuracies of GPR test/survey**

| Quality level | Horizontal location accuracy [1] |
|---|---|
| Reliable | ± 150mm or ± 15% of detected depth whichever is greater. This accuracy level is only valid if alignment of utility is continuously observed in C-scan. |
| Survey unreliable (SU) [2] | Undefined |
| Survey not successful (SNS) [3] | |

Remarks:

[1] Accuracy levels may possibly be affected by the limitations stated in Table 2. Horizontal location refers to the centreline of the utility.

[2] A unique colour shall be used to label and annotate SU pipe/cable in drawing(s). The alignment and cover depth may be predicted from the record drawing. Reason(s) of SU shall refer to Table 2 and/or Section G Limitations.

[3] A unique colour shall be used to label and annotate SNS pipe/cable in drawing(s). The alignment and cover depth may be predicted from the record drawing. Reason(s) of SNS shall refer to Section G Limitations.

[4] If Survey Officer decides that such horizontal accuracy level cannot be reached, the suggested level of accuracy shall be suggested in the survey sheet. Reason(s) shall refer to Section G Limitations.

[5] Depth accuracy shall be derived with uncertainty models according to JCGM (2008).

## C – Qualified Personnel

### C1 – Personnel

The Signatories and Survey Officers for all NDTSID shall meet the personal requirements in Section C2 and C3 below, respectively.

### C2 – Signatory

C2,1 A **Signatory** of a report shall either have:

(i) a Bachelor of Science or Engineering (e.g. Geomatics/Land Surveying) degree with specialization in underground-utility (UU) or a Bachelor of Science or Engineering (e.g.

Geomatics/Land Surveying) degree with not less than 200 contact hours of UU training plus final year project, provided by a recognized tertiary institution plus at least ***three*** years of technical and managerial experience of underground utilities, within which a period of two years is substantially[1] related to the subject matter in this specification, or

(ii) a valid certificate or diploma[2] of specialization in GPR issued by a recognized organization operating under international standards or qualifications framework level 4 plus at least ***five*** years of technical and managerial experience of underground utilities, within which three years are substantially related to the subject matter in this specification, or

(iii) at least a higher certificate or diploma issued by a recognized technical institute or an equivalent qualification in a relevant discipline, with at least ***seven*** years of direct technical and managerial experience, within which five years are directly related to the subject matter in this specification, plus relevant training courses[2] covering the content in this specification.

[1] Direct technical (interpretation and diagnosis) and managerial involvement of 10 test/survey reports in different contracts/works orders.
[2] A typical certificate or diploma shall include all aspects covered in this specification.

## C3 – Survey Officer

C3,1 A **Survey officer** shall normally be supervised by a Signatory having the necessary qualifications, experience and technical knowledge. A Survey Officer shall either have:

(i) a higher diploma or above (e.g. Geomatics/Land Surveying) with not less than 75 contact hours of UU training provided by a recognized tertiary institution, plus at least ***one*** year of on-the-job experience substantially[3] related to the subject matter in this specification, or

(ii) a valid certificate or diploma[4] of specialization in GPR issued by a recognized organization operating under international standards or qualifications framework level 3, plus at least ***two*** years of substantial on-the-job experience[3] related to the subject matter in this specification, or

(iii) at least a higher certificate issued by a recognized technical institute or an equivalent qualification in a relevant discipline, plus at least ***three*** years of substantial on-the-job experience[3] related to the subject matter in this specification, plus relevant training courses covering the content in this specification[4].

[3] On-the-job direct involvement in 10 test/survey reports in different contracts/works orders.
[4] A typical certificate or diploma shall include all hands-on aspects covered in this specification.

C3,2 A Survey Officer shall be evaluated based on technical competence and the lab/survey company is required to keep a separate list of qualified Survey Officers who are permitted to perform each survey/test and sign the worksheet, for the purpose of checking by the Accreditation body. As approvals are granted in the context of the survey/tests being performed by a particular lab/survey company, they shall not be considered as personal qualifications.

## D – Instrumentation

### D1 – Radar Control Unit and Display

The most commonly used GPR equipment consists of a transmitter and a receiver dipole antenna, a radar control unit for converting analogue radio signal to digital format, and data storage and display devices. A circuit within the synchronized radar control unit triggers pulses and sends them to the transmitter and receiver electronics. The transmitter electronics produce output pulses radiating into the ground through the transmitting antenna. The receiving antenna receives the EM waves reflected from interfaces between media with significant contrast of dielectric properties and conductivity, and amplifies them for display and analysis. The synchronized signals control the transmitter and sampling receiver electronics in the antenna(s) so as to generate the reflected radar pulses with a time base in nanoseconds. These waveforms may be filtered and amplified, and are transmitted along with the timing signals to the display and recording devices. Real-time signal processing, such as stacking, is available in most GPR systems as a means of improving signal-to-noise ratio. When working in areas with background ‘cultural’ noise, such as from radio and overhanging power cables, and in high-loss materials, different types of time varying gain are necessary to adjust signal amplitudes for display.

### D2 – Antennas and Control Cables

Antennas are manufactured both with and without shielding made of metal or highly radio absorbent material. Shielding reduces the levels of energy radiation escaping from the sides and top of the antenna, thereby enhancing the signal to noise ratio by minimizing the effects of reflections from surface coupling and above ground targets. However, low-frequency antennas (less than 100 MHz) are rarely shielded, while most high-frequency antennas are shielded. The typical centre frequency of commercially available antennas ranges from 10 to 3000 MHz, which generate pulses that have a 2 to 3 octave bandwidth. As a rule of thumb, lower-frequency antennas yield longer wavelengths and allow deeper exploration, but suffer from poorer resolution when compared with higher-frequency antennas, and vice versa.

### D3 – Equipment Calibration/Verification

The requirements for equipment calibration/verification intervals for GPR are given in Table 4. These requirements shall be complied with unless overridden by more stringent testing specifications.

If a laboratory/surveying company has the necessary reference equipment and expertise, then calibration/verification could be done internally. Nevertheless, the laboratory/survey company must have the necessary resources consistent with the accuracy required and any standards relevant to the calibration/verification concerned. The personnel conducting in-house calibration/verification shall be properly trained and calibration/verification procedures shall be documented. All calibration/verification procedures and records shall be documented and kept properly.

Equipment shall be properly stored and maintained. A suitable environment shall be provided for storage. When handling heavy testing equipment on site, laboratory/surveying company shall comply with any relevant construction site safety regulations applicable to their testing personnel. Equipment that is moved from one location to another shall, where relevant, be checked before use. Precautions shall be taken to ensure that, after transportation to a site, testing equipment remains in a serviceable state. Appropriate checks shall be performed on site to confirm the equipment’s service state before testing/surveying commences.

**Table 4 Specific Calibration/Verification Requirements**

| Type of equipment | Maximum period between successive calibration/ verification | Calibration/verification procedure or guidance documents and equipment requirements |
|---|---|---|
| GPR | 1 year | Measure the two-way transit time of the radar wave travelling from the antenna to a flat reflector in air through at least five distinct reference distances. The reference distances shall not be smaller than two GPR wavelength (B4,2,3) to achieve a far-field reflection from the flat reflector. The distance increments shall not be less than 200mm. The flat reflector can be a wall, a slab or a metal plate, and its size shall not be less than size of the circular First Fresnel Zone at a particular distance (B4,2,3). Definition of the time zero position in the radar waveform, as well as trigonometrical corrections regarding the relative positions of the radar's transmitter, receiver and the flat reflector shall be considered. The curve of reference distances against radar travel time values shall be plotted to obtain a gradient that is equivalent to the radar wave velocity in air. The measured velocity in air shall be compared with the theoretical value (i.e. 0.2998 m/ns). If the error is larger than 5% or exceeds the value recommended by the manufacturer, whichever is the lesser, a full check/repair of the radar equipment by the equipment manufacturer is required. |
| | Before each test (verification before use) | Carry out on-site verification of the survey wheel/odometer following the manufacturer's recommendations if the radar system is triggered by survey wheel/odometer. A radargram with meaningful signals shall be displayed with appropriate gain settings. Record and report the verified value before each test. |
| Other equipment related to this GPR survey (e.g. total station, digital level) | 1 year (calibration) | Accuracy requirement provided by the manufacturer shall be observed. |

## E – General Testing and Survey Procedure

The test/survey shall be accredited by the relevant Hong Kong Accreditation Service of its MRA partner. The following standardized working procedures in Figure 1 shall apply to general test/survey works. For sites with specific conditions and requirements, a method statement shall be supplemented separately.

The site's boundary shall be confirmed and agreed with the client's representative and be marked to provide on-site limits for the field crew led by Survey Officer. The geo-referencing by topographic survey shall use well-established control points. A comprehensive desktop search of the available and 'best-known' utility maps shall be completed to provide the potential layout of utilities before the GPR test/survey. Temporary traffic arrangements (TTA) shall be prepared by the crew for the sake of safety.

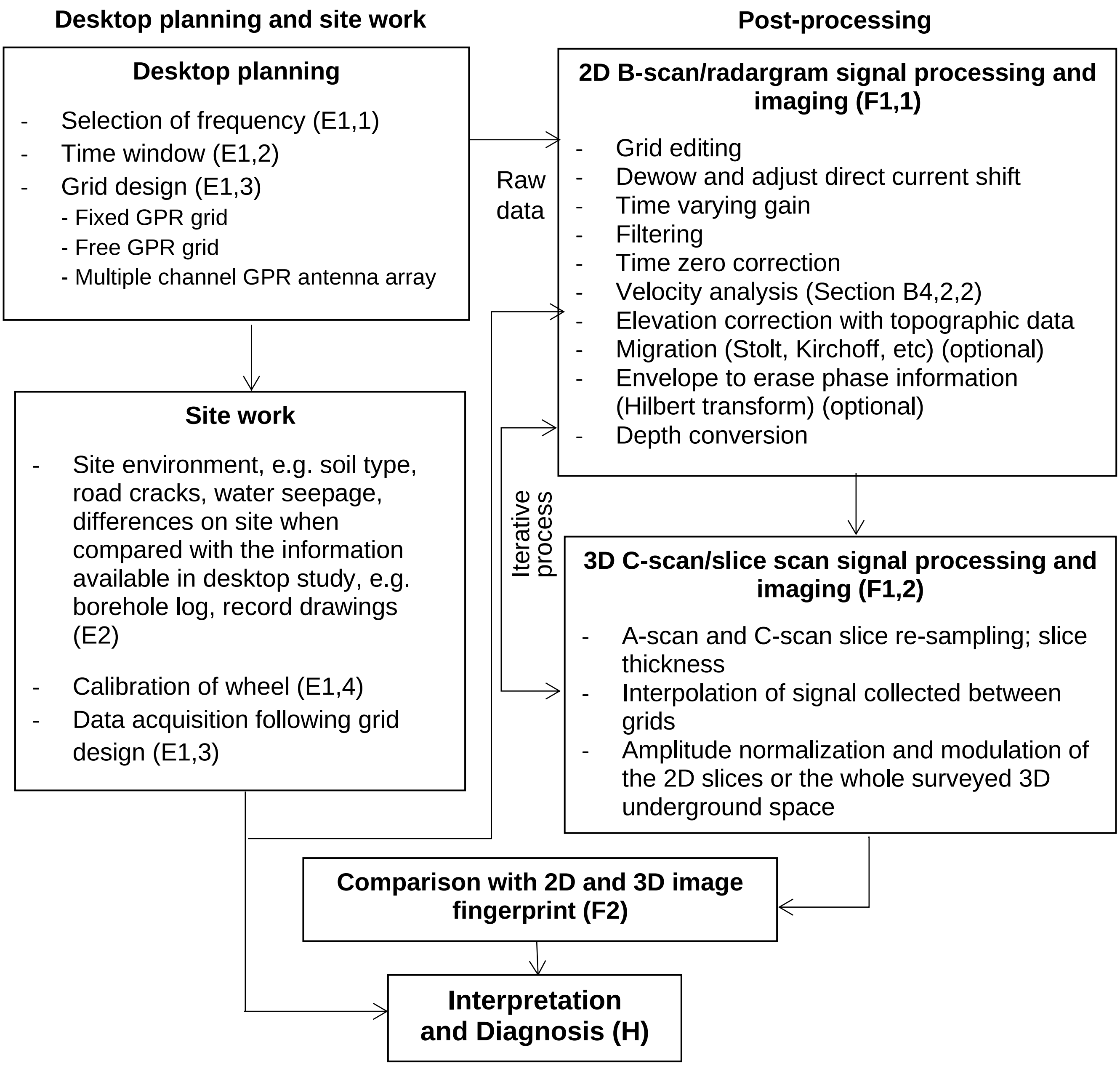
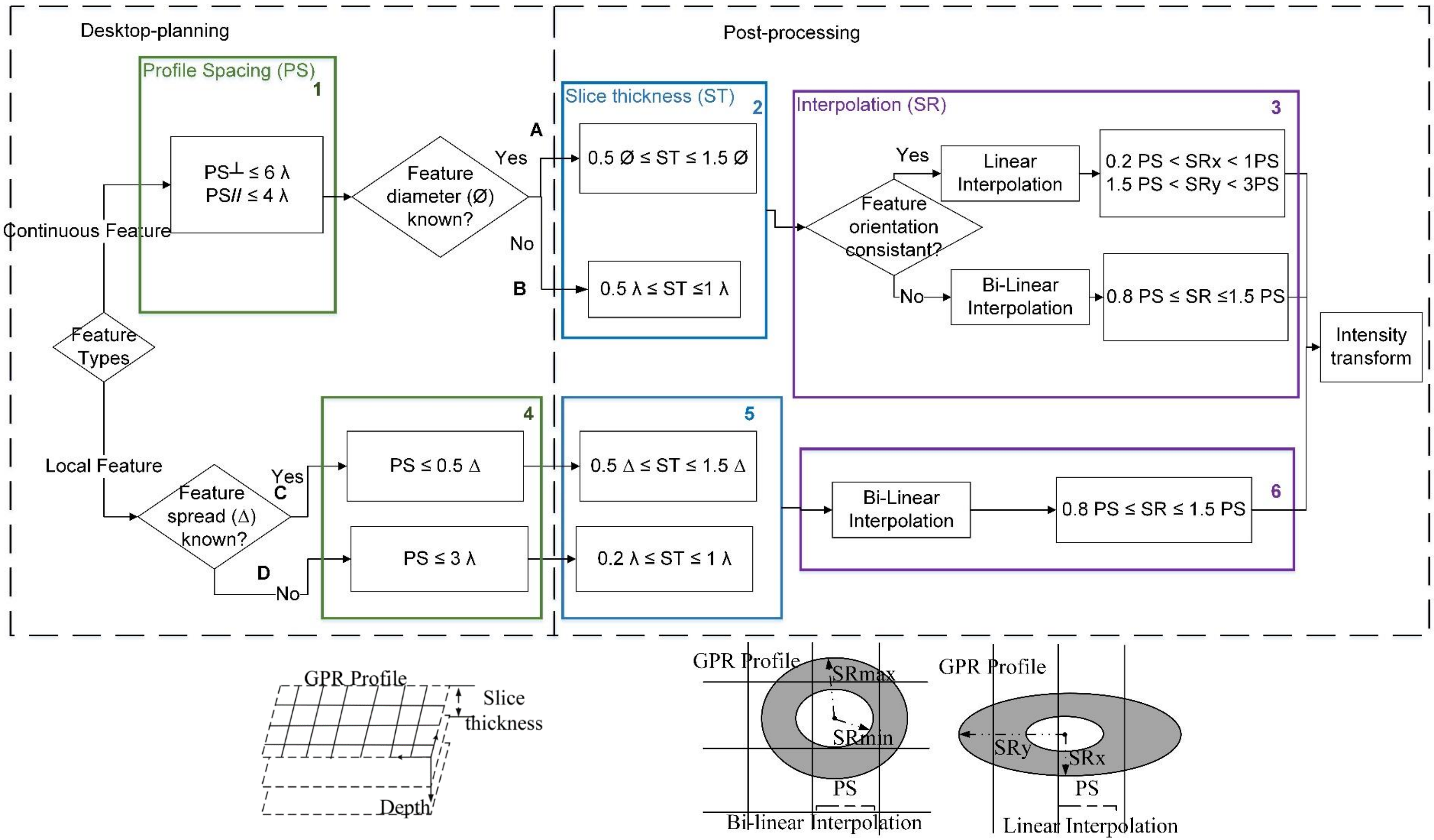



**Figure 1 Typical flow of data acquisition, 2D and 3D signal processing and imaging (modified based on Jol (2009)'s standard flowchart)**




a b

Remarks: (1) v can be estimated base on equation [2 - 4]; (2) $PS_{\perp}$ refers to the GPR profiles that are perpendicular to linear object orientation, and $PS_{//}$ refers to GPR profiles that are parallel to the linear object orientation; (3) In interpolation, SR max and SR min represent maximum and minimum acceptable search radius (SR), respectively, while SRy and SRx denotes long axis and short axis of elliptical search radius in linear interpolation, respectively.

**Figure 2 Standardized desktop planning of grid design and post-processing 3D imaging flow (Luo et al. 2019)**

## E1 – System Set-up in Office and at Site

### E1,1 Selection of antenna frequencies

The first yardstick of a reliable GPR survey is the selection of antenna frequency on the basis of three considerations: (1) the estimated depth of the target of interest, for example using utility as-built plans; (2) the assumed spatial resolution of objects, and (3) the assumed size of scatterers due to scattering by inhomogeneous objects existing in the host material, such as cobbles in soil recorded in a trial pit and/or borehole log. Mathematically, individual consideration of frequency ‘ $f_C^D$ , $f_C^R$ , $f_C^C$ ’ can be objectively determined with equations [8] to [10], respectively. Then, the actual selected frequency ‘ $f_C$ ’ must fulfil the criteria presented as equation [10] which fall into a range spanning $f_C^D$ , $f_C^R$ and $f_C^C$ (Annan, 2004). If this criterion cannot be fulfilled, it implies that the object is not detectable by GPR, and other methods should be considered.

Consideration 1: $f_C^D = \frac{1200\sqrt{\varepsilon' - 1}}{D} MHz$ ……..[8]; Consideration 2: $f_C^R = \frac{75}{\Delta s\sqrt{\varepsilon'}} MHz$ ……..[9]

Consideration 3: $f_C^C = \frac{30}{\Delta L\sqrt{\varepsilon'}} MHz$ ……..[10])

Criteria for selection of frequency $f_C$ : $f_C^R < f_C < \min(f_C^D, f_C^C)$ ……….[11] (Annan, 2004)

where $f_C$ is a selected centre frequency within the range of the 1st ( $f_C^D$ ), 2nd ( $f_C^R$ ) and 3rd ( $f_C^C$ ) consideration, $\varepsilon$ ’ is the relative permittivity of the host material, $\Delta s$ is the spatial resolution ($m$), $\Delta L$ is the size of major scatterers existing in the host material ($m$), and $D$ is the target depth ($m$).

### E1,2 Time window

The time window refers to the maximum travel time span within which a reflection from an object of interest is presented. Too small a time window would lead to objects of interest being missed. On the other hand, too large a time window would lead to a loss of resolution, thus affecting the imageability of objects of interest. An optimal time window is therefore critical and can be determined using equations [12] and [13]. The two required inputs are the expected depth (D) of the objects of interest and the permittivity values ( $\varepsilon'$ ) of the host material. The former can be obtained from the task requirements, which may indicate the depth of objects previously recorded. The latter can be estimated using Table 1 and any relevant information available, such as soil types in borehole logs, soil sampling from trial pits, soil tests, geological maps, and literature. In general, the deeper and wetter the host material is, the longer the time window required will be.

$$v = \frac{2D}{t} \text{ …..[12]} \qquad ; \quad T_w > safety\ \ factor \times \frac{2D_{\max}\sqrt{\varepsilon'}}{c} \text{ …..[13]}$$

In equation [12], $v$ = wave velocity in the host material, D = expected depth of the objects of interest, and $t$ = two-way travel time. Combining equations [4] in Section B4.2.2 and [12] produces equation [13], in which ‘$t$’ is replaced by $T_w$ = time window, a buffer factor of 1.3 is commonly used, $\varepsilon'$ = real part of permittivity, c = speed of light (0.2998 m/ns), and $D_{max}$ = maximum reachable depth.

### E1,3 Grid spacing

The choice of GPR grid spacing requires prior consideration of 3D imaging in the flow diagram in Figure 2 by making assumptions about the GPR wavelength ( $\lambda = v/f$ ) in materials. The geo-referenced grid orientation and profile spacing must be planned prior to site work.

### E1,3,1 Fixed GPR grid

a. Set out the location of origin (0,0) and orthogonal x-y survey lines on site in lines as straight as possible. For irregular site areas, the grid is not necessarily orthogonal but can be irregular in shape. The start and end points of each traverse must be carefully geo-referenced using appropriate surveying methods and be presented in maps.

b. Grid marks must be placed at equal intervals along the survey lines using markers, survey flags and tapes, measuring wheels, an electronic measuring device, or other location system.

c. All survey lines shall be geo-referenced using survey equipment for subsequent data processing, imaging and presentation. A topographical survey may be carried out for elevation correction.

### E1,3,2 Free GPR grid

For most GPR surveys with a single channel system, laying down grids on-site according to Section E1,3 takes up most of the surveying and recording time site work. Auto-tracking of GPR antenna position with a $360^0$ prism and/or GNSS receivers is therefore always preferred. For auto-track total station, a $360^0$ prism shall be mounted at the midpoint between the GPR transmitter and receiver, which then records the 3D position through the laser reflected back to the total station. When the GPR antenna is towed in a survey area in zig-zag mode, the auto-track total station tracks the real time local coordinates, thus replacing the data collection procedure in Section E1,3,1 and allowing survey within an irregular grid.

### E1,3,3 Multiple channel GPR antenna array

The use of single channel GPR systems is constrained by the need to block road traffic during use and its limited underground footprint over a particular traverse. With advances in instrumentation and computer processing power, antenna arrays can be formed by aligning multiple antennas to cover a larger footprint. The advantages are clear, in that this setup allows the survey of a wider area in single traverse even at highway speeds, which avoids the tedious temporary traffic blockages and bureaucratic procedures that are required in single channel GPR imaging. In addition to the traditional pulse GPR, with its fixed centre frequency and use of a particular bandwidth, such array setups are also available in step frequency continuous wave (SFCW) configuration, which generates an almost flat response over a wide bandwidth (e.g. 10MHz to 1500MHz). This setup therefore offers imaging at multiple depths and multiple resolutions in a single traverse.

However, the ‘along array’ resolution (data collected perpendicular to the direction of movement of the array) offers typically lower resolution than that collected ‘along track’. For some applications, and where key services are orientated along the line of the road or pavement, these multiple channel arrays will not provide data as good at that collected from an antenna (or array of antennas) where the scan lines are perpendicular to the objects of interest.

## E1,4 Calibration of wheel

The wheel(s) connected to the GPR odometer shall be calibrated on-site. The method of calibration requires a fixed and representative distance to be decided on-site, and the wheel is then towed over that distance and the number of hits are counted. The ratio between the actual distance and the count becomes the calibration factor for a particular survey area. This process must be repeated three times and an average of the ratio is then calculated.

## E2 – Site inspection

Several factors must be taken into consideration when there are differences between the information available in borehole logs and record drawings in the desktop study and the situation observed on site. Such factors include, but are not limited to, construction details, ground surface damage and deformation, soil conditions observable in nearby trial pits, water seepage, anticipated properties of the target and host material, the topography, and access to the site. Any sources of electromagnetic noise, especially radio, as well as operational constraints shall also be recorded and avoided as much as possible. An additional factor would be comparison of visible indicators of buried services (road scars, covers, etc.) with any previous knowledge of services expected to be present - particularly from record drawings which ideally would be available to the Signatory/Survey Officer.

## F – Imaging and Diagnostic Procedure

## F1 – 2D and 3D Signal Processing and Imaging

F1,1 2D

**Table 5 A suggested sequence of 2D signal and image processing tasks based on Fig.1.**

| | |
|---|---|
| Dewow and adjust direct current shift | 'Dewow' and 'adjust DC shift' refer to temporal filtering to remove very low frequency and direct current components from the data. Very low frequency components of the data are associated with either inductive phenomena or possible instrumentation dynamic range limitations. |
| Time Gain | GPR signals are rapidly attenuated as the wave propagates into the ground. Reflection events from greater depths may be invisible or indiscernible. Equalizing amplitudes by applying a radar time-dependent gain function compensates for the rapid fall-off in radar signals from greater depths. This is referred to as "time varying gain" (Goodman and Piro, 2013), and an example is automatic gain control (AGC), which is a continuously adaptive gain that is helpful when it is important to show all the information irrespective of amplitude fidelity. Manual gain with a user-defined gain function is another alternative. Exponential or linear gain imitates and amplifies based upon the mathematical model of the attenuation curve of the data. Another widely used gain is manual y-gain, which allows the user to define multiple points with desired amplitude through time in each A-scan. |
| Filtering (temporal, bandpass, background) | Filtering can be applied *before or after time gain* as long as the effect of the gain is understood. Temporal filtering means filtering along the time axis of the data set. Different types of temporal filtering may be applied in bandpass filtering using fast Fourier transforms (FFT) through various types of linear and non-linear time domain convolution filter operators.<br><br>A bandpass filter is a 1D filter that works in the frequency domain. Waveforms are transformed to frequency domain using Fast Fourier transforms (Daniels, 2004; Malagodi et al., 1996). A certain range of frequencies are retained while the rest are removed. As the signals are decomposed into their spectral components, the amplitudes of different frequencies can be adjusted by reducing or enhancing the desired frequencies (Goodman and Piro, 2013). High pass and low pass spatial filtering are two well-known filters: the high pass spatial filter retains dipping responses and removes flatter events, and vice versa for the low pass filter. Median and mean filters are used to smoothen noise spikes. These filters are 2D filters and can be applied in both the time or space domain. |

| | |
|---|---|
| | Background removal is another 2D spatial filtering that removes repeated responses in every trace. It eliminates constant and systematic clutter noise across the radargram. A popular background removal process involves calculating the average pulse across the entire radargram and then subtracting it from each individually recorded pulse (Bernabini et al., 1995; Malagodi et al., 1996). |
| Time zero correction | The 0 ns position changes depending upon the ground material. The definition of the first measured arrival as time 0 is debatable. When an antenna is placed on the ground surface, the direct wave is altered in shape and shifts later in time by up to several tenths of a nanosecond, due to the dielectric loading of the ground material in the near field of the antenna (Yelf, 2004). Time zero correction refers to moving the 0 ns position of each trace in order to eliminate the delay from electronic zero to ground zero. It is suggested that GPR users should estimate the time zero in each application with their own experiments. |
| Velocity analysis | Equation [2] or [3] in Section B4,2,2 shall in general be followed. For equation [3], which is the most common case of data post-processing, a hyperbolic/parabolic shape response occurs when a GPR wave is diffracted by a circular reflector. The mathematical form of the hyperbolic reflection relates spatial position ($x$) to travel time ($T$). A handy interpretative aid to the estimation of GPR wave velocity is to visually fit a model hyperbolic shape to the GPR data, based on the two-way travel time described in equation [3]. By overlaying and adjusting an as-fit velocity model over the apex of the hyperbolic/parabolic reflection and then inputting the radius of the reflector object, the wave velocity in the media can be estimated as a basis for estimating an object's depth. A more complicated yet comprehensive way is to take into account the antenna separation distance, object diameter, angle between the utility alignment and GPR traverse, etc (Sham and Lai 2016; Xie et al. 2018). |
| Elevation correction with topographic data | For undulating ground, GPR scans will be shifted based on elevation changes. Standard topographic adjustment requires the estimation of velocity using the radargrams, and the scans are then shifted vertically to account for the change in topography (Tanaka et al., 2009). The tilt of the scan is estimated by a ground slope calculation using measurements of the local topography in the GPR scan. This slope is used to project the ray signal emitted from the tilted antenna. |
| Migration (Stolt, Kirchoff, etc) | Most GPR antennas emit a broad beam of radio energy into the ground, causing hyperbolic/parabolic reflections to be recorded from round objects in the ground. Objects oblique to the antenna are recorded because of the broad range of beam angles. Migration regresses hyperbolic/parabolic reflections back to point source reflections by adding up all the energy along hyperbolas across the radargram, and places this energy at the apex of the hyperbola. Kirchoff migration in the time domain and FK migration in the frequency domain are two popular migration processes that yield similar results in most cases. Note that migration is only useful for circular objects. |
| Envelope to erase phase information (Hilbert transform) | The envelope of the recorded radar signal refers to the Hilbert transform. It is a mathematic process using a Fourier transform. The negative reflections are shifted 90 degrees and processed with an inverse Fourier transform. The recorded pulse is then 'enveloped' to produce a reflection that looks like the actual geometry of a circular object. In this process, phase information is lost. |
| Depth conversion | After estimating time zero and GPR wave velocity using one or more of the velocity estimation methods in Section B4,2,2, the depth of an object can be estimated by measuring the two-way travel time. An apparent depth axis shall be added to one |

| | |
|---|---|
| | side of the radargram, while the time axis shall appear on the other side. Note also that the estimated depth after migration and envelop shall appear deeper than that of the hyperbolic/parabolic reflections. For accurate depth ranging purposes, depth estimation shall be based upon the observation of the hyperbolic/parabolic reflections rather than the processed reflections after migration and envelop. |

F1,2 3D

**Table 6 A suggested sequence of 3D signal and image processing based on Fig. 2.**

| | |
|---|---|
| Re-sampling of A-scans | This re-samples and re-groups a number of A-scans into an averaged pixel cell to be represented in and prepared for subsequent slice imaging. |
| Re-sampling of C-scan slice | Depth slices show the radar reflection intensity within a certain thickness at a user-defined depth. A single slice with certain thickness presents summed reflections within this range of depth. Slices with larger thickness record more reflection energy, but this also introduces uncertainty over feature depth. For slice thicknesses that are much smaller than a feature's diameter, the feature cannot be fully delineated in a single slice. |
| Interpolation of signals collected between grids | Very often survey profiles are not dense enough to map a full-resolution GPR image because of site constraints and limited survey time, even though full-resolution has proven to be superior (Grasmueck et al., 2005). Interpolations with a radiated survey search radius (SR) are required. A smaller radius retains more true measurements while local extrema are also maintained, whereas a larger radius smooths out information and details of smaller features can be lost.<br><br>Two commonly used algorithms are inverse distance and kriging, which fill up gaps between survey grids. For geometric interpolation, one option is bi-linear interpolation, which involves taking GPR profiles of all directions into computation, while the other is linear interpolation that is applied to single orientation GPR profiles and interpolation is made primarily transverse to the profile direction. |
| Amplitude normalization and modulation of all C-scan slices | The received signal intensities are transformed into digits represented by a user-selected colour palette. There are in general three types:<br><br>1. Relative normalization: displays each time-slice map based on its own maximum and minimum grid values;<br>2. Absolute normalization: displays the maximum and minimum within the entire 3D volume;<br>3. User-defined normalization: allows the user to manually set the upper and lower boundary of the display value. |

## F2 – Fingerprint Database

Each lab/company shall establish their own fingerprint database of B-scan radargrams for manual or automatic matching of field data. Some examples are given below in Table 5:

**Table 7 Descriptors for a few common types of buried objects**

| Types of buried objects | Descriptors |
|---|---|
| Underground utility (metallic) | When a GPR antenna is traversed across the object hyperbolic/parabolic reflections appear in the radargram. If the GPR traverses are perpendicular to the utility alignment, the hyperbolic/parabolic response is the steepest. The included angle between the traverse and the utility alignment shall not be more than 45° (Xie et al., 2018). A utility and its alignment can be confirmed in C-scans if hyperbolas of similar nature are found in adjacent radargrams, where an underground utility is presented as a continuous linear shaped object in C-scans. |
| Underground utility (non-metallic) | All of the above are valid except that the first arrival reflection of a non-metallic utility shall be in opposite phase when compared to the metallic utility in the same site, provided that the reflection is not interfered by other reflectors/scatters. Certain decaying reverberations shall be expected. |
| Layer (e.g. concrete backwalls, road pavement/ subgrade interface) | A continuous layer response is present along the radargram. |
| Metallic manhole cover | Strong reflections without attenuation start from the time/ground zero to the bottom of the time window. |
| Manhole wall or buried vertical structure | Strong and flat reflections beyond time zero with reflection tails extended and inclined linearly at the two edges of the flat reflection. |
| Air void | There are three types classified by void shapes and void sizes relative to wavelength. Type 3 is the smallest one of the three types:<br>Type 1: Bowl shaped for large shallow subsurface void;<br>Type 2. Strong reverberation response decay with increasing depth;<br>Type 3. Small point reflector that generates local hyperbola response.<br>In C-scans, an air void is present as local anomalies with high reflection intensity, and shall not be continuously connected as in the case of utilities (Lai et al. 2018b). |
| Reinforced concrete | Strong hyperbolic reflections in the shallow subsurface zone with regular spacing and similar cover depth. |
| Buried concrete raft/slab/plinth | Very similar in appearance to a type 2 air-filled void, except that the reverberation patterns are more regular and repeat with depth. |

*Note: the above descriptors of particular features in GPR radargram fingerprints are for reference and serve as general guide only. Different cases may give different responses, especially when objects are densely populated. Interpretation is subject to the expertise of the Signatory and Survey Officer.*

## G – Survey/Test Report

The report shall include, but not be limited to, the following sections:

- Introduction and background
- Site areas and boundary and methods of geo-referencing of all collected data,
- Site conditions
- Theories and principles
- General test/survey procedures and site-specific procedures
- Instrumentation
- Summary of findings and interpretations in the form of C-scans images and representative B-scans
- Calculated uncertainties of depth measurement of utilities according to Guideline of Uncertainty Measurement
- Survey drawings
- Difficulties/limitations due to site constraints and/or reasons with calculations listed in Table 2.
- Conclusion
- Site photos in Appendix
- Record drawings (reference utility plans provided by utility companies and clients) in Appendix.

## H – Interpretation and Diagnosis

Interpretation and diagnosis are a by-elimination flow based on the following three key steps:

1. The signal processing procedure in section F1,
2. Comparison of signals with an established GPR database created by the lab/survey company and with reference to descriptors comprising, but not limited to, those in section F2,
3. Assessment of survey results in concert with information from other complementary near-surface geophysical methods, such as PCL/EML and non-geophysical methods such as visual inspection or oral history.

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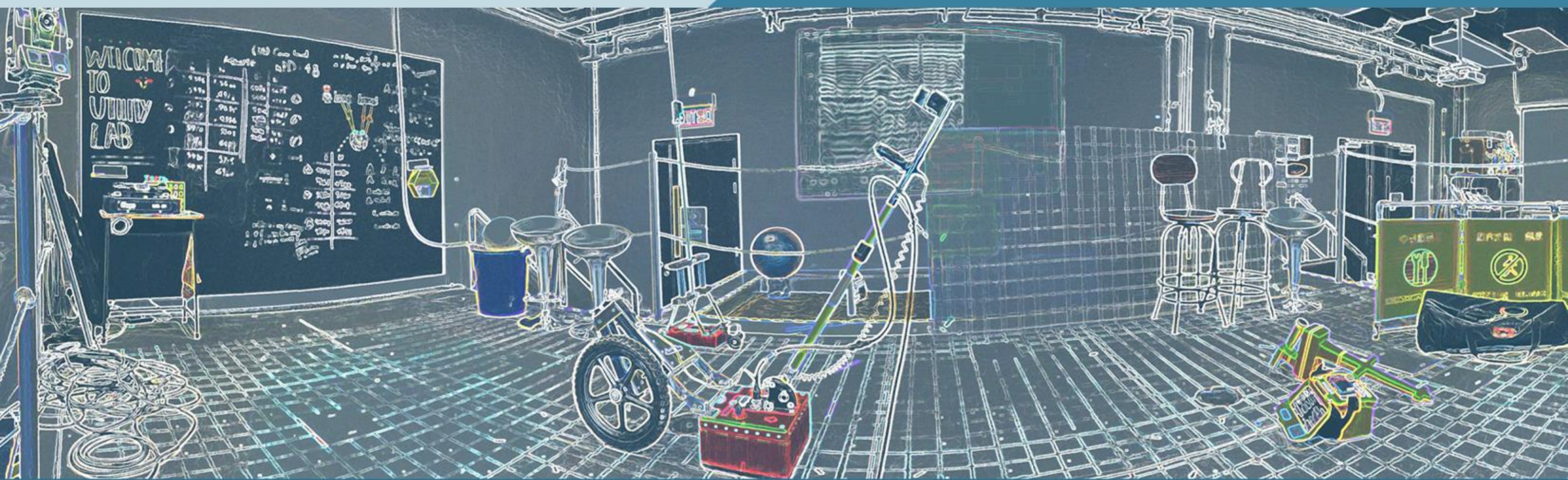
PREPARED BY

DEPARTMENT OF LAND SURVEYING AND GEO-INFORMATICS (LSGI),
THE HONG KONG POLYTECHNIC UNIVERSITY





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