Journal of Microwaves, Optoelectronics and Electromagnetic Applications, Vol. 17, No. 3, September 2018
DOI: http://dx.doi.org/10.1590/2179-10742018v17i31321

A Review of Ground Penetrating Radar Antenna Design and Optimization

X. L. Travassos[1], S. L. Avila[2], R. L. da S. Adriano[3], N. Ida[4]
[1]*UFSC, Campus Joinville, Rua Dona Francisca, 8300 – CEP 89219-600, Lucas.Travassos@ufsc.br*
[2]*IFSC, Campus Florianópolis, Av. Mauro Ramos, 950 – CEP88020-300, Sergio.Avila@ifsc.edu.br*
[3]*UFMG, Campus Pampulha, Av. Antônio Carlos 6627 – CEP 31270-901, rluiz@cpdee.ufmg.br*
[4]*University of Akron, Akron, OH 44325-3904, ida@uakron.edu*

***Abstract*—Ground Penetrating Radar is a complex nondestructive evaluation technique where the antenna is the most critical part. The antenna is responsible for transmission and reception of waves at the proper level and frequencies defined in the GPR system specifications. Important GPR features such as resolution and penetration depth depend on its characteristics. In this context, this work outlines the fundamental GPR system theory in order to discuss procedures for improving antennas to GPR applications. Additionally, recent works regarding GPR antenna optimization are reviewed and placed in the context of a framework for GPR antenna design and optimization.**

***Index Terms*—**GPR Antenna, design, optimization.

I. Introduction

Nondestructive evaluation (NDE) is the process of inspecting, testing, or evaluating materials, components or assemblies for discontinuities, or variations in characteristics without affecting the serviceability of the system itself. In 2017, many nondestructive testing (NDT) societies signed a cooperation agreement to regulate their actions [1]. The ASTM D6432-11 has as scope the standardization for using the surface ground penetrating radar method for subsurface investigation [2].

Ground-penetrating radar (GPR) is a nondestructive inspection tool that uses electromagnetic (EM) fields to image the subsurface [3][4]. The technique is based on emitting EM waves into a solid to assess its condition. Usually a waveform with wide frequency content is designed for this aim. The application of EM waves to inspect the underground brings advantages and difficulties for the user. The electrodynamics of the process can be summarized as follows: when the EM wave encounters a hidden body or a boundary having different electrical characteristics part of its energy is reflected and part of it is refracted. The resulting waves travel with different velocities and possess information on the target characteristics.

Imaging is achieved through data processing of the wave launched at and the wave reflected from the structure under test. The main issue in using GPR is to relate the received EM field to its true spatial location. If the physical process is well interpreted, GPR can be used to detect subsurface objects, changes in material properties, voids and cracks.

GPR has many applications in different types of materials. Recent studies can be outlined as: archeology, desert soil inspection, lossy dielectrics, boundary layer detection, airborne GPR,

  ISSN 2179-1074

diffraction tomography, excavation, landmine detection, forensic surveys, real time inspection of pavements from moving vehicles, high-conductivity surfaces, directional borehole, layered vegetation, wood and forest litter, the applications are endless. As an example, Fig. 1 describes a GPR assessment of concrete conditions where the goal is to locate reinforcement bars. Manufacturers have been developing new systems for a variety of applications. Benchmarking of commercial GPR systems is discussed in [5] and [6]. It includes information on GPR manufacturers and their products, field tests and data analysis.

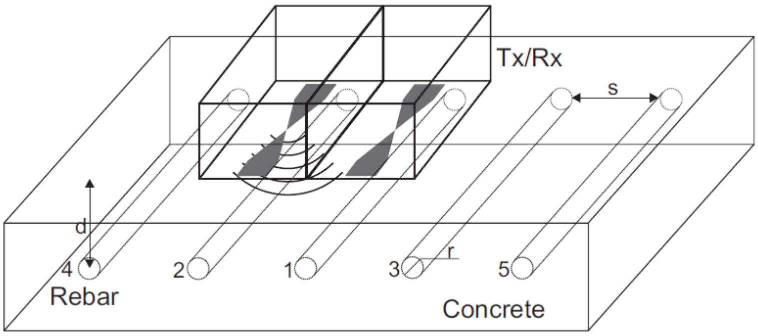

Fig.1. GPR assessment of concrete condition.

The unique advantages offered by GPR are related to the overall performance achieved by electromagnetics at radio and microwaves frequencies. With reasonable power requirements, they combine a reasonably large penetrating range (more than optical and infrared sensors but less than acoustic and seismic methods) with sufficient spatial resolution (greater than acoustic and seismic but lower than infrared and optical techniques) and a fair contrast between host and target media. But the ability to detect a broad range of targets also presents drawbacks, because inhomogeneous soils or additional scattering from non-target objects (known as clutters) interact with the scattered field of the actual target, masking the detecting pulse.

The main GPR limitations [3][4] and some recent studies about them are:

i. For some GPR applications the medium behaves approximately linearly. Examples of materials that affect target detection are high-conductivity materials or heterogeneous conditions i.e. in lossy dielectrics [7], layered vegetation [8], desert soils [9], seawater [10], and forest litter [11] the behavior is nonlinear;
ii. Relatively high energy and time consumption can be problematic for wide field surveys [12]-[16];
iii. The lateral survey resolution is based on prior information of targets and the material under test that need to be identified. This information is used to define the spatial sampling of the survey for B or C-scans [17]-[21];
iv. Refocus radargram to the true space location of medium boundaries as observed in [8], [14] and [22]-[24];
v. The frequency range of the antenna is directly related to its size and the depth of penetration

capability according to [8] and [24]-[27].

There are several issues that can be improved in a GPR system to overcome the limitations described. The aim of this paper is to describe the most relevant GPR features for an NDT assessment, and some of the techniques to improve the performance of the principal device in a GPR system: the antenna. The organization of the paper is as follows. Section II provides an overview of the GPR scenario, main characteristics of commercial GPR and applications, and discusses relevant information for the design of any survey. Section III explains the parameters needed for a successful GPR antenna design. Section IV proposes a framework for GPR antenna design and optimization.

II. THE ANTENNA IN THE GPR SYSTEM

As stated before, GPR has limitations concerning complex geometries and electrical properties. To improve the technique several developments are continually being investigated considering different applications. These developments are reflected in published research and in award of patents. A selection of recent patents relevant to GPR is: a method of GPR concrete road construction cushion thickness quick detection [28]; method for detecting irregular aggregate permittivity [29]; systems and methods for detecting soil characteristics [30]; methods for forming 3D image data and associated apparatuses [31]; method of grouting compaction identification of prestressed concrete beams [32].

Different GPR applications and the main GPR limitations cited demand different types of antennas. There are several types of antennas used in GPR. For instance, some applications demand a high depth penetration with low resolution while other applications require opposite characteristics. High resolution applications require antennas with higher bandwidths which in turn results in low penetration depth of inspection.

The tradeoff between resolution and depth of penetration is defined when the antenna central frequency is chosen. On the other hand, target identification usually imposes much more strict requirements on antennas in comparison with a system for merely target detection. It is important to notice that the antenna is a system in itself with its own transfer function that can be frequency-dependent with a non-linear phase response that can be critical for an impulse GPR system. Since the main objective of GPR systems is the generation of an image, phase distortion is a serious problem. On the other hand, in frequency modulated or synthesized GPR, the requirement for linear phase response from the antenna can be relaxed. This allows the use of certain types of antennas with complex frequency response, as their effect can be corrected by system calibration if necessary.

Considering the foregoing, important aspects of GPR antenna design are:

i. The antenna should have a wide frequency bandwidth for better resolution. The maximum depth of investigation decreases when the electromagnetic wave frequency increases. In reality, most sub-surface radar systems operate at frequencies below 5 GHz, as the examples in Tables I and II show;
ii. The antenna should have well-behaved and consistent performance across the antenna's operational band, including the radiation pattern, gain, impedance matching and a requirement for low

dispersion. High gain and narrow beamwidth are fundamental to resolve close proximity targets.

Most applications require the antenna to be small in size and low in weight. For energy consumption purposes, the antenna length is related to its central frequency [33]. Compact and rugged physical characteristics are especially important for mounting the system in confined spaces.

Those antenna characteristics are highly related to the GPR system specification. In order to illustrate the variety of possibilities, Tables I and II show some applications and types of GPR systems considering the waveform and the coupling to the structure under test.

TABLE I. APPLICATIONS USING TIME-DOMAIN WAVEFORM

Ref.	**Application Media**	**Antenna Type**	**Coupling (Air/Ground)**	**Bandwidth [GHz]**	**Ringing concerns**
[11]	forest litter	horn	A	0.8 to 5.2	no
[13]	pavement inspection	half-elipse	A	0.25 to 0.75	yes
[14]	landmine detection	bowtie	A	1.5	yes
[24]	forensic survey	horn	A	0.27 to 0.9 MHz	no
[34]	boundary layer detection	loaded dipole	G	0.25 to 0.75	yes
[35]	metallic target behind concrete wall	horn and vivaldi	A	1.5 to 4.5	no

TABLE II. APPLICATIONS USING FREQUENCY-DOMAIN WAVEFORMS

Ref.	**Application Media**	**Antenna Type**	**Coupling (Air/Ground)**	**Bandwidth [GHz]**
[15]	pavement inspection	aperture array	A	0.2 to 3
[16]	generic	mimo array	A	0.3 to 4
[23]	generic	horn	A	0.8 to 4
[27]	dispersive media	vivaldi	A	0.8 to 3
[36]	generic	bowtie	G	0.2 to 0.6
[37]	soil hydraulic	spiral, vivaldi and bowtie	A	0.8 to 5.2
[38]	layered media	horn	A	0.8 to 2
[39]	soil permittivity	loaded dipole	G	0.5 to 4.5

Table I presents recent works for different GPR applications for time-domain systems. Time-domain systems are basically characterized by sending a pulse or impulsive waveform to the structure under test. This type of waveform has a short period of time and a large bandwidth. As can be seen in Table I, it is possible to use various types of antenna with this waveform. However, some types of antennas present some drawbacks when considering time-domain waveforms or the coupling to the structure under test. Planar bowtie and dipole antennas can cause late-time ringing when used for transmitting a short time pulse. Late-time ringing can blur target information in a GPR assessment. In addition, these antennas can exhibit coupling problems when used on irregular surfaces. For those applications, horn antennas are more appropriate since they can be located at some height from the structure under test.

Most of the commercial GPR systems use time-domain waveforms. However, there are developments and ongoing research into frequency-domain options. The later have some advantages over time-domain systems since they require less energy and provide more information about the target characteristics. Table II shows some recent works for several applications that use frequency-domain waveforms in the

GPR system. According to Table II frequency-domain GPR systems can be used for a variety of applications. Some applications may require better images. One important characteristic of images is the phase-dependent feature. To improve GPR images antenna arrays can be used to minimize phase problems. In addition, air or ground-coupled options can be used for different depth or resolution specifications.

When it comes to commercial options, time-domain systems are prevalent as shown the Table III. This is due to the fact that frequency-domain systems are relatively new compared to the time-domain option. However, since the electronics of frequency-domain systems are less expensive than the time-domain option there is a growing offering of this system in the market.

TABLE III. SOME COMMERCIAL GPR SYSTEMS.

Manufacturer	Waveform	Antenna Type	Coupling (A/G)
Ditch Witch	Impulse	dipole	G
Easyrad	Impulse	dipole	A, G
Geoscanners	Impulse	bowtie, airbone and borehole	A, G
Logis-Geotech	Impulse	horn	A, G
GSSI	Impulse	horn and shielded array	A, G
IDS GeoRadar	Impulse	horn and shielded array	A, G
Mala Geoscience	Impulse	Dipole	G
TerraPlus	Impulse, CW	bowtie and borehole	G

Advantages and disadvantages of the different waveforms for GPR are also dependent on operational requirements of the final system, including weight and size, power consumption, complexity and off the shelf availability of the hardware, and therefore its cost. Spectral regulations can also play a role in choosing the operational frequency and bandwidth, with effects on the achievable resolution and depth of penetration, as well as on the design of the antennas.

Another important feature is the coupling compromise: the antenna input impedance is directly affected by the distance between the antenna and the structure under test. Ground-coupled GPR can couple more energy into the ground and extract more energy out of it, which results in clearer data and greater depth of investigation. In addition, surface coupling and antenna ringing represent problems, which complicate the collection of information without proper signal processing. The next section discusses some important GPR system parameters.

III. GPR SYSTEM DESIGN PARAMETERS

GPR systems manufacturers offer several configurations according to their system components. The system configuration directly affects the performance of the NDT assessment. In numerous applications, prior information about the structure under test and the target characteristics are known. Considering this, the system specification plays a major role in the success of the assessment. In order to understand the need for an enhanced antenna some important GPR parameters are discussed next.

A. Waveform

Most of the GPR equipment is based on two categories: time or frequency-domain options. Fig. 2 shows the most relevant options considering these categories. GPR systems that shape a time-limited waveform considering changes in its amplitude are known as impulse GPR. Continuous wave (CW) GPR are based on band-limited signals. This type of GPR transmits a signal of infinite duration, as a continuous sine wave, and receives it simultaneously. In this configuration, it is possible to detect buried targets but it not possible to resolve range since the signals do not change. To improve detection the signal bandwidth should be widened. This can be done by using some sort of modulation.

For instance, in amplitude modulation the continuous wave can be modified with amplitudes 1 and 0 at different times during the inspection. This is called pulsed GPR. Since the transmission and reception times are well defined it is possible to associate then with the target range. However, when dealing with GPR and its applications it is desirable to have control of the power spectral density and in turn the resolution of the assessment.

Another approach to do this is adding more frequencies by increasing or decreasing the oscillation in the waveform. This configuration is called frequency-modulated continuous wave (FMCW) [40]. Instead of using transmitted and received times of pulses FMCW uses the difference in frequency. This type of GPR system suffers from interference issues.

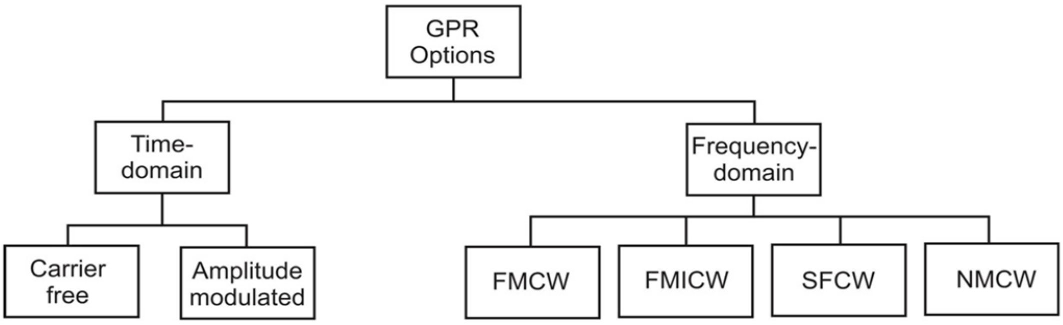

Fig. 2. GPR systems options.

A different method can be employed to both CW or pulsed GPR where the transmitted frequency of tones or pulses shifts in a given interval or steps across a defined bandwidth. In this way, the signal spectrum is finite and not continuous. This technique is called stepped frequency continuous wave (SFCW)[41]. The frequency step avoids phase ambiguity by measuring the phase difference between returned signals at each frequency. In addition, the hardware associated with SFCW is simpler than that employed in FMCW. A variation of the SFCW technique involves gating the timing of the transmitter and receiver circuits.

A comparison between impulse and CW GPR can be found in [42]-[44]. The impulsive system is still prevalent over the CW option. However, the development of digital signal-processing technology, resulting in cheaper, faster and more accurate equipment, as well the development of inverse algorithms for GPR [36]-[38] and [45] is making the former a popular choice.

As mentioned above, advantages and disadvantages of different waveforms for GPR are also dependent on operational requirements. One of the challenges when using impulse waveforms is that of producing a pulse short enough to achieve the desired bandwidth, i.e. with suitable fast rise and fall times. The antenna should be designed to avoid ringing effects or distortion of the pulse shape. Another challenge arises if the received pulses are sampled in real time in the analogue-to-digital converter (ADC), since the ADC must operate at high enough frequencies to digitize correctly the waveforms. A common problem for active radar systems for CW is the strong backscattered signal from the air-ground interface. This undesired signal can overshadow the reflections from actual targets, especially those with low radar cross section such as human beings, and limit the dynamic range of the receiver, which could be saturated and blocked. Although techniques have been developed to address this problem including the frequency modulated interrupted continuous wave (FMICW) or the noise modulated continuous wave (NMCW) waveforms, which can be used as an alternative technique or combined with the existing ones. FMICW signals have additional effects over normal FMCW, namely range-dependent received power according to the mean received signal of the gating sequence, presence of "blind ranges", risk of aliasing, and overall reduction of the received power [43].

B. System Bandwidth

Bandwidth describes the range of frequencies over which the antenna can maintain desirable parameters with minimal deviation. Regarding GPR systems, the bandwidth is one of the determining parameters used to decide upon an antenna type. For instance, some antenna types have very narrow bandwidths and cannot be used to transmit pulses with large frequency content. Bandwidth is typically quoted in terms of the input impedance. This is due to the reflected waves that are generated with the change in the antenna impedance which in turn augments the voltage standing wave ratio (VSWR). VSWR is directly related to the S_{11} parameter [33].

C. Antenna Position

GPR systems can also be classified by type of coupling to the structure under test as air-launched or ground-coupled. The antennas can be in contact with the medium in what is referred to as ground-coupled GPR, or they can be above it in air-coupled GPR. The efficiency of a GPR antenna can be substantially reduced when it operates close to a dispersive medium because of the demand for more power. The specification of how close the antenna can operate from the structure under test is another important issue. The antenna input impedance is directly affected by the distance between the antenna and the structure under test.

Ground-coupled GPR results in clearer data and greater depth of investigation. However, it needs proper signal processing due to the coupling to the surface and antenna ringing problems. Air-coupled GPR on the other hand produces more difficult data to work with, but since the antennas are not in contact with the ground, data can be collected at a much higher speed without damaging the antennas. Planar PCB antennas are mainly used in ground-coupled GPRs for their nondispersive characteristics.

Brazilian Microwave and Optoelectronics Society-SBMO received 07 May 2018; for review 23 May 2018; accepted 24 Aug 2018
Brazilian Society of Electromagnetism-SBMag

ISSN 2179-1074

For air-coupled applications, horn antenna has an advantage over other types because of its narrow beamwidth, which facilitates a higher gain over a wider frequency range. A comparison between air-launched and ground-coupled systems can be found in [46] and [47].

D. Antenna Polarization

Polarization mismatch occurs when the radiated field is distorted when propagating in the medium under test. This distortion depends on electric characteristics of the medium such as heterogeneity and anisotropy [33]. Some commercial GPR systems use linear polarized antennas. Because of this the survey is susceptible to the target orientation relative to antennas. If the target has a transverse orientation relative to the antenna, it may not be detected. To improve the assessment cross-polarized antennas have been used in order to solve orientation issues. In this configuration the transmitting antenna radiates two patterns that are orthogonal to each other. By using cross-polarized antennas it is possible to detect simultaneously the target reflection in two orthogonal polarizations.

E. Ringing Effect Distortion for Impulsive Systems

Different types of antennas are in use for GPR systems. The resistively loaded dipole is simple, easy to design and possess linear polarization. However, it has a major disadvantage of poor gain. This makes other planar antennas, such as bow-tie and frequency-independent structures, a more attractive choice. These two are mainly used in impulse GPR applications because of their non-dispersive characteristics and their relatively high gain. Nevertheless, both suffer from significant impedance mismatch at the feed point when used for air coupled GPR applications [46][47]. In addition, there is the ringing effect distorting in the time-domain waveform [33]. Resistive loading is usually used to overcome this drawback but this technique leads to deteriorating gain performance over the frequency band [34]. Horn antennas have narrow beamwidth that naturally guarantee a higher directivity gain over a wider frequency range. The main design challenge of horn antennas is to achieve an impedance match in order to minimize feed point and aperture reflections. All of these antennas have potential to be used in GPR systems.

F. Pulse Fidelity

Pulse length is not the only signal trait that must be maintained by the antenna, and cannot be used as the sole metric for determining antenna performance. Pulse shape can also have an effect upon radar performance. Therefore an additional metric must be used to evaluate radar antennas, known as pulse fidelity F [48]. Mathematically, pulse fidelity F is the maximum cross-correlation between the normalized output pulse $a(t)$ and the reference input pulse $r(t)$. The value of F is maximally equal to 1 when the input and output pulses are identical in shape. A parameter τ is used to time sweep $r(t)$ during optimization of F, eliminating the effect of non-zero time delay between waveforms. Pulse fidelity is relevant for impulse GPR systems.

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G. Group Delay

Any single-frequency signal passing through a radiating antenna will experience a time delay as a function of frequency called group delay. Group delay is the negative derivative of phase with respect to frequency, typically obtained from the crosstalk between the transmitting and receiving antennas (S_{12} parameter) in an appropriated test setup environment [49]. A constant group delay versus frequency leads to a constant propagation time delay and an undistorted output signal. The radar software evaluates the time delay of the return pulse, corrects for the known antenna group delay, and determines a single value of distance, the antenna to target round-trip distance. A variable group delay versus frequency causes a frequency dependent variation in time delay. Consider an ultra-wideband frequency range from f_1 to f_2. Evaluating at f_1 and f_2 returns the distances d_1 and d_2. Larger group delay variations between f_1 and f_2 lead to larger apparent discrepancy when determining the range to target, between d_1 and d_2. Therefore, radar distance resolution is directly influenced by antenna group delay performance. The relationship between group delay and radar resolution can also be seen by analyzing the effect of a variable group delay on radiated pulse length. Impulse trains are produced at the receiving antenna when a radiated pulse reflects off of closely spaced objects. Non-dispersed pulses are easily resolved as their amplitude decreases to zero before the subsequent pulses arrive. However, dispersed pulses can be wider than the time differences between returns, causing adjacent pulse overlap. This overlap prevents the radar software from distinguishing between returns from closely spaced objects, decreasing system spatial resolution.

As well as the ringing effect distortion or pulse fidelity, the group delay obtained from the S_{21} parameter focus on the pulse-preserving capabilities of the received signal. This leads to some restrictions regarding the antenna design. Any antenna used in a GPR system must be designed to minimize group delay variations over the radiating bandwidth. However, for successful evaluation of the S_{21} parameter, the environment in which GPR devices are expected to operate needed to be proper modeled. This can be quite challenging for multipurpose GPR systems. An alternative approach is to obtain the group delay from the normalized far-zone electric field for a single antenna [50]. Using the information from the far-field group delay and antenna gain it is possible to analyze the pulse-preserving capabilities of the antenna without considering the GPR environment.

H. Antenna Types

Based on what has been presented, the properties of the GPR system and the application requirements will dictate which antenna features need to be adjusted for better performance. Technical and methodological aspects concerning the design of antennas for GPR applications are discussed in [51]-[53]. These studies compare bow-tie antennas, Vivaldi antennas, horn antennas, loaded dipole antennas, spiral antennas and tapered slot antennas based on antenna features. For example: if the antenna designed is intended for a GPR system mounted on the front of a vehicle the system uses a linear array oriented to aim at the ground in front of the vehicle. The primary application of this radar is ground-

Brazilian Microwave and Optoelectronics Society-SBMO received 07 May 2018; for review 23 May 2018; accepted 24 Aug 2018
Brazilian Society of Electromagnetism-SBMag *ISSN 2179-1074*

penetration imaging to detect buried objects. From an antenna design perspective, these devices can be almost any shape and size. In order to ensure strong radar returns from potentially narrow objects with unknown orientations antenna polarization must be considered. For instance, an x-oriented linearly polarized antenna could miss objects with small x-directional cross-sections relative to the wavelength.

The current optimum UWB antenna choice for impulse radar applications is the hexagonal horn with abrupt radiator. This UWB horn design usually operates from 0.27 MHz to above 12 GHz. It has inherently constant group delay versus frequency due to the abrupt radiator design, which causes all frequencies to radiate from the same location on the launcher plate. It also has very low cross-coupling due to the horn structure. However, this antenna design is linearly polarized and has manufacturing issues that limit its potential in portable radar applications. Each horn must be soldered and manually tuned due to the complicated geometry of the launcher plate inset within the horn wall. This raises costs while reducing repeatability and consistency between antennas. An alternative for the horn antenna to limit size and cost is required. It must also be circularly polarized. In the short list of antenna types that are simultaneously UWB, circularly polarized, and machine-fabricable in a micro-strip environment, spiral antennas are a particularly valuable choice due to their frequency-independent (FI) properties. According to [54], there is a class of antennas whose pattern and impedance are practically independent of frequency for all frequencies above a minimum cutoff value. The key significance of frequency independence on spiral antennas is that a change in frequency only rotates the active region, the radiating area, along the spiral arms. As long as the arm length is sufficient, any frequency can effectively radiate. Therefore the scaling factor determines the spiral arm length and consequently the antenna's lower cutoff frequency, allowing for FI antennas to be scaled in size according to the desired frequency response. By choosing a scaling factor large enough to achieve desired electrical performance but small enough to improve upon the hexagonal horn size, it should be possible to create a design that rivals or exceeds the performance of existing designs at a lower cost. The primary issue preventing frequency independent antennas from use in GPR systems is pulse dispersion. Because the active region moves as a function of frequency, FI antennas radiate dispersed signals [55].

I. Regulation and Standards

In order to design a GPR antenna, it is important to comply with regulation and standards. IEEE Standard Definitions of Terms for Antennas [56] establishes definitions for antennas and for systems that incorporate an antenna as a component of the system. The antenna requirements for GPR systems is defined by USA Code of Federal Regulations: technical requirements for ground penetrating radars and wall imaging systems [57]; and technical requirements applicable to all ultra-wide band (UWB) devices [58]. Among other specifications, FCC restricts the GPR operation to frequencies below 10.6 GHz. Other restrictions concern electromagnetic compatibility: particular attentions to the effective (or equivalent) isotropic radiated power (EIRP) limits per bandwidth, for example for 960 MHz to 1610 MHz is -65.3 dBm and for 3.1 GHz to 10.6 GHz is -41.3dBm [2][57].

Brazilian Microwave and Optoelectronics Society-SBMO received 07 May 2018; for review 23 May 2018; accepted 24 Aug 2018
Brazilian Society of Electromagnetism-SBMag

ISSN 2179-1074

The concepts and discussions presented in sections I – the GPR application, II – the antenna in the GPR system and III – GPR system design parameters make possible discuss a framework for GPR antenna design and optimization.

IV. Framework for GPR Antenna Design and Optimization

To improve the GPR system response, a given antenna topology can be reshaped or modified using a general optimization framework as depicted in Fig 3. The electromagnetic model, the reference antenna topology or the optimization tool can be chosen according to the GPR system requirements as follows.

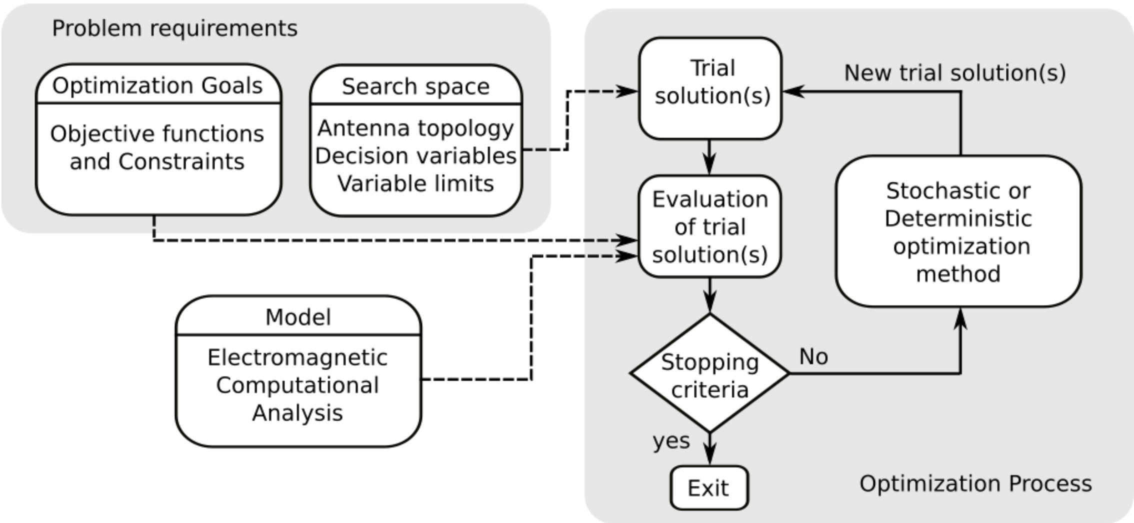

Fig. 3. Generalized antenna optimization process. Adapted from Fig. 1 in [59].

A. *Electromagnetic Model*

Real world problems impose a complex task in the modeling of the GPR assessment. Several issues contribute to this. The most important are: the inhomogeneous material electric properties (dispersive lossy dielectrics, non-linear or anisotropic materials); complex geometry (irregular surface and subsurface, complex antennas and buried targets in several cases must be represented in 3D); and time-dependent analysis. In this context, numerical modeling is required in order to solve Maxwell's equations in complex and realistic GPR application.

For the electromagnetic computational analysis of the antennas and the entire GPR surveys, most publications use the finite-difference time-domain method (FDTD) [60][61]. FDTD can cover a wide frequency range and treat nonlinear material properties, which make it suitable for GPR applications. The use of libraries is also becoming commonplace by its easy. EM fields simulation has several examples of open-source tools. For instance, there is the GPRmax community. GPRmax is an open-source software that simulates GPR applications using FDTD numerical method written in Python [62]. Other example is the MIT Electromagnetic Equation Propagation (MEEP), a free FDTD simulation software package to model electromagnetic systems [63].

State-of-the art of commercial software point to multiphysics couplings, such as EM heating, temperature dependent material properties, EM field dependent material properties and strain and stress dependent material properties and deformed geometry. Examples of commercial software are ANSYS HFSS [64], Altair FEKO [65], CST Microwave Studio [66] and GSSI RADAN [67]. We did a survey with more than 80 commercial software that have been used to GPR applications. The most representative commercial methods are FDTD (~35%).

B. GPR Antenna Optimization Goals

If the goal is to design an optimized antenna, the features for the use of this device must be addressed. The system properties also should be considered. These properties impose restrictions on antenna type and design. Table IV summarize some recent approaches in the design of GPR antennas. It is highlighted here the objectives chosen, the adjusted parameters and the optimization methods used. The majority of studies look for an antenna geometry that meets certain performance specifications, not the entire GPR application.

Considering all aspects explored in section I, II and III as well as the works studied in Table IV, this work admits that the GPR antenna design is based on three aspects:

- Low cost: the antenna should be built in a micro-strip structure;
- Low profile: the antenna should be planar with the smallest volume possible;
- High electromagnetic performance: steady and proper gain, directivity, half power beam width (HPBW), impedance matching, VSWR (S_{11}), group delay and pulse fidelity.

The group delay variation provides insight into the quantity of pulse dispersion, and the pulse fidelity quantifies the differences between input and output pulse shape (specific for impulse GPR systems). Therefore, an antenna's ability to effectively radiate a short pulse is fully characterized through return loss, group delay and pulse fidelity testing.

C. Optimization Process

Electromagnetic optimization problems are often computationally expensive, nonlinear and composed by conflicting goals [60][61]. The GPR antenna design involves simultaneous optimization of multiple objectives that often are competing. As consequence, there may not exist one solution that is the best with respect to all objectives. Usually, in a multiobjective optimization problem (MOP) the aim is to determine the tradeoff surface, which is a set of non dominated solution points, known as Pareto-optimal (PO) [79][80].

There are several methodologies to perform MOP, each of them having their own advantages and disadvantages. Analyzing the methods presented in Table IV it may be note that, with exception of [73], all the papers are based on parametric optimization. In parametric optimization, the antenna topology is chosen a priori, and a set of variables are chosen to control the geometry of the antenna. It

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has the advantage of preserving the main characteristics of the chosen antenna, for instance, optimization based on Vivaldi or horn antennas will keep the high gain characteristics of these antennas. Additionally, previous knowledge about the behavior of the antenna can be very useful to define an initial guess and the most important parameters. This can reduce the search space during the optimization process.

TABLE IV. GPR ANTENNA OPTIMIZATION OBJECTIVES AND METHODS

Ref.	Antenna Type	Goals and Methods
[26]	dipole	To fit into the mass and volume allocation, wire antennas made of identical loaded dipoles have been selected; the resistive profile along the monopoles needs to be chosen to ensure proper behavior of the antenna once they are deployed on the surface. No optimization method has been cited.
[68]	bowtie	Antenna geometry optimization using a multiobjective genetic algorithm (Non dominated Sorting Genetic Algorithm II), looking for (i) S_{11} below 10dBi; (ii) maximum gain; and (iii) the width of the band where the gain is between its maximum value and 3dB below it.
[69]	eye-shaped slot	Antenna geometry is fine-tuned for maximum gain and minimum ringing using exhaustive parametric analyses.
[70]	horn	Structure anatomy for impedance matching throughout an ultrawide band. The design starts with an analytic model that is optimized using exhaustive parametric analyses.
[71]	bowtie	The sharp corners are rounded to minimize the end-fire reflections. The design starts with a triangular bowtie antenna. The design is improved with rounding corners and resistive loading introduced using inbuilt optimization tool available in the CST Microwave Studio.
[72]	fractal horn	The geometry of the patch antenna is changed in order to satisfy the condition of S_{11} below -10dB. An Ordinary Kriging predictor is used as a surrogate model of the cost function while the Differential Evolution algorithm is used to effectively minimize it.
[73]	fractal bowtie	To reduce the center operating frequency of the miniaturized antenna, a design strategy is given to determine a reasonable distribution of conductive material within a given domain. A gradient-based topology optimization method has been used.
[74]	spiral	The geometry of this antenna combined equiangular spiral and Archimedean spiral smoothly looking for a better VSWR performance, axial ratio and gain. The optimization method was not specified.
[75]	horn and spiral	Optimization of antennas group delay, axial ratio, and pulse fidelity.
[76]	Vivaldi	The antenna dimensions are changed using exhaustive parametric analyses in order to optimize: the bandwidth, radiation efficiency (S-parameters) and the gain.
[77]	horn	Reflections and ringing effects are reduced by antenna geometry adjust.
[78]	wired bowtie	VSWR and bandwidth optimization by tapering the arms and applying Genetic Algorithm to choose the parameters for tapered configuration.

An alternative to parametric optimization is the topology optimization [81][82]. As presented in [83], topology optimization is a flexible and powerful structure-designing method. It enables the exploitation of large-scale degrees of freedom (DoFs). As consequence, better performance structures can usually be expected by topology optimization methods than by the parameterized models with fixed topology and a small number of DoFs. However, the large-scale DoFs, allied to the computationally expensive nature of the antenna optimization problem, poses some convergence issues on the optimization processes. Some good approaches to overcome these problems are presented in [83]. Another possibility is to use hybrid approaches as presented in [73] where a topology strategy is used to determine the distribution of conductive material within the antenna while keeping some bowtie-like structure.

Typically, topology optimization results in high performance nonconventional antennas that fulfill the goals assigned in the optimization process. However, in most of time, the irradiation mechanism of the optimized antenna is now well known and sensitivity analysis and robustness test must be introduced in the optimization process to minimize the influence of the manufacturing uncertainties.

Regarding the optimization methods presented in the references on Table IV, they can be classified as: exhaustive search [69][70][76][77], deterministic methods [73], and stochastic methods [68][72][78].

Exhaustive search works well when accumulated experience in design usually implies good starting points and each parameter can be set independently, However, brute force methods quickly become inefficient as the number of parameters increase. Although modifying some initial configuration from a well known antenna can improve its performance, it offers no optimality guarantee.

Deterministic algorithms, on the other hand, enjoy theoretical guarantees on convergence to a local optimum under certain problem assumptions [84]. They are usually based on a local analysis of the optimization problem and outperform the other methods when a good start point is available.

Stochastic methods, such as genetic algorithm (GA) [68] and differential evolution (DE) [72], are very popular, as they require little knowledge about the function properties [84] and can find global optimum with very high success. They are useful in situations where continuity and differentiability cannot be assured. Although robust, they are known to be slow, since they require a considerable amount of function evaluations.

Deterministic and stochastic techniques can also be coupled in hybrid configurations, hybrid methods try to combine the global search characteristic of stochastic methods with the fast convergence of the deterministic ones. There are several optimization algorithms, each of them having their own advantages and disadvantages. The best choice depends on the size of the search space, the number and behavior of the objective functions and even the familiarity of the designer with the method chosen, since some methods presents some parameters that can considerably increase the convergence of the method when well-tuned.

V. CONCLUSIONS

The antenna can be considered as a two-port transducer system characterized by a transfer function that can be frequency-dependent and may have a non-linear phase response. The performance of this device is critical for time or frequency-domain GPR systems. The system configuration directly affects the performance of the NDT assessment and requires different characteristics and features from their antennas.

This work outlined some fundamentals of the GPR system theory in order to translate the GPR system configuration into antenna requirements. Although different GPR configurations impose different restrictions on antenna type and design, the procedure to achieve high performance antennas is consistent and can be described as a generalized optimization problem. This context allowed us to discuss a framework for GPR antenna design and optimization.

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  ISSN 2179-1074