The Influence of Spatial Sampling in GPR Surveys for the Detection of Landmines and IEDs

Federico Lombardi and Hugh D. Griffiths
Department of Electronic and Electrical Engineering
University College London
London WC1E 6BT
f.lombardi@ucl.ac.uk, h.griffiths@ucl.ac.uk

Maurizio Lualdi
Department of Civil and Environmental Engineering,
Politecnico of Milan
Milan 20133
maurizio.lualdi@polimi.it

Abstract— **Landmine detection with GPR, is conditioned by a properly focusing of the detected anomaly in the subsurface, and this is theoretically possible only if the data have been acquired fulfilling the spatial Nyquist criterion. An under-sampled data will suffer from missing features, thus will carry a lower informative level. Especially in extreme and adverse environments, this constraint could be a huge issue. In addition, target complexity or soil heterogeneity could introduce the need for 3D acquisitions, thus significantly enhancing the time spent by an operator on the field. The aim of this paper is to provide a comparison between images obtained relaxing the Nyquist criterion, to show that even if it does not hold, the informative content of the final radar image will not be too much corrupted.**

Keywords—Ground Penetrating Radar; spatial sampling; imaging; data acquisition;

I. INTRODUCTION

Compared to 2D images, 3D image reconstructions are much more effective and more easily understood by the end-user, and the transmitted information is greater as spatial correlation is explored simultaneously in both the X and Y directions. Indeed, the interpretation of data from 2D sections is far from straightforward. Instead, the 3D migrated data can clearly indicate the presence and the extension of complex targets. Many applications could take advantage of this 3D technique: subsurface utility mapping [1], landmine detection [2] [3], building diagnostics [4], civil engineer [5], geological [6] [7] and archaeological survey [8].

In principle, the technology for performing 3D GPR acquisitions is readily available, but in practice the specifications and methods employed are often a trade-off between budget and quality [9]. Indeed, 3D acquisitions are very time demanding, and this is mostly because (1) a “true” 3D survey can only be achieved if the spatial sampling limits required by the Nyquist theory are fulfilled in both the in-line and cross-line directions, and (2) the 3D focalization of data that produces effective 3D target reconstructions requires the data to be accurately geo-referred. This becomes dangerously demanding in the humanitarian demining field, where the time spent by an operator on the ground is strictly related to the sampling requirements. Recalling that several minefields are located in harsh environment or highly unfriendly areas, any saves of time would mean bettering the working time of a deminer.

The focus of the paper is to exploit the influence of the spatial sampling on the informative content and if the final migrated image could be employed as effectively. After a brief theoretical overview, two field examples demonstrate that significant results can be obtained even pushing the sampling beyond the limit, thanks to the focusing algorithm applied for correcting geometrical distortion of GPR raw data.

II. SAMPLING REQUIREMENTS FOR SCATTERING TARGETS

The wavefield response of any subsurface geometry can be generated by the superposition of point diffractions. Migration or focusing processing collapses diffraction hyperbolae to their diffraction apexes; therefore the basic imaging requirement for a random subsurface geometry is to properly sample all diffractions.

Strictly theoretically, there is a bound beyond which the acquired data will be corrupted and aliased, making the acquisition useless. This limit is set by the Nyquist criterion [10] which expresses the main requirement that must be fulfilled to collect a dataset that can be successfully transformed into a realistic reconstruction: the surveyed area must contain an adequate measuring point density to prevent spatial aliasing problems. A narrower sampling, highly desirable for obvious reasons, would bring higher SNR and quality but the informative contents of the data would not be increased. On the contrary, an undersample data would bring aliased data, and no processing steps could compensate for this data loss.

In order to reconstruct the buried features as accurately as possible, trace spacing (derived similarly to the seismic zero-offset case, [11]) should be dense enough for the unaliased recording of all diffraction hyperbolae. Aliasing occurs when the sample interval Δx is higher than (1):

$$\Delta x \geq \frac{v}{4 \cdot f \cdot \sin\theta} \tag{1}$$

Where v is the wave velocity, f is the working frequency and θ is the dip angle along a diffraction hyperbola. For angles of 60 degrees and larger, the sine function could be approximated as unity, thus leading to the common adopted sampling parameter:

$$\Delta x \leq \frac{v}{4 \cdot f} = \frac{\lambda}{4} \tag{2}$$

Applying the Nyquist criterion requires the GPR measurements to be spaced by quarter of the wavelength of the highest signal and noise frequency in all directions, because diffraction hyperbola cones have rotational symmetry.

Frequency dependences in geological materials are dominantly caused by dielectric relaxation processes related to the presence of water. Almost every geological material tends to absorb the higher part of the GPR wave frequency because water is much easier to be polarized.

Equation (2) represents the most restrictive requirement, corresponding to the most unfavourable situation when a very near-to-surface target is struck laterally by a surface wave. In such a case, assuming a constant velocity medium and a monostatic system, the diffraction curve that appears in the radar section consists of two symmetric dip lines that leave the surface from the target position (Fig.1). Instead, for deeper targets, the diffraction curves are hyperbolas that asymptotically tend to become straight lines of the surface target.

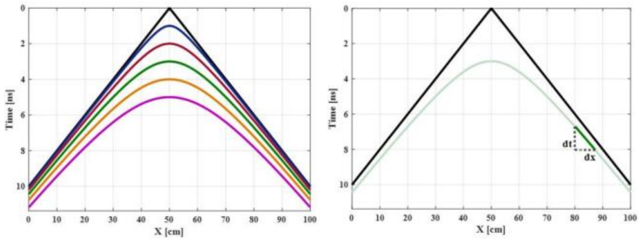

Fig. 1 Diffraction curves expected on a radar profile executed with a monostatic system for scattering targets buried at different depths.

Commonly, the hyperbola contains considerable variation in amplitude along its locus as well as some deviation from the ideal hyperbola shape, mostly due to geological heterogeneity.

The shape of the hyperbola and the slopes of the asymptotes on either side are controlled firstly by the antenna radiation pattern, by the velocity of the wave and, consequently, on the dielectric permittivity between the surrounding soil and the target. Increasing the dielectric constant of the target can cause a change in both the shape and the relative magnitude of the radiation pattern due to changes in the magnitudes and phases of the reflected signals [12] [13].

The Nyquist theory requires that the reflection time-delay between two subsequent measuring points is less than half a wave period. Applying this condition to any generic point in a diffraction hyperbola results in equation (3)

$$\Delta x \leq \frac{1}{4 \cdot f \cdot {}^{dt}\!/\!_{dx}} \tag{3}$$

Needless to say, (3) becomes (2) when the target depth is zero. In real situations the diffraction hyperbolas are of limited aperture because of absorption and antenna directivity. A common rule is to consider the aperture as the interval which contains almost the 80 percent of the hyperbola [11].

Further on, (2) can be relaxed to a less restrictive condition, that of (3), to be applied where the diffraction dip is higher, i.e. at the limit of the diffraction aperture.

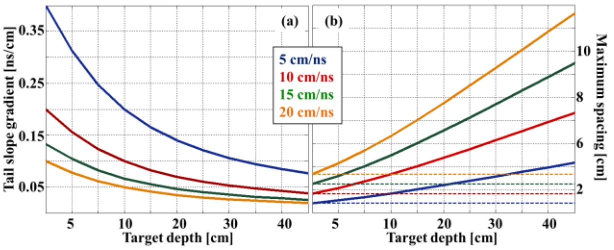

Fig. 2 Effects of target depth on (a) hyperbola tail gradient, and (b) minimum sampling requirement with varying medium velocity. Dashed lines represent the quarter wavelength criterion.

III. APPLICATION TO LANDMINE DETECTION

To validate the spatial sampling requirement experimentally, a set of 2D measurements has been acquired over the landmine test pit at the Joint Research Centre (JRC) in Ispra, Italy [14]. Fig. 3(a) shows the setting of the acquisitions.

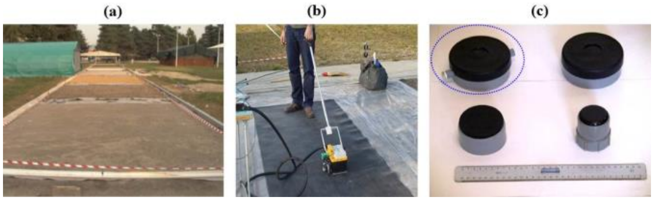

Fig. 3 Pictures of the acquisition equipment and operations at the JRC

Inline sampling of the GPR equipment (Fig. 3(b)) was controlled by an odometric wheel which ensured a highly accurate and precise sampling. Acquisition parameters are listed in Table I.

TABLE I. EXPERIMENTAL CAMPAIGN

Acquisition Parameters and set up	
Central frequency [GHz]	1
Bandwidth [GHz]	0.5 – 1.5
Time window [ns]	15
Time sampling [ns]	0.0913
Spatial sampling [cm]	0.4785

Acquired target, imaged in Fig. 3(c), was a large antipersonnel landmine, with a diameter of 11 cm and a metal content represented by the safety pin, buried in a loamy soil at progressive depth (5 to 20 cm).

Initially the data were collected with very dense spatial sampling, then this was progressively decimated to explore the maximum spacing possible to preserve the quality of the final result. Considering a computed velocity of 15 cm/ns (via synthetic hyperbola matching) and a maximum frequency of 1.5 GHz, the Nyquist requirement sets a sampling limit of 2.5 cm, corresponding to 5 times the acquired inline sampling.

The experimental calculation of the formulation in (3) has been made computing the asymptotic slope at the limits of the hyperbola (Fig. 4).

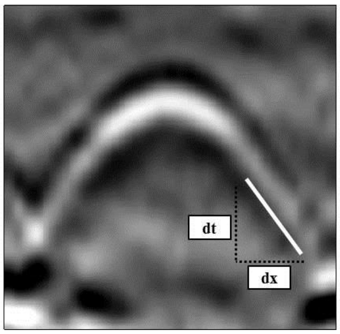

Fig. 4 Gradient calculation for diffraction hyperbola.

Fig. 5 shows the results for the target buried at 5 cm below the surface.

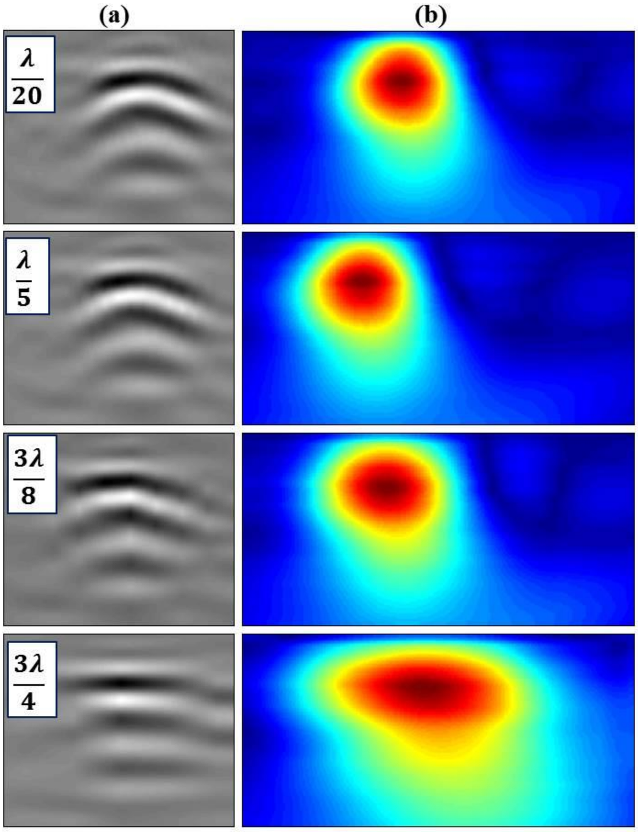

Fig. 5 Landmine buried at 5 cm. (a) Raw data, and (b) processed data.

Considering the diffraction hyperbola (Fig. 4), the requirement become less strict. The minimum distance increases to 3.2 cm, which corresponds to a reducing gain of approximately 30% of the number of needed traces.

This is confirmed experimentally, as target imaging begins to degrade when the ratio between the Nyquist requirement of (2) and the asymptotic formulation of (3) is higher than 1.5. Putting too much effort on oversampling system is not worthy, except for a SNR enhancement in case of trace stacking, as can be inferred by the identity of the first two frames.

Of course, the target is still detectable even when the adopted sampling is sparser than (3), but the focusing operator is not capable of reconstructing the proper target geometry: the shape of the focused target is misleading, as well as the raw data imaged a completely different kind of target. Considering also the shadow effect around the target, a highly undersampled image will also affect the results of the focusing operator. In addition, the performance will be significantly reduced by a less homogeneous soil, as the target hyperbola would be harder to detect and its aperture could not be sufficient larger to apply the asymptotic assumption.

Fig. 6 presents the raw and focused profiles of the same target buried deeper at 15 cm deep.

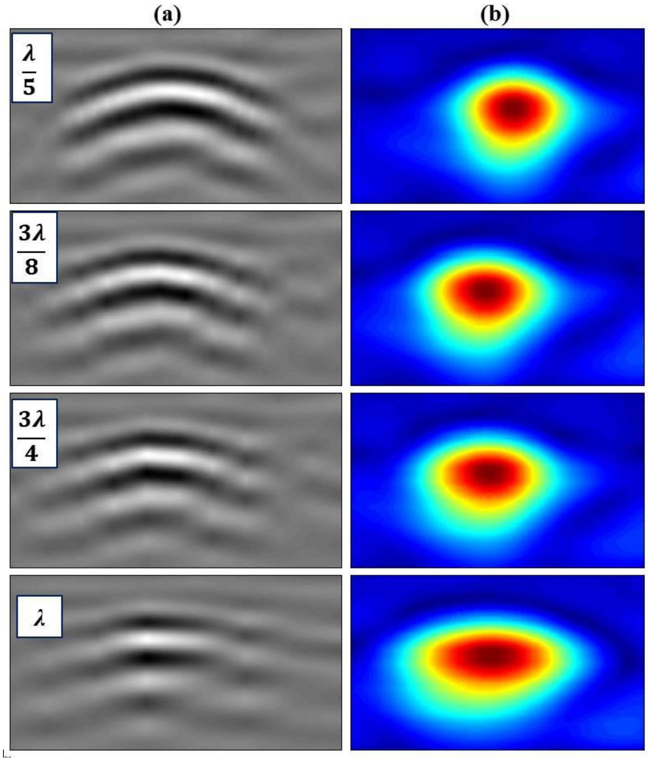

Fig. 6 Landmine buried at 15 cm. (a) Raw data, and (b) processed data

For deeper targets, as inferable from Fig. 3, the minimum trace spacing becomes less strict, as the aperture of the hyperbola becomes wider and thus the gradient will decrease.

In view of a Nyquist requirement (2) of 2.5 cm, the minimum spacing calculated in (3) returns a value of 5 cm, thus halving the needed sampling points. The condition could be clearly verified by a comparison between the last two frames of Fig. 6, in which there is a severe degradation in target reconstruction beyond a reducing factor of 2, while no significant differences are noticeable when the data are sampled adopting a suitable sampling grid.

The same scheme has been applied to targets buried at depth of 10 and 20 cm, whose results are presented in Table II and Fig. 7.

TABLE II. EXPERIMENTAL VALIDATION

Depth [cm]	Spacing from (3) [cm]	Experimental [cm]	Comparison with (2)
5	*3.2*	*3.4*	*1.3*
10	*4*	*3.8*	*1.6*
15	*5*	*4.5*	*2*
20	*6*	*5.8*	*2.4*

As investigated, the degree of relaxation is proportional to the target depth; hence, depending on the expected depth of the target of interest, the reducing factor could reach significant magnitude.

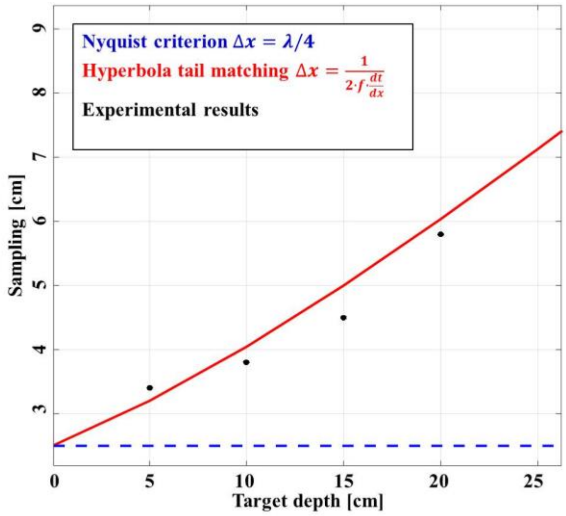

Fig. 7 Experimental validation and comparison.

IV. CONCLUSIONS AND DISCUSSION

GPR imaging is strongly dependent on the obedience to the Nyquist sampling criterion, in both inline and crossline directions. More dense data will not gain any further information on the objects, while going beyond the limit could considerably affect the image resolution and target reconstruction. While commonly defined as a quarter of the maximum wavelength propagating in the subsurface, if one considers the diffraction hyperbola, this could be smoothened up to some degrees, allowing a faster data acquisition. This element is fundamental for applications in which the time is a vital variable, as for landmine clearance. Adding the 3D necessities for resolving geometrically complex targets and avoiding misleading interpretation, relaxing the limit becomes of even higher importance.

The paper, after giving a formal definition of the less restrictive formulation of the limit, provides a quantitative analysis of the saving capabilities and an experimental proof of it. This sampling formulation takes into account the asymptotic behaviour of the hyperbolic signature of buried targets, relaxing the requirements of Nyquist criterion, which assume a surface laying target.

With a field example with targets buried at different depths, highly oversampled in both time and space, results demonstrate that the informative content of an image could be conserved also going beyond the commonly adopted Nyquist limit of a quarter wavelength. The obtained relaxation is not negligible: even for shallower targets as landmines and some IEDs, the reduction factor could reach a magnitude of 6, meaning that 1 profile out of 6 needs to be acquired. This has a meaningful impact on the time spent on the field by the operator, especially when the targets or the soil characteristics require a 3D approach to provide reliable results.

Further works will include the analysis of the needed precision in trace acquisition for ensuring high resolution 3D GPR images fundamental aspect when dealing with uneven soil topography.

REFERENCES

[1] M. Lualdi, and F. Lombardi, “Utilities detection through the sum of orthogonal polarization in 3D georadar surveys”. Near Surf. Geophys., vol. 13, n. 1,pp. 73-81, 2015.

[2] A. Yarovoy, V. Kovalenko, F. Roth, E. Ligthart, A. Fogar, and L. Ligthart.” Landmine Detection and Discrimination Based on GPR Data”, Tenth Int. Conf. on Ground Penetrating Radar, 21-24 June 2004, Delft, The Netherlands, pp 677-680

[3] L. Zanzi, M.Lualdi, H.M. Braun, W. Borisch, ad G. Triltzsch, “An ultra high frequency radar sensor for humanitarian demining tested on different scenarios in 3D imaging mode”, Proc. of GPR, April 29 - May 2, 2002, Santa Barbara, pp. 240-245.

[4] M. Lualdi, and F. Lombardi, “Orthogonal polarization approach for three dimensional georadar surveys. NDT & E Int., vol. 60, pp. 87-99, 2013.

[5] N. Gucunski, C. Rascoe, and A. Maher, “3d-GPR in transportation infrastructure evaluation”, Proc. SAGEEP 2008, 6-10 April 2008, Philadelphia, pp 471-476.

[6] R. Streich, J. Van der Kruk and A.G. Green, “Three-dimensional multicomponent georadar imaging of sedimentary structures”, Near Surf. Geophys., vol 4, no. 1, pp. 39-48, February 2006.

[7] M .Lualdi, and L. Zanzi, “2D and 3D GPR imaging to map the fractures and to evaluate the integrity of limestone ornamental rocks”, Proc. SAGEEP 2003, April 6-10, San Antonio (TX), USA, pp. 613-622.

[8] M. Lualdi, and F. Lombardi, “Effects of antenna orientation on 3-D ground penetrating radar surveys: an archaeological perspective. Geophys. J. Int., ggt421, 2013.

[9] M. Lualdi, “TRUE 3D Acquisition using GPR over small areas: A cost effective solution”, Proc. SAGEEP 2011, 10-11 April 2011, Charleston, pp. 541-550.

[10] H. Nyquist, “Certain topics in telegraph transmission theory.”, Trans. of the Am. Inst. of Electr Eng., 47(2):617–644, 1928.

[11] Ö. Yilmaz, “Seismic data analysis”. Tulsa: Society of expl. geophys, 2001.

[12] N. Osumi, and K. Ueno, “Microwave holographic imaging of underground objects”. IEEE Trans. on Ant. and Prop., vol. 33, n.2, pp. 152-159, 1985.

[13] F.T. Ulaby, “Radar measurement of soil moisture content”. IEEE Trans. on Ant. and Prop., vol. 22, n.2, pp. 257-265, 1974.

[14] P. Verlinde, and A. Lewis, “The joint Multi-sensor Mine-signatures project: an opportunity for testing data fusion algorithms” Proc. of the 6th Int. Conf. of Inf. Fusion, pp. 245-252, 2003.