PACS №: 41.20.Jb

Richard Yelf and Daniel Yelf
Georadar Research Pty Ltd
412 Eastbank Rd, Coramba Coffs Harbour,
NSW 2450, Australia
e-mail: richard.yelf@georadar.com.au
georadar@bigpond.com

Where is True Time Zero?

Contents

1. Introduction 159

2. Waveform Polarity Definition 159

3. Shift of Time Zero Position 159

4. Antenna Lifting Tests 159

5. Zero Time Position Survey 160
- 5.1. First break position . . . 160
- 5.2. First negative peak . . . 161
- 5.3. Zero amplitude point . . . 161
- 5.4. Mid-amplitude point . . . 161
- 5.5. First positive peak . . . 161
- 5.6. First positive peak with antenna lifting test . . . 161
- 5.7. Calibrated time prior to first positive peak . . . 161

6. Georadar Method of Setting Time Zero 162

7. Conclusion 162

Abstract

The accurate setting of the zero time position relative to the ground surface is a parameter which concerns all Ground Penetrating Radar (GPR) operators and it is an essential factor for conducting accurate shallow depth measurements in GPR. But where is the true ground surface on our radargrams?

This paper examines the setting of the true zero time position. It presents the results of a survey defining where GPR users and equipment manufacturers currently set their zero time position.

In field operations it is necessary to place the zero time at a clearly definable and stable location in the early wavelet. This is commonly at either the negative or positive maximum peaks of the first wavelet, or the zero amplitude point between these two peaks. This position needs to be corrected for in subsequent data processing in order to make accurate and reproducible depth or thickness measurements in materials.

In reality the precisely calibrated true ground surface position in time is not where is it commonly thought to be located on the early time wavelet, due to the inherent characteristics of the signal generating electronics, the transmitting and receiving antennae and variations in the electrical properties of the investigated medium in close proximity to the antenna.

An understanding of the near-field characteristics of a bow-tie antenna, coupled with extensive comparisons via empirical observations from numerous coreholes, enables us to predict where the true zero time actually occurs in a pulse GPR system.

1. Introduction

Conducting GPR surveys at an 'audit' level on civil engineering structures requires millimetre resolution in both vertical and horizontal planes [1]. High frequency TEM horn antennae can provide suitable vertical resolution [2], but not the horizontal definition required to diagnose the structure and dimensions of items such as steel beams, rebars, ducts and void formers. Consequently, the antenna of choice for most GPR consultants is a miniature bow-tie dipole, placed close to the measurement surface.

To perform accurate time domain measurements with GPR systems, there are numerous factors which need to be considered and addressed, including: system performance, bandwidth, jitter, internal and external noise, time base stability, antennae frequency, setting the zero time position and velocity calibration.

This paper addresses the setting of the Time Zero (T_0) position for impulse radar systems using surface-coupled antennae. The true time zero position of the radar wave radiated from a ground-coupled GPR antenna is not necessarily a fixed value. It depends on the individual antenna, the height of the antenna above the surface and electrical properties of the medium beneath the antenna.

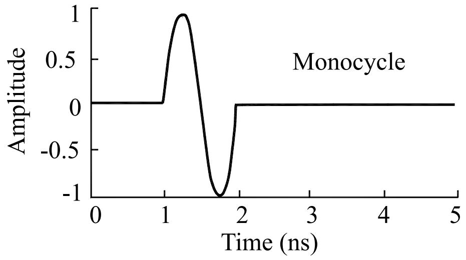
2. Waveform Polarity Definition

In pulse GPR systems, the avalanche transistor effect is used to generate a short duration impulse similar to a monocycle (Fig. 1a). When radiated from a bow-tie dipole antenna into air, this results in a Ricker type wavelet (Fig. 1b), with some inherent ringing decay. For this discussion, we define the negative and positive peaks of the waveform as shown in Fig. 1b.

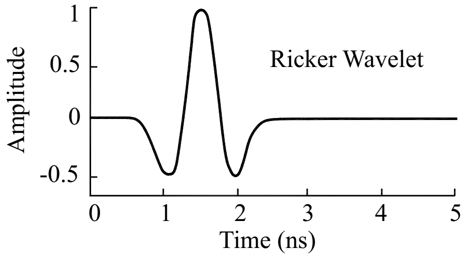
The radiated waveform from a bow-tie dipole antenna with a nominal centre frequency of 1.5 GHz is shown in Fig. 2, with the direct wave on the left and the received wavelet reflected through air from a steel sheet shown on the right. The received signal is a complex combination of non-sinusoidal wavelets [3,4], with multiple reflections from feed points and dipole ends [5], and displaying multi-lobed frequency spectra characteristics.

3. Shift of Time Zero Position

When a 1.5 GHz bow-tie antenna is placed on or near 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 [5]. Also the nominal centre frequency of a 1.5 GHz antenna in air is reduced to 0.75–1.2 GHz on the ground surface. The arrival time of a reflected wave from a buried target, or the backside of concrete layer, will similarly shift to a later time when the antenna is coupled to the medium. This phenomena has been termed "radiation delay" [Roberts, it pers. com.]. It is especially noticeable in materials with high moisture contents, for example in new ("green") concrete and hence is a critical factor for accurate measurements on pre-cast concrete structures in the process of curing from the mould.



(a) Monocycle impulse.



(b) Ricker waveform.

Fig. 1.

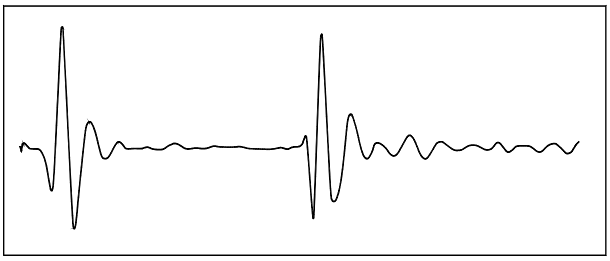


Fig. 2. A-Scan recorded with a 1.5 GHz bow-tie dipole antenna in air over a metal reflector. TWT (Two Way Travel) range 15 ns.

Fig. 3 shows the received waveform recorded for a 1.5 GHz antenna when placed on a fully cured dry concrete surface on the soffit (underside) of a bridge deck. The first reflection is from the lower flange of a steel I-beam, the second labelled reflection is from the upper flange. Note the significant changes in shape and time position of the direct wave compared with Fig. 2, recorded with the same antenna.

4. Antenna Lifting Tests

A standard method of calibrating time range for GPR systems is to measure the two-way travel time

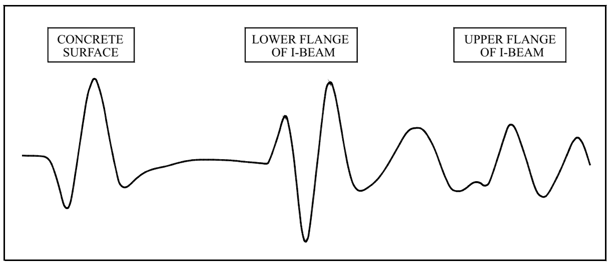


Fig. 3. Received waveform recorded with a 1.5 GHz antenna placed on concrete surface. TWT range 8.8 ns.

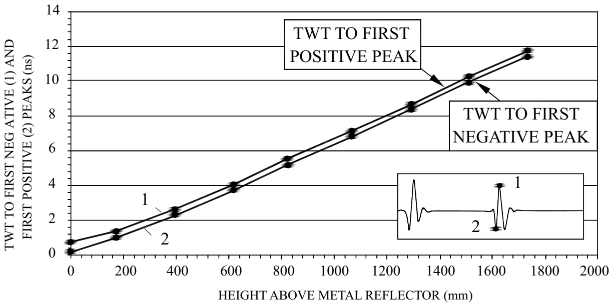


Fig. 4. Calibration of time range by raising 1.5 GHz antenna in fixed 220 mm stages above a metal sheet.

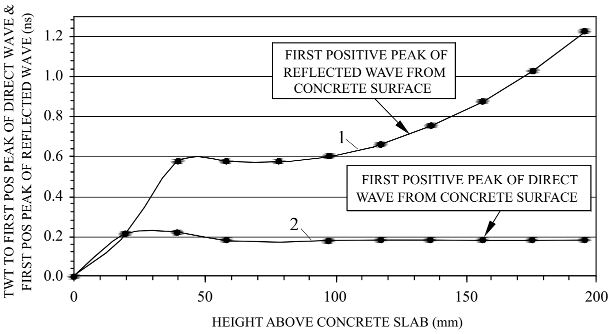


Fig. 5. Shift in positive peak position when raising a 1.5 GHz antenna in fixed stages of 20 mm above the surface of a concrete slab.

(TWT) of a short duration impulse reflected from a metal sheet placed on the floor while the antenna is raised above it in progressive steps. For lower frequency antenna, this test is normally performed horizontally, using a large steel reflector (such as a garage door), or in transmission mode between separate Tx and Rx antennae for calibration prior to tomographic surveys.

Fig. 4 shows the results of an antenna lifting test, performed with a 1.5 GHz antenna raised vertically above a metal sheet. The projection of the linear section of the resultant height v. time graph (from the mid — far field region) is used by some GPR users to predict the apparent T_0 position. However, inspection of the origin section of this graph shows a distortion in the early time ($<$ 1.5 ns) position.

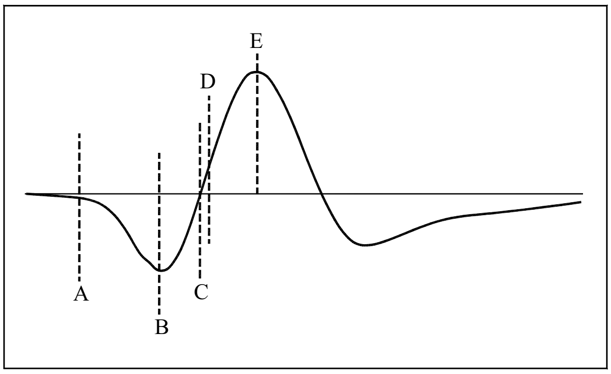


Fig. 6. Locations A–E of zero time positions on early wavelet proposed by GPR users in a recent survey conducted by Georadar Research.

Fig. 5 shows the measured shift of the positive peaks of the direct wave and reflected wave as a bow-tie antenna is lifted in small steps from a concrete surface up a maximum height of 230 mm. In the first 1.0 ns there is a pronounced shift in arrival time of the reflected ray (line 1). Placing T_0 at the time axis intercept predicted by a liner extrapolation of arrival times recorded in the far field (as per Fig. 4) will produce an error of c.0.2 ns for this antenna (line 2).

5. Zero Time Position Survey

A survey conducted by Georadar Research asked GPR manufacturers and a sample population of GPR users (ranging from relative novices to experienced consultants) where they set T_0 on their data. The survey results revealed considerable diversity in the approaches to this problem, with almost as many methods postulated as there were respondents to our survey.

Essentially, the various methods and positions proposed for setting T_0 can be divided into 5 categories, labelled A to E on Fig. 6. These are described here in progressively increasing time, with two additional sub-variations of these categories designated as F and G:

5.1. First break position

This location was suggested by GPR practitioners with a traditional seismic background. In the field, this location is difficult to pick for high frequency ground-coupled antennae and also may be unstable in time, due to variations in the electrical properties of the ground in the near-field of the antenna. Algorithms using this position for setting T_0 appear to work well for mid frequency antennae providing the surface is not too conductive, and are used effectively e.g. for time slicing in archaeological 3D processing programs where the preservation of soil surface layer characteristics are important.

5.2. First negative peak

This position is easy to identify in the field for manual setting of T_0. It is marginally more stable with slight variations in height than the first positive peak (see method E). It is used either as the assumed (uncalibrated) value for manual setting of T_0; or as a reference point in combination with empirical coring methods to set zero time slightly in advance or arrears of this first negative peak. No commercial algorithms were reported using this position.

5.3. Zero amplitude point

The zero amplitude point between the first negative and first positive peaks is reportedly used by the automatic T_0 setting algorithms in the GPR systems of several manufacturers. Statistically, most GPR users tended to favour a position near this point, although this may be dominantly influenced by manufacturer's algorithms. This position is easy to compute, appears to be reproducible and relatively stable across diverse surfaces. It is useful for picking two-way travel-times and hence depths to buried targets. In our experience the method is suitable for low and mid frequency antennae (e.g. 25–500 MHz), but less applicable for high frequency antennae (1–2 GHz) used in shallow engineering applications, due to the movement of the negative peak relative to first positive peak.

5.4. Mid-amplitude point

One leading manufacturer uses an algorithm to automatically set T_0 at the mid-amplitude point between first negative and first positive peaks in their GPR systems. As with method (C) this location is relatively easy to compute, and has proved to be highly stable with regard to reproducibility for a given antennae provided the recording time range was kept constant. The algorithm is not consistent for setting T_0 across different time ranges, e.g. for a 400 MHz antenna with time range of 70 ns T_0 is located at approximately the zero amplitude point (same as C), but as the time range is shortened T_0 moves progressively later towards the first positive peak, being almost coincident with this positive peak at 17.5 ns. The same automatic routine tested did not work for setting T_0 with higher frequency antennae (e.g. 1.5 GHz), due to the complexity of sensing the direct wave peak amplitude position with delay line present between the Tx electronics and the antenna. The T_0 position is therefore set manually by inspection for these high frequency antennae.

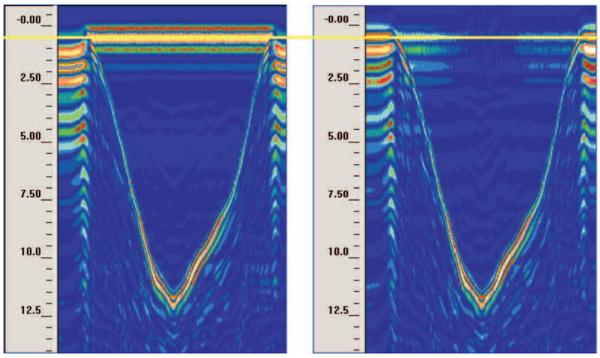
5.5. First positive peak

This point is the largest amplitude of the direct wave, hence is very easy to identify and thus favoured for manual setting T_0 in the field by many GPR users. It is slightly less stable with variations in height above the surface than method B. Methods F and G are variations of method E.

5.6. First positive peak with antenna lifting test

As a variation of method (E), several pavement survey companies reported using the first positive peak in combination with an antenna lifting test. This test is performed in the field prior to each survey by raising the antenna slowly from the ground surface to shoulder height, and then returning it to the ground while observing the reflected waveforms as a V shaped return on a B-scan (Fig 7a – raw data). A horizontal background removal (BGR) filter is applied (Fig 7b) and a suitable colour palette is used to distinguish positive and negative polarity reflections.

Using this method the direct wave on the ground is easily separated from the direct wave in air, with T_0 being set at the first positive peak in air (yellow line). Note that there is a slight shift to an earlier time position in the direct wave when the antenna is on the ground surface, as shown on the extreme left and right sides of Fig. 7a.



a) b)

Fig. 7. Antenna lifting test in combination with first positive peak, as described in Method F. Raw data on left, BGR Filter on right. 1.5 GHz antenna, range 15 ns.

5.7. Calibrated time prior to first positive peak

This method uses the easily identified positive peak of the direct wave (as in E), and sets the T_0 position at a calibrated time in advance of this positive peak based on the analysis of coring results.

In 1998 a research project was conducted by New Hampshire DOT and GSSI to try to accurately measure the cover depths of rebar in new bridge decks using GPR [7]. As a result of the findings, the New Hampshire DOT decided to make the GPR technique their standard method for QA/QC on bridge decks and for determining contractor pay factor. They used a GSSI Model 5100 antenna (with nominal centre frequency of 1.5 GHz). Zero time was set at a fixed time position of -0.1 ns preceding the positive peak of the direct coupling, with one ground truth point (obtained by coring down into a rebar). This gave an approximate velocity that provided reasonably accurate depths from 1.5–3.5 inches (38–88 mm). The exact time zero was not known. The calibrated velocity may not have been the exact velocity, but the empirically derived value was accepted as good enough to compensate for the possible error in calculating the correct T_0.

6. Georadar Method of Setting Time Zero

Due to involvement in several large (>Aus$1000 M) infrastructure construction projects since 1999, Georadar Research has had the opportunity to acquire a large number of core calibration points for T_0. Our shallow GPR data was mainly recorded using a 1.5 GHz antenna, mounted in a custom sled with 3 mm UHMW wear resistant base and minimal (# 1mm) air gap. Our measurements were typically made on fully cured high strength concrete surfaces, or mid strength concrete with asphalt overlay.

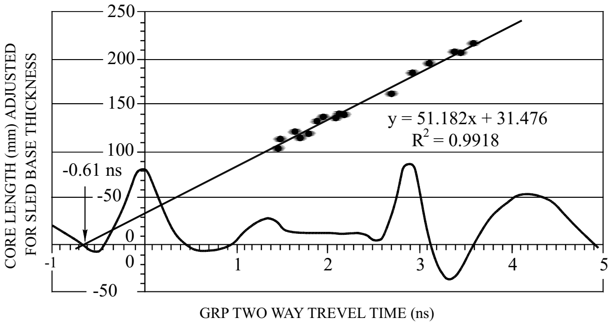


Fig. 8. Method of zero time calibration employed by Georadar Research, using detailed calibration with numerous coreholes.

The approximate T_0 is set in the field at the first maximum polarity peak of the direct wave. Multiple core locations are chosen by inspection of the field GPR data on screen. Coring is carefully supervised, and length measurements made on cores allowing for surface roughness of the cores and deriving mean surfaces. In processing, T_0 is set accurately (within 0.02 ns) of the first negative peak. Travel time is measured to identified interfaces or targets at the core sites and a graph of travel time v. core length constructed. The velocity (V) is derived from the gradient and the T_0 position is read from the time axis intercept of this graph, shown at -0.61 ns in Fig. 8, with waveform superimposed on graph. This places T_0 slightly in advance of the first negative peak for this material (fully cured high strength concrete, $V = 10.23$ cm/ns, dielectric 8.6). The accurately calibrated values of T_0 and velocity are used for calculation of true depths for layer or target digitising. Using the calibrated values of T0 and V gave a mean difference of 1.5 mm between the GPR predicted depth and blind core results, with maximum difference of 4 mm.

7. Conclusion

Zero time is not a constant value, but must be determined for each surface material type, and antenna set up configuration. It requires on-site calibration.

Setting the zero position accurately in the field is a difficult task. Most operators tend to choose a relatively stable and easily identified location (e.g. the first negative or the first positive peak of direct wave) and correct for this later.

We found that method (G) using a carefully calibrated time value in advance of the first positive peak of the direct wave gives the most consistently accurate results for shallow depth estimates. For a 1.5 GHz bow-tie antenna we found that the zero time position (equivalent to the actual surface of concrete) lies at a time position of -0.61 ns prior to the first positive peak of the received wave. This places it slightly (c. 0.06 ns) ahead of the first negative peak for this antenna under these conditions.

Acknowledgment

Numerous individuals and GPR organisations replied enthusiastically and contributed to our survey on setting T_0. In particular we wish to thank the following persons:

Peter Annan (S&S), Les Davies (TERAD), Xavier DJrobert (Lab. Central des Ponts et Chaussees, France), Dean Goodman (GPR-Slice), Johannes Hugenschmidt (EMPA), Harry Jol (Univ. of Wisconsin-Eau Claire), Jason Jones (QLD MRD), Andreas Kathage (GeoHiRes/GSSI), Jan van de Kruk (ETH), Guido Manacorda (IDS), Gary Olhoeft (Colorado School of Mines), Roger Roberts (GSSI), Timo Saarenketo (Road Scanners), Evert Slob (TU Delft), Erica Utsi (Groundvue), Per Wikstr'm (Radar Team), Daniel Yelf (Georadar Research).

Manuscript received November 15, 2006

References

[1] Yelf R., and Carse A. Audit of a road bridge superstructure using GPR // Proc. 8-th

International Conference on GPR, 23–26 May 2000, Gold Coast, Australia. – SPIE V. 4084. – P. 249–254.

[2] Hugenschmidt J. A one to one comparison between radar results and reality on a concrete bridge // Proc. 9-th International Conference on GPR, 29 April–2 May 2002, Santa Barbara, USA. – SPIE V. 4758. – P. 427–431.

[3] Harmuth, H.F. Radiation of Nonsinusoidal Electromagnetic Waves // Advances in Electronics & Electron Physics, Suppplement 23, Academic Press Inc. – 1990.

[4] Harmuth, H.F., Boules R. and Hussain M. Electromagnetic Signals : Reflection, Focusing, Distortion, and Their Practical Applications. – New York: Kluwer Academic/Plenum Publishers, USA. – 1999.

[5] Sato M., Iguchi M., Sato R. Transient response of coupled linear dipole antennas // IEEE Trans. on Antennas and Propogation – Feb 1984. – V. AP-32, №2. – P. 133–140.

[6] Roberts R.J. and Daniels, J.J. Modelling near field GPR in three dimensions using the FDTD method // Geophysics – V. 62, № 4. – P. 1114–1126.

[7] Perkins A.D., Amrol J.J., Romero F.A. and Roberts R.L., OT Specification development based on evaluation of ground-penetrating radar system performance in measuring concrete cover (reinforcement depth) on new bridge deck construction // Structural Material Technology IV, 28 February–3 March, 2000. Technomic Publishing Co. – P. 53–60.